Integrating the Bonded Concrete Overlay of Asphalt (BCOA-ME) Design Procedure into the AASHTOWare Pavement ME Software

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Integrating the Bonded Concrete Overlay of Asphalt (BCOA-ME) Design Procedure into the AASHTOWare Pavement ME Software

Abstract

This report documents the implementation of a portion of the design procedure for short jointed bonded concrete overlay of asphalt pavement procedure (BCOA) as developed at the University of Pittsburgh by J. M. Vandenbossche, N. Dufalla and Z. Li ("Bonded Concrete Overlay of Asphalt Mechanistic-Empirical Design Procedure," *International Journal for Pavement Engineers*, DOI: 10.1080/10298436.2016.1141410, 2016) into the AASHTOWare Pavement ME.

A portion of the BCOA was implemented into the AASHTOWare Pavement ME software maintaining as many of the theory, key concepts, assumptions, and inputs as possible. The BCOA was renamed Short Jointed Plain Concrete Pavement over Asphalt Concrete (SJPCP/AC). These include full contact friction/bond between PCC and AC layers, relatively high load transfer efficiency of the transverse joints, and the critical longitudinal fatigue cracking location found in these midrange slab sizes. Ranges of key inputs include slab thickness (4 to 8 in PCC) and joint spacing from 5 to 8 ft. Unlike in the BCOA, the very short slabs, e.g., <4.5 ft., were not included in the implementation due to the obvious overlap of truck wheelpaths and the shorter spaced longitudinal joints which results in poor performance with corner cracks and debonding beneath the corners. BCOAs with less than 6 in full lane width slabs were also not included in the AASHTOWare Pavement ME software. Longer jointed conventional full contact friction/bonded PCC overlays of asphalt pavement are already included in the AASHTOWare Pavement ME software. Other computational differences include those required to match the computational procedures of the AASHTOWare Pavement ME (e.g., axle load spectra vs ESALs; monthly AC dynamic modulus, PCC strength and modulus, monthly unbound material resilient modulus).

The calibration included 30 sections from three states with 371 cracking observation points. The range of age was from 2 to 18 years, and the total number of trucks ranged from 1 to 10 million in the heaviest trafficked lane. The longitudinal cracking calibrated model had excellent fit with a high R^2 and low standard error, and no statistical bias. The sensitivity analysis indicated that all key factors produced the expected change in longitudinal fatigue cracking. Several actual designs were completed using the site conditions of existing JSPCP/BCOA projects. The AASHTOWare ME thicknesses turned out to be reasonable in most cases. Longitudinal fatigue cracking was included, as is the case for the slabs included in the BCOA-ME procedure. Joint faulting and smoothness (IRI) are two other equally important performance criteria that are not included since they were not in the BCOA-ME procedure. They are included in all of the other AASHTOWare Pavement ME applications (JPCP overlays, new and reconstructed JPCP). Faulting is developing on some of the SJPCP test sections under heavy Interstate traffic. Before this design procedure can be considered robust, there needs to be a faulting model as well as an IRI model added to provide a reliable SJPCP design.

Integrating the Bonded Concrete Overlay of Asphalt (BCOA-ME) Design Procedure into the AASHTOWare ME Software

1 Introduction

BACKGROUND

This report documents the implementation of a portion of the design procedure for short slabs in bonded concrete overlay of asphalt pavement procedure (BCOA) into the AASHTOWare Pavement ME software. The BCOA-ME was developed at the University of Pittsburgh by J. M. Vandenbossche, N. Dufalla and Z. Li ("Bonded Concrete Overlay of Asphalt Mechanistic-Empirical Design Procedure," *International Journal for Pavement Engineers*, DOI: 10.1080/10298436.2016.1141410, 2016).

SCOPE

The scope of the implementation was to duplicate, as closely as possible, the theory, assumptions, inputs, and calibration process used in the development of the BCOA-ME into the computational algorithms utilized for accumulative damage in the AASHTOWare Pavement ME. Basic assumptions such as the contact friction/bond between PCC and AC layers, a high amount of load transfer at the transverse joints, and location of the critical bending stress made in the development of the BCOA-ME procedure were maintained in the AASHTOWare ME procedure. Only slab dimensions ranging from 5 to 8 ft were implemented. Inputs were matched as closely as possible. Differences mostly include those required for the BCOA-ME to match the computational procedures of the AASHTOWare Pavement ME. Longitudinal fatigue cracking initiating at the slab bottom was directly considered. A database of 30 sections and 371 observations was assembled for calibration of the longitudinal cracking transfer function. Excellent goodness of fit statistics was obtained. Transverse cracking, joint faulting, and smoothness (IRI) were not included in the procedure. PCC slab thickness ranging from 4 to 8 in and an existing AC layer thickness ranging from 3 to 8 in were included. Joint spacing ranging from 5 to 8 ft was included but less than 5 ft or greater than 8 ft was not included.

TERMINOLOGY

The terminology used to describe these bonded concrete overlays of existing asphalt pavement varies. In this document, to match AASHTOWare ME abbreviations, the term "short jointed plain concrete pavement (SJPCP) over AC" (or SJPCP/AC) overlays is included in the software.

- **Short Jointed Plain Concrete Pavement (SJPCP):** This title is defined specifically as bonded concrete overlay placed over an existing asphalt pavement. These relative thin (4 to 8 inches) concrete overlays are bonded to the existing asphalt pavement surface and have a short joint spacing (5x5, 6x6, 7x7 and 8x8 ft). These overlays are referred to as Bonded Concrete Overlay Asphalt Pavements (BCOA-ME) by the developers.

- **Ultra-Thin PCC overlays**: Ultra-thin PCC overlays (e.g., <4 inches) is not included in the AASHTOWare ME. The SJPCP bonded overlays can be designed between 4 and 8 in with longitudinal joint spacings of 5 to 8 ft.
- **Conventional full lane width JPCP bonded overlays over existing asphalt pavement:** This design is already included in the AASHTOWare ME designated as JPCP/AC and has a minimum thickness of 6 in and minimum joint spacing of 10 ft.

CRITICAL STRESS LOCATION FOR SJPCP

When the truck axles are near the transverse joint in the general area of the wheel paths, which generally lies between the longitudinal joints (typically 6x6 ft), a critical tensile bending stress occurs at the bottom of the slab under the wheel load. This stress increases when there is a high positive temperature gradient through the slab (the top of the slab is warmer than the bottom of the slab). Repeated loadings of heavy axles under those conditions result in fatigue damage along the bottom of the transverse joint of the slab, which eventually results in a longitudinal fatigue crack that propagates to the surface of the slab and along the slab length. Bottom-up longitudinal fatigue cracking is calculated as a percent of the total number of slabs, which is the output parameter used for structural design.

MAJOR TECHNICAL ADVANTAGES/DISADVANTAGES

The major technical advantage for short joint spacings is to greatly minimize thermal and moisture curling of the slab. Minimizing slab curl in itself is a great advantage of SJPCP to reduce slab cracking.

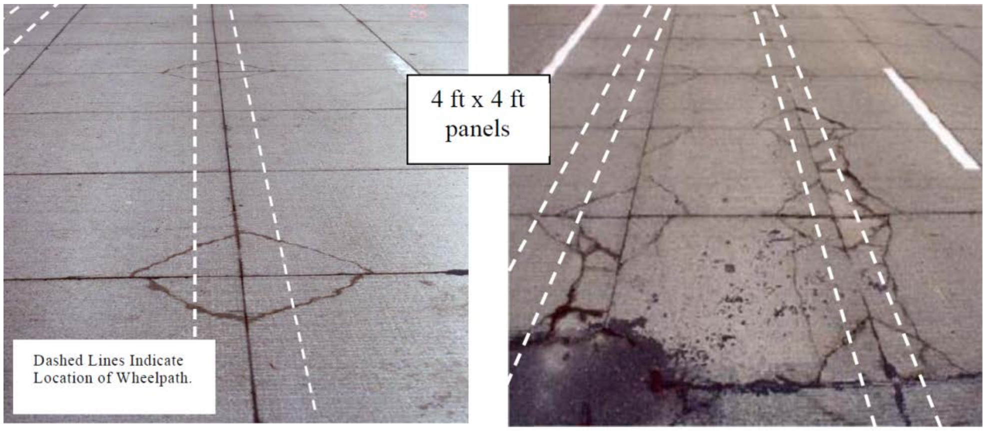
On the other hand, there are significant potential problems that come with such short joint spacings (more than twice as many joints and higher deflections). The greatest risk is the potential for debonding of the PCC and AC layers where contact friction and bond is lost through stripping or erosion. When this occurs, a large increase in the critical bending stresses results with an accompanying increase of fatigue damage and rapid major cracking of the slabs.

When the wheel paths of the trucks cross over the non-doweled corners of the small slabs, they also cause high deflections which are believed to contribute to increased potential for erosion or stripping of the underlying AC and also faulting of the transverse joints followed by increased roughness.

The following discussion addresses the overlap of the longitudinal joint and the truck wheelpaths. Vandenbossche, Barman, Mu and Gatti (2011) made the following observation regarding this issue based on the performance of BCOA at MnRoad:

- <u>“The amount of cracking and the cracking patterns that develop in each section were directly influenced by the joint layout and stress that developed as a function of the joint layout.</u> For example, one of the longitudinal joints of a 4x4 ft joint layout (Cells 93 and 94) was located at the inside wheelpath, which resulted in high edge stresses. This resulted in corner cracking for both the 4-in and 3--in overlays. Figure “1” shows two distress photos in Cell 94 in 2001 and 2003 (with typical wheel paths).” (See Figure 1)
- “In Cell 95, the performance of the 3 in overlay with the 5x6 ft panels was significantly better than the 3-in overlay in Cell 94 with 4x4 ft panels. <u>For the 5x6 ft panels, the longitudinal joint was moved outside of the wheelpath and the loads were applied in the inner portion of the slab.”</u> Vandenbossche, Barman, Mu and Gatti (2011).

The authors continue on to say that Cell 96 with, 6 ft wide slabs (6 ft longitudinal joints), has not shown any corner cracks over 11.5 years. Cells 60 and 63 with 6x5 ft joint spacing had also not shown any corner cracks over 4.5 years. They also note that comparable performance was obtained to date between a 4-in PCC slab with 4x4 ft spacing and a 3-in PCC slab and 6x5 ft spacing. Vandenbossche et al then conclude that an optimum design would be the 6x5 ft with a 3 in thickness (for this specific project) since this is a much lower cost than the thicker 4 in with 4x4 ft that would have a thicker slab and much great joint sawing and sealing costs.



(a) Cell 94 during 2001 (b) Cell 94 during 2003

Figure 1. Illustration of overlap of truck wheelpaths and longitudinal joints for a 4x4 ft joint spacing at MnRoad, Cell 94. (Vandenbossche, 2011)

This report first describes BCOA-ME design procedure developed at the University of Pittsburgh, then the key issues and recommendations for joint spacing for the AASHTOWare ME procedure, illustrations of typical SJPCP pavements, design inputs, calibration database, the global calibration of the longitudinal cracking model, sensitivity analysis of the AASHTOWare

ME designs for SJPCP, and finally a summary of the implementation. Appendices are included that contain the design and performance data for 30 sections.

2 Bonded Concrete Overlay of Asphalt (BCOA-ME) Procedure (University of Pittsburgh)

This work focused on the implementation of a portion of the BCOA-ME procedure developed by J. M. Vandenbossche, N. Dufalla and Z. Li, “Bonded Concrete Overlay of Asphalt Mechanistic-Empirical Design Procedure,” International Journal for Pavement Engineers, DOI: 10.1080/10298436.2016.1141410, 2016, into the AASHTOWare ME. The procedure covers three different types of commonly defined PCC overlay designs and critical fatigue cracking distress:

1. Longitudinal joint spacing 2 to 4.5 ft: Corner cracking is modeled and used for performance criteria because truck wheel paths near the corners of the small slabs result in predominantly corner fatigue cracking.
2. Longitudinal joint spacing >4.5 to 7 ft: Longitudinal cracking is modeled and used for performance criteria because truck wheel paths in the center of the slabs result in predominantly longitudinal fatigue cracking.
3. Longitudinal joint spacing full lane width (e.g., 12 ft): Transverse cracking is modeled and used for performance criteria because truck wheel paths (plus curling stresses) near the outside longitudinal joint result in transverse fatigue cracking.

This implementation of the BCOA ME into the AASHTOWare Pavement ME focused on the No. 2 type of design. The No. 1 design is not recommended for the AASHTOWare Pavement ME implementation because of significant engineering and construction cost reasons described in this document. No. 3 is already included in the AASHTOWare ME and permits the design of full lane width bonded JPCP overlay (6 in and greater) of existing AC pavement.

The University of Pittsburgh team (as well as the MnRoad researchers, see Burnham, 2005) identified early on that when the <4.5 ft longitudinal joint spacing was constructed with multiple longitudinal joints across the lane and small panel sizes, that corner cracks was the predominant distress that caused failure of the pavement and would have to be considered directly in design to prevent its occurrence. They also identified that for 6 to 7 ft longitudinal joint spacing, longitudinal fatigue cracking was the predominant type of distress that had to be directly considered in design.

In addition, the University of Pittsburgh team determined that for full lane width and length slabs, transverse cracking was the predominant distress that had to be directly considered in design. This agreed with the NCHRP 1-37A design procedure that included transverse cracking (both top down and bottom up) directly in design.

3 Key Issues for Joint Spacing for SJPCP

Key issues regarding joint spacing design, performance, and cost are summarized as follows.

KEY ISSUE NO. 1: WHEELPATHS, LONGITUDINAL JOINT LOADING, AND CRACKING

A valuable key contribution to the design procedure for BCOA-ME (University of Pittsburgh) was the observation of the developers that the joint spacing (or panel size) affected the type of cracking that developed on many projects around the US.

> "However, a performance review indicates that actual failure modes are dictated more by slab size than PCC overlay thickness. Whitetopping projects with 6x6 ft joint spacing more frequently experience longitudinal cracking while smaller slabs (such as 3x3 and 4x4 ft) experience corner cracking."
>
> "A review of the performance of whitetopping projects across the United States supports these conclusions." (Li, Dufalla, Mu, and Vandenbossche, 2013)

Because of this finding, equations were developed to calculate the critical stresses for different slab sizes.

- Equations for critical stresses for corner loading of slabs with equal to or less than 4.5 ft longitudinal joint spacing.
- Equations for critical stresses for transverse joint loading of slabs with >4.5 to 7 ft longitudinal joint spacing.
- Equations for critical stresses for conventional full lane width (12 ft) JPCP slabs.

These equations were then used in the BCOA ME (University of Pittsburgh) design procedure to compute fatigue damage, which was then correlated to field cracking.

The explanation of why corner cracks occur with <4.5 ft joint spacing and longitudinal cracks occur with 4.5 to 7 ft joint spacing is related to the wheelpaths and magnitude of stresses.

- A longitudinal joint spacing that splits the traffic lane into two slabs (e.g., 6 ft for a 12 ft traffic lane) has a wheel path that travels up the center of each of the 6 ft slabs, as illustrated in Figure 2. The 47-in width of the wheel path is calculated using a standard deviation of 10 inches and a 99 percent confidence interval for a Normal distribution. The graphic shows that a high percentage of the wheel loads will not be close to the corners of the slab but largely in the center portion of the 6 ft wide slabs. Thus, the critical fatigue point occurs along the bottom of the transverse joint. This repeated bending stress will eventually lead to fatigue damage and a longitudinal bottom up crack that will propagate along the slab, as shown in Figure 3.

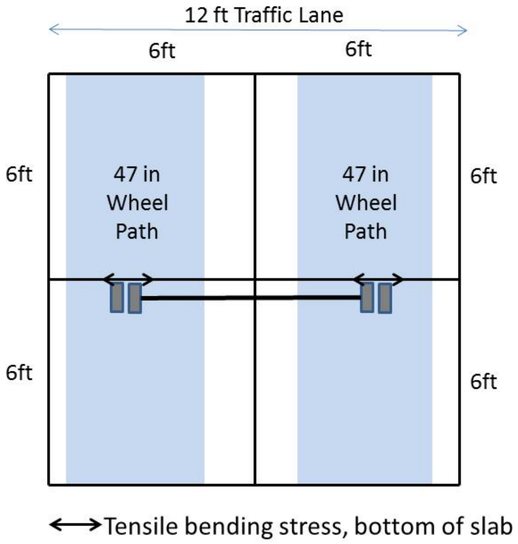


Figure 2. Truck wheel paths and longitudinal cracking (Normal distribution with standard deviation = 10 in and 99% confidence interval, and 6x6 ft slabs.

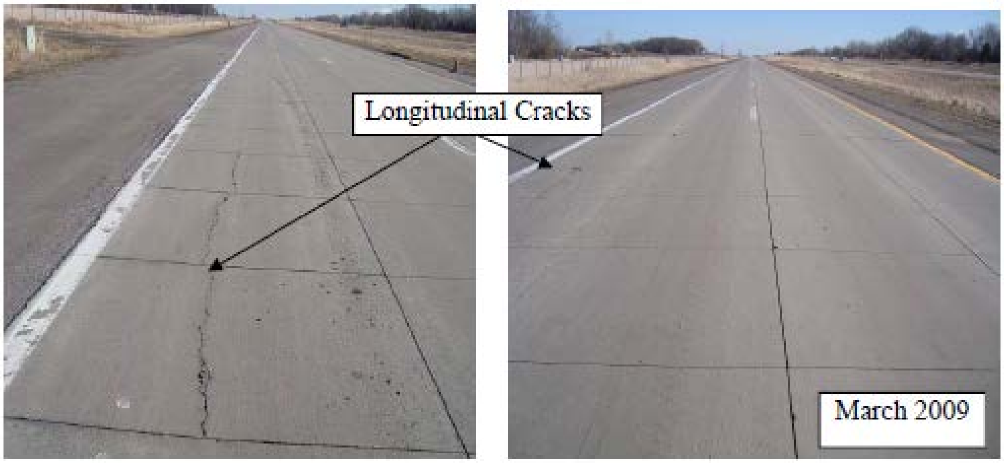


Figure 3. MnRoad SJPCP Test Sections with 6x6 ft joint spacing and longitudinal fatigue cracking. (Vandenbossche, Barman, Mu, Gatti, 2011)

When there are two (4x4 ft) or three (3x3 ft) longitudinal joints (actually anything shorter than ½ the lane width), there is a much greater chance that a wheel load will hit a slab corner and cause a high bending stress at the surface. Figure 4 illustrates the same wheel paths for a 4x4 ft longitudinal joint spacing. Here it can be seen that all of the interior corners are within the width of the wheelpaths and thus will be loaded much more often than with the 6x6 ft joint spacing. In addition to a higher number of repetitions is the higher corner bending stress at the top of the slab (with no dowels for load transfer). This leads to high fatigue damage and corner cracking rather than longitudinal cracking for this joint design as shown in Figure 5.

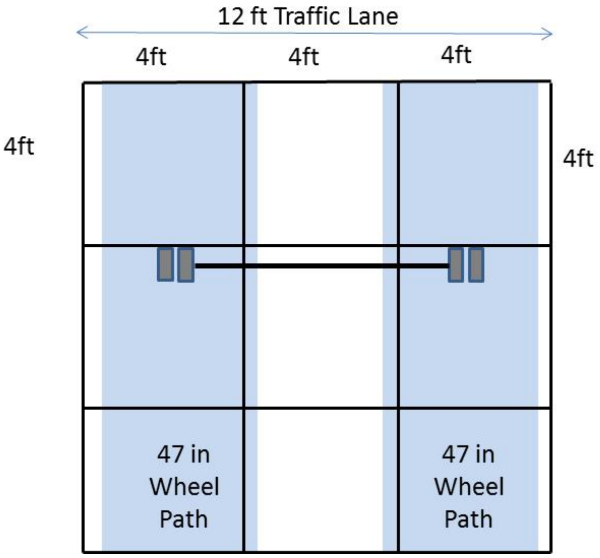


Figure 4. Truck wheel paths and for 4x4 ft slabs showing greater potential for loading of slab corners developing into corner cracks. (Normal distribution with standard deviation = 10 in and 99% confidence bands, truck width = 102 in).

Figure 5. MnRoad test section with 4x4 ft joint spacing and corner fatigue cracking. (Burnham, 2005)

Additional illustrations of truck wheel loads traveling down a traffic lane near the longitudinal joints is shown in Figures 6a and 6b for a 4x4 ft SJPCP overlay in Wisconsin. Note how close the wheels are to the longitudinal joints and the loading of many corners for short jointed SJPCP, which results in much higher bending stresses in the PCC than loading at the transverse joint.

Figure 6a. Wisconsin SJPCP with 4x4 joint spacing. Note the closeness of the wheel loads to the longitudinal joints and corners.

Figure 6b. Wisconsin SJPCP with 4x4 joint spacing. Note that with any lateral wander, the wheel loads will load the slab corners more frequently.

These results indicate that when shorter slabs (e.g., less than ½ the traffic lane width) are to be used, they must be designed to prevent corner cracking. This will increase the required thickness of the SJPCP over that of the ½ lane width joint spacing and panel size. One example run using the BCOA-ME software (University of Pittsburgh) indicated the following for 1 million ESALs:

- 3.8 in PCC/6 in AC required for 6x6 ft slab size (longitudinal cracking).
- 5.2 in PCC/6 in AC required for 4x4 ft slab size (corner cracking).

This represents a 5.2/3.8 = 1.4, or 40 percent increase of required slab thickness between these two panel sizes due to higher bending stresses and numbers of truck wheels within the vicinity of the longitudinal joints.

Tom Burnham, Senior Road Research Engineer at MnRoad states the following with regard to MnRoad performance:

> "Panel sizes that place wheelpaths near the edges of UTW slabs resulted in accelerated distress and poorer performance." (Burnham 2005)

KEY ISSUE NO. 2: JOINT SPACING AND SLAB CURLING

The key benefit of a shorter joint spacing (5 to 8 ft as opposed to 12+ ft) is that it greatly reduces thermal and moisture gradient curling of the slabs. However, the impact of varying short joint spacing from say 5 to 7 ft may still have an effect on bending stress due to variations in accumulated fatigue damage along the transverse joint in the truck wheel paths at the slab bottom. An example showing the impact of joint spacing is provided using the new calibrated AASHTOWare ME design (to be discussed in Sections 7 and 8):

- **MnRoad 63**. The initial AADTT is 4844 two-way truck traffic. Over the next 20 years, the project is expected to carry a total of 17.7 million trucks in the outer design lane. The PCC is 4 in and the AC is 8 in thick. The subgrade is AASHTO Class A-7-5, A-7-6, and A-6 and the weather station used was Minneapolis, MN. The calibrated AASHTO ME for SJPCP was run for varying joint spacings to determine the impact on longitudinal fatigue cracking. Program runs were made for lane widths of 10 ft (slabs 5x5 ft) to 14 ft (slabs 7x7 ft). The truck loading was assumed to remain in the center of the traffic lane. Results are shown in Table 1. Results show that as the lane width varies from 10 to 14 ft, with longitudinal joint spacing from 5 to 7 ft, and keeping the truck centered in the traffic lane, the longitudinal fatigue cracking increases significantly for this design. Note from Table 1 that the truck offset distance from the slab edge increases. This increase in truck offset moves the wheel load more and more near the center of the slab where the accumulation of fatigue damage is higher, thus higher fatigue cracking.

Table 1. AASHTO ME runs for MnRoad Cell 63 SJPCP showing impact of joint spacing (truck centered in lane).

PCC Thickness	AC Thickness	Joint Spacing (Lane Width)	Truck Lateral Offset from Lane Edge(in)*	Longitudinal Cracking @ R=95%
4 in	8 in	5x5 ft (10 ft)	9 in	7%
4 in	8 in	6x6 (12 ft)	21 in	21%
4 in	8 in	7x7 (14 ft)	33 in	68%

*Truck axle is 102 in wide and centered in traffic lane. The lateral standard deviation of the truck remains constant at 10 in.

KEY ISSUES NO. 3: JOINT SPACING IMPACT ON JOINT FORMING AND FILLING COSTS

The shorter the joint spacing, the more joint forming and filling is required, thus a much higher construction and maintenance cost. For example, Table 2 shows the number of feet of joint sawing (and filling if used) that is required for a mile of two-lane SJPCP with varying joint spacings.

Table 2. Results illustrating total transverse and longitudinal joint sawing and filling required for various joint spacings for a 1 mile of two-lane in same direction.

Lane Width, ft	Longitudinal Joint Spacing, ft	Transverse Joint Saw/Fill, ft	Longitudinal Joint Saw/Fill, ft	Total, ft	Ratio of 6x6 ft
12	3	42,240	36,960	79,200	2.1
12	4	31,680	26,400	58,080	1.6
10	5	25,344	15,840	41,184	1.1
12	**6**	**21,120**	**15,840**	**36,960**	**1.0**
14	7	18,103	5,280	23,383	0.6
16	8	15,840	5,280	21,120	0.6

Designing a joint spacing of 3x3 ft would more than double the amount of sawing and sealing the joints as compared to 6x6 ft spacing. A 4x4 ft design would increase lineal feet to saw and seal by 60 percent of that for 6x6 ft spacing. Thus, from a cost standpoint, there is a major incentive to design a longer joint spacing. Of course, the joint spacing must be compatible with the lane width and other geometric factors to avoid corner loading problems and corner cracking.

In addition to the saw and sealing aspect, when the joint spacing is shorter than ½ the lane width, the required design thickness of the PCC slab will increase using the BCOA ME design procedure (University of Pittsburgh) to consider and prevent corner cracking. The example previously shown indicated a 40 percent increase in PCC thickness. Thus, selection of shorter joint spacing than ½ lane width will require a thicker PCC overlay design to prevent corner cracking.

JOINT SPACING AND PCC/AC CONTACT FRICTION/BOND

The PCC/AC bond and contact friction is of course the most critical design issue and is absolutely required for long term good performance. When the longitudinal joint spacing is less than ½ the lane width, this results in having many additional wheel loads hitting the slab corners, which deflect far more than loading the transverse joint when the slab is ½ the lane width. When a corner is loaded, the deflection may be double that of a slab edge. Thus, the underlying bonded AC layer will also be deflecting about twice as much at the corners as they are loaded. These repeated high deflections at the corners in the wheel paths, especially if filled with water, may result in increased erosion causing debonding and loss of contact friction at the corners. If this occurs, then the pavement would likely develop fatigue corner cracking much sooner than designed. If this mechanism is valid, then efforts should be made to avoid corner loadings for SJPCP, or else this should be taken into consideration in design which would result in an even thicker PCC slab.

JOINT SPACING IN THE AASHTOWARE PAVEMENT ME DESIGN PROCEDURE

One of the major design decisions for SJPCP pavement design is the joint spacing. Other closely related design decisions include PCC thickness and the condition of the underlying existing AC layer and its ability to bond to and provide contact friction with the slab. Joint spacing (or panel size) affects the following:

- Type of fatigue cracking that develops (corner, longitudinal, transverse), thus slab thickness to prevent these types of cracking.
- Underlying erosion or debonding of the PCC slab from the AC layer, which affects faulting and smoothness as well as fatigue cracking.
- Cost of the joint forming and sealing operation.

The most common longitudinal joint spacing in use today on state and local highways is in the order of 6x6 ft, or approximately ½ the lane width. Joint spacing ranging from 2x2 ft to 6x6 ft or longer have also been constructed in the US and other countries since the early 1990s. The panel size is typically related to lane width and other geometric conditions. For example, a lane width of 10 ft (narrow low volume roadway) would accommodate a 5x5 ft joint spacing and a typical lane width of 12 ft would accommodate a 6x6 ft joint spacing. This panel size typically places the longitudinal joints such that the truck wheel paths load the transverse joints but not the corners in the wheel paths.

The scope of the BCOA ME (University of Pittsburgh) overlay design procedure for joint spacing, type of fatigue cracking, PCC thickness, and AC thickness are shown in Table 3. The recommendations for implementing the BCOA ME into the AASHTOWare ME are also shown in Table 3. Note that these recommended inputs and prediction models have all been successfully implemented into the AASHTOWare ME software and calibrated to field longitudinal cracking.

The AASHTOWare ME bonded concrete overlay of asphalt (SJPCP) includes the scope of the BCOA-ME for all inputs except panel size of 2x2, 3x3, and 4x4 ft and a PCC thickness less than 4 in.

- **Joint spacing (panel size) minimum limit:** It is recommended to not include design procedures for panel sizes ranging from 2 to 4 ft, since this will place the longitudinal joints within or near the truck wheelpaths. Much larger numbers of wheel loads impact the slab corners leading to significant corner cracking on many projects and potentially increased debonding of the PCC and AC layers due to high deflections at corners. While the PCC slab thickness can be increased to account for the more frequent wheel loadings and higher critical corner stresses, this would result in increased costs of construction along with greatly increased joint forming and sealing costs.

Table 3. BCOA ME (University of Pittsburgh) and recommended AASHTOWare ME joint spacing, slab thickness, and AC thickness.

Key Design Inputs	Critical Type Cracking	BCOA ME (U Pittsburgh)	Recommended AASHTOWare ME
Joint Spacing*			
2x2 ft	Corner	Yes	No
3x3 ft	Corner	Yes	No
4x4 ft	Corner	Yes	No
5x5 ft	Longitudinal	No	Yes
6x6 ft	Longitudinal	Yes	Yes
7x7 ft	Longitudinal	Yes	Yes
8x8 ft	Longitudinal	No	Yes
12x10 ft	Transverse	Yes	Existing Software (PCC 6+in)
12x12 ft	Transverse	Yes	Existing Software (PCC 6+in)
12x15 ft	Transverse	Yes	Existing Software (PCC 6+in)
PCC Slab Thickness	NA	3 to 6.5 in	4 to 8 in (5-8 ft Jt. Sp.) 6 to 12+ in (10-20 ft Jt. Sp.)
AC Layer Thickness	NA	3 to 10 in	3 to 8 in

*Joint spacing shows: Width x Length. Width is longitudinal joint spacing and length is transverse joint spacing (12x10 would be 12 ft longitudinal joint spacing and 10 ft transverse joint spacing). Varying the length by 1 ft plus or minus is acceptable (e.g. a 6x6 could be 6x5 or 6x7 ft) with no problem.

- **Optimum joint spacing (panel size):** Joint spacings or panel sizes of approximately ½ the lane width (e.g., 5 ft joint spacing for a 10 ft lane width, 6 ft joint spacing for a 12 ft lane width, 8 ft for a 16 ft wide ramp) would result in a greatly reduced number of wheel loads on the slab corners as well as reduced joint forming and sealing costs.
- **Locating the longitudinal joint at ½ the lane width**: The critical distress type is longitudinal fatigue cracking that is considered directly in design. The critical stress calculation models, the fatigue damage model, and the calibrated transfer function have been successfully developed and incorporated into the AASHTOWare ME software.
- **Adding longitudinal joints that result in less than ½ of the lane width (e.g., 2 to 4 ft):** The corner stress models (Neural Nets) can be developed and incorporated into the AASHTOWare ME and then fatigue damage at the corner calibrated similar to what has been done for longitudinal cracking. However, this design would result in increased construction costs due to (1) increased joint forming and sealing costs, (2) increased PCC design thickness, and (3) accelerated debonding or loss of contact friction at the PCC/AC interface near the slab corner resulting in increased cracking and maintenance. There are no known engineering or economic reasons to design panel size less than 5 ft.

ROBUST DESIGN?

The BCOA ME (University of Pittsburgh) considers only fatigue cracking for design. The AASHTOWare ME procedure for SJPCP likewise includes only fatigue cracking and also does not include joint faulting and IRI smoothness. Therefore, use of the AAHSTO ME procedure is deficient in the sense that slab cracking is directly considered and controlled, but joint faulting and smoothness (IRI) are not, which could result in a shortened life until diamond grinding is required. It is highly recommended that joint faulting and IRI be included into the procedure and calibrated using the available MnRoad and other data.

4 Illustrations of SJPCP Sections Included in the Calibration Database

This section provides just a few examples of SJPCP bonded overlays that are included in the calibration database to illustrate the performance of sections with varying joint spacings. SJPCP bonded overlays have been constructed in many US States as well as foreign countries. Some of the oldest and best well documented test sections come from MnRoad, which provided many test cells for use in the calibration. Colorado, who pioneered this design in the US, has constructed many SJPCP projects since 1990 with great success. Illinois also has many projects built since 2000. Several projects have been built in other States including Missouri, Kansas, and Minnesota (especially at MnRoad where performance has been well documented). The country of Chile, who pioneered this short jointed design as both bonded to AC and also placed on granular base courses, has seen a dramatic reduction in slab cracking compared to conventional full lane wide JPCP.

MNROAD

Many SJPCP test sections were constructed since 1997 and performance has been monitored along I-94 that is subjected to heavy truck traffic. In general, sections that had joint spacing ½ of lane width (6 ft) and were 5 to 6 in thick PCC (over 6 to 8 in AC) exhibited predominantly longitudinal cracking as identified in the BCOA ME (University of Pittsburgh) design procedure and shown in Figure 7.

Figure 7. MnRoad section with 6x6 ft joint spacing and 6 inch PCC over AC exhibited predominantly longitudinal cracking (A few corner cracks occurred along outer edges).

An illustration of the impact of longitudinal joint spacing (or panel size) is shown by a comparison of Cells 94 and 95. Both sections had 3 in PCC and 10 in AC designs. Cell 94 had 4x4 ft joint spacing (less than ½ the lane width) and Cell 95 a 6-ft wide slab (or ½ of the lane width). Figure 8 shows the performance of Cell 94 after 7 years. The truck lane (78 percent of the one-way trucks) indicates about 94 percent slabs with corner cracks along the wheel paths. The passing lane (22 percent of trucks) showed far less, as can be seen.

Figure 8. Cell 94 MnRoad driving lane with 3 in PCC, 4x4 ft joint spacing (longitudinal joints within wheelpaths, and 94 percent slabs with corner cracks. (Burnham, 2005)

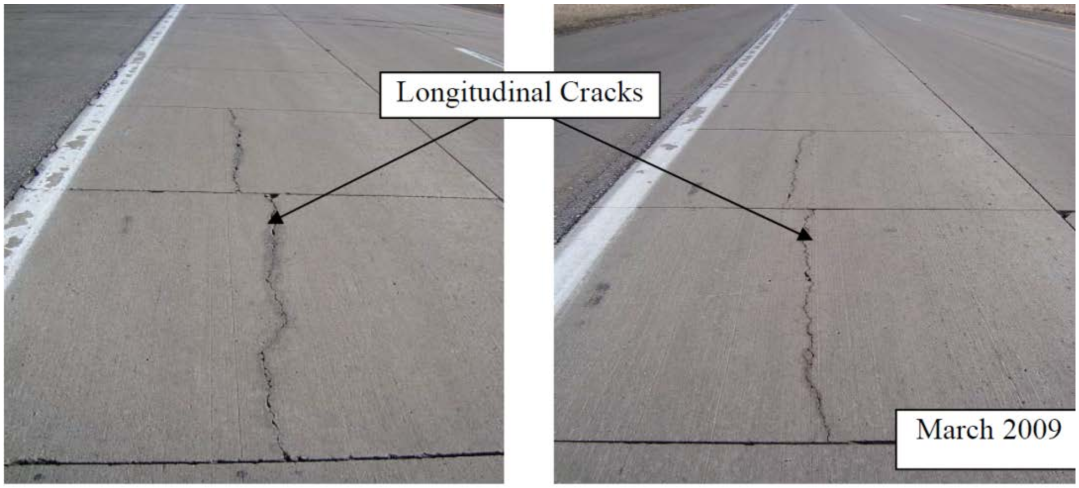
Figure 9 shows the performance of Cell 95 with a ½ lane 6 ft width longitudinal joint spacing and 3 in PCC for both truck and passing lanes after 7 years. The truck lane exhibited 32 percent corner cracks and the passing lane far fewer. Conclusions from the technical report are summarized:

> "The performance of ultra-thin whitetopping (UTW) test cells at the MnRoad project was clearly related to traffic volume, wheel load placement, and layer bonding. The amount and severity of distress was significantly higher in the driving lanes (higher traffic volume) of each test cell. Also, panel sizes that place wheel paths near the edges of UTW slabs resulted in accelerated distress and poor performance." (Burnham, 2005)

Left: Driving Lane Right: Passing Lane

Figure 9. Cell 95 MnRoad with 3 in PCC, 6Wx5L ft joint spacing over 10 in AC. (Burnham, 2005)

A classic photo of longitudinal fatigue cracking at midslab is shown in Figure 10 for Cells 61 and 63. These SJPCP are 5 and 6 in PCC with 7 and 8 in AC layers and both have 6Wx5L ft joint spacing.



(a) Cell 61 (b) Cell 63

Figure 10. Photo of longitudinal fatigue cracking at midslab is shown (Cells 61 and 63). (Vandenbossche, Barman, Mu, Gatti, 2011)

COLORADO

Colorado has been building many thin whitetopping (basically SJPCP) projects since 1990 and has conducted research and development of a ME based design procedure. Based on these results, the following guidelines were established:

- PCC thickness: 4 to 6 in, depending on traffic.
- PCC panel size: 6x6 ft. This would place the longitudinal joint in the center of the traffic lane, between the wheelpaths, most of the time.
- Milling and cleaning the AC surface prior to overlay.
- Deformed tie bars across the longitudinal joints spaced at 36 in.
- Joints are sealed with silicone including a backer rod.

One example project on Colorado 119 (Design3) has 6x6 ft joint spacing, 6.3 in PCC, 3.4 in AC over granular base is shown in Figure 11. This project was constructed in 1997 and has served for 18 years. The project was recently surveyed and found to have 2.4 percent longitudinal cracking and minimal corner or transverse cracking.

Figure 11. Photo of Colorado 119, Design 3.

ILLINOIS

Many different short jointed SJPCP overlays, including UTW, have been constructed in Illinois. They have generally exhibited good performance. Figure 12 shows a project near Champaign, IL on highway CH 2 that was built in 2001 and is several miles long. This project has ½ lane width joint spacing at 5.5Wx6L ft, 5.75 in PCC, 6.5 in of AC, and 10 in of granular base. The project is under low truck traffic and has zero longitudinal cracking, corner cracking, or transverse cracking after 15 years.

Figure 12. Photo of Illinois CH 2, zero cracking after 15 years, zero longitudinal cracking.

MISSOURI

Missouri has constructed a number of BCOA overlays. (Missouri DOT, 2004) The US 60 overlay is the oldest and largest BCOA. It was built in 1999 (17 years old) and is over a mile long. Since then, Missouri built another seven or eight overlays, but they have been primarily at intersections, not along continuous mainline pavement.

The US 60 BCOA had a 4x4 ft joint spacing, the PCC overlay thickness was approximately 4.5 in with about 4 to 5 in AC depending on the milling depth. Current two-way truck traffic is approximately 1300. The primary failure mechanism has been corner cracking, as shown in Figure 13; which further validates the BCOA-ME team's assessment of primary failure mode for 4x4 ft slabs where the corners are close to the truck wheelpaths. After 16 years, there is less than 3% of the panels with corner cracks and no longitudinal or transverse cracking (see photo in Figure 14). This excellent performance indicates that good long term bonding between the PCC and AC was achieved and that PCC/AC thicknesses were appropriate for the traffic level to generally limit corner cracks.

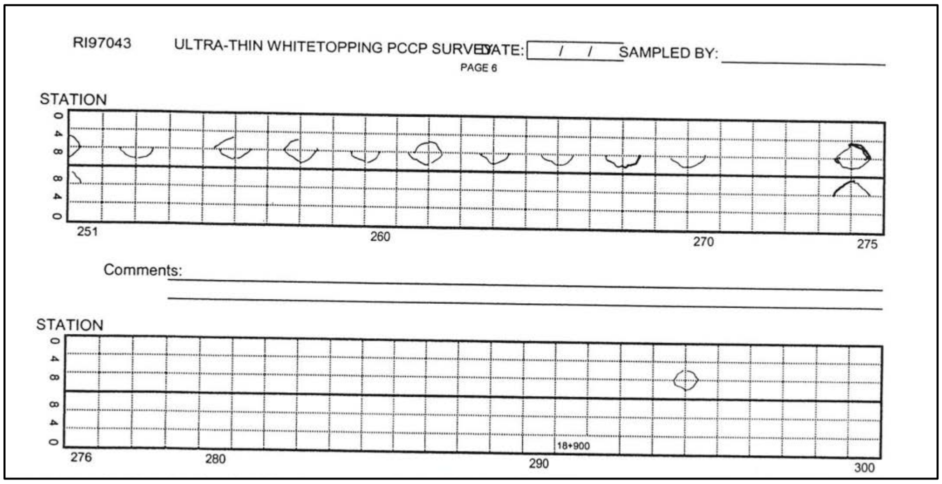


Figure 13. Condition survey of Missouri US 60 (4.5 in PCC and 4-5 in AC) after 16 years showing less than 3 percent corner cracking. Joint spacing is 4x4 ft with longitudinal joint near to the truck wheel paths, and good long term bond was achieved.

Figure 14. Recent photo of Missouri US 60 after 16 years in service, 4x4 ft joint spacing. (Photo courtesy of John Donahue, MoDOT)

CHILE

Chile has pioneered the SJPCP pavement overlay and new construction since the 1990's. Use of this short jointed design has dramatically reduced all types of cracking on conventional JPCP (e.g., joint spacing 12 to 19 ft) in Chile. One SJPCP project is located on Route 5 NBL along the Pan American Highway, Talca, Chile. The project was placed in 2008 on the heaviest traffic highway in Chile with 8,000 AADTT (trucks and buses) in two directions. The design included the following:

- 6.3 in PCC (outer lane SJPCP only, inner lane was AC overlay of existing JPCP).
- 2.3 in HMA.
- 8 in badly cracked JPCP with 4 in CTB base.
- Longitudinal joint at ½ lane width: 12/2= 6 ft at center of traffic lane.
- Transverse joints spaced at 6.7 ft.
- Joints sawed with narrow bade, 0.08 in wide and no sealant.

The performance over 7 years has been excellent with no observed cracking or joint faulting, as shown in Figure 15. The longitudinal joint is between the truck wheelpaths right down the center of the traffic lane. The AC over the existing cracked JPCP apparently bonded well and no problems have developed.

Figure 15. BCOA project (outer lane) on Route 5, the Pan American Highway that runs north/south in Chile carrying very heavy truck traffic Talca, Chile (6Wx6.7L ft joint spacing).

5 Design Inputs

LONGITUDINAL CRACKING CRITERIA

Longitudinal fatigue cracking initiates at the bottom of the PCC slab in the wheel path along the transverse joint. The level of acceptable longitudinal cracking has a large effect on design thickness and should be established by the design agency for this type of design after careful review. The initial design examples indicate that a slightly lower cracking criterion is needed, as shown in table 4.

Table 4. Suggested longitudinal cracking criteria for design.

Pavement Type	Performance Criteria	Maximum Value at End of Design Life
SJPCP/AC	Longitudinal fatigue cracking	Interstate: 10 percent slabs* Primary: 12 percent slabs* Secondary: 15 percent slabs*

*Performance criteria levels need review by agency for adequacy.

RELIABILITY

Design reliability is estimated the same as recommended in the AASHTOWare Pavement ME Manual of Practice (MOP).

TRAFFIC

Traffic inputs are the same as for conventional JPCP using the load spectral approach.

CLIMATE

Climate inputs are the same as for conventional JPCP from first order weather stations.

JOINT SPACING

Joint spacing can range from 5x5 to 8x8 ft, depending on lane width and other factors. This short joint spacing minimizes slab curling and potential for cracking significantly. However, the longitudinal joint spacing must be such that they do not coincide with the wheel paths of heavy trucks. Where ever this has occurred, many corner cracks have developed. In addition, the longitudinal joints should be tied to restrain them from opening over time. Note the longitudinal joint was not tied at MnRoad, but some of the joints are now starting to open.

Examples of varying joint spacings are given as follows:

- If lane width is 10 ft, a 5x5 ft slab would be practical as the truck wheel loads would travel approximately down the middle of the slab and not over the longitudinal joint.
- If lane width is 11 ft, a 5.5x5.5 ft width slab would be practical as the truck wheel loads would travel approximately down the middle of the slab and not over the longitudinal joint.
- For a lane width of 12 ft, a 6x6 ft width slab size would be practical as the truck wheel loads would travel approximately down the middle of the slab and not over the longitudinal joint.
- For a 16 ft wide ramp, an 8x8 ft slab size would be acceptable as the truck wheel loads would travel approximately down the middle portion of the slab and not over the longitudinal joint.
- Slab length can vary somewhat as illustrated below:
    - 5x5 or 5.5x5.5 ft joint spacing: the slab length can vary up to 7 ft.
    - 6x6 or 6.5x6.5 ft joint spacing: the slab length can vary up to 8 ft.
    - 7x7 or 7.5x7.5 ft joint spacing: the slab length can vary up to 8 ft.
    - 8x8 ft joint spacing: the slab length can vary up to 8 ft.

TRANSVERSE JOINT LOAD TRANSFER EQUIVALENT (LTE)

The recommended annual transverse joint LTE is 80 percent, which was the value used to calibrate the procedure. However, provisions are available for a seasonal LTE input if desired. This value is based on measurements from MnRoad on various sections of SJPCP overlays. The 80 percent basically indicates that the AC layer does not typically crack beneath the short spaced transverse joints. However, the LTE input can be varied from 25 to 95 percent. This was found to be a very sensitive input in most cases. DeSantis et al 2016 provides some guidance on when the crack may reflect through the existing AC layer.

CONCRETE SLAB THICKNESS

Slab thickness can vary from 4 to 8 in, which is the range over which the stress calculating NNs were developed using the ISLAB finite element software. This was found to be a very sensitive input.

AC LAYER THICKNESS

AC layer thickness can vary from 3 to 8 in. Even if the existing AC layer is thicker than 8 in, it is recommended to limit this layer to 8 in to avoid a design with too thin of PCC slab and having it fail from another distress. This was found to be a very sensitive input.

AC LAYER CONDITION

The existing AC layer “damaged” dynamic modulus is a critical design factor. This “damaged” modulus is combined with the PCC modulus to calculate an “equivalent” slab thickness which is used for stress calculation. Thus, any reduction in the “damaged” AC layer modulus will ultimately increase longitudinal fatigue cracking of the PCC overlay. The Level 2 input of the percent fatigue cracking was used to estimate the “damaged” AC modulus but its scope was redefined as a “calibration factor” and modified to include three aspects of the layer: (1) the extent of fatigue cracking (or other types of cracking that is considered to be full depth and would cause a reduction in AC modulus over time, (2) material deterioration anywhere in the depth of the layer that would reduce the AC modulus over time, and (3) partial debonding or loss of contact friction between the PCC slab and AC layer over time.

These combined impacts were considered by determining the percent area of AC cracking required to achieve the measured longitudinal cracking for each section. The results showed a fairly narrow range from 50 to 75 percent for 30 sections with a mean of 65 percent. When the mean value of 65 percent was used for every section in the calibration of longitudinal cracking, the resulting calibration curve fit the field data very well with no bias as shown in Section 7. Thus, 65 percent became a constant calibration factor that is fixed in the software using Level 2 input. Level 1 and Level 3 were disabled in the software at this time.

SHOULDER

The shoulder can be a tied PCC shoulder that matches the joint spacing of the adjacent lane. The load transfer efficiency (LTE) is set at 40 percent. The shoulder can be untied meaning AC or turf material. The LTE for this case is set at 20 percent. A tied shoulder was found to increase required thickness slightly (due to the additional restraint), however, this may be well worth it to help reduce erosion at the outer slab edge causing joint faulting and corner cracking through us of a tied PCC shoulder.

6 Calibration Database

Significant effort was expended to develop a comprehensive database of SJPCP projects and test sections so that an effective calibration could be conducted. The major source of historical and reliable data was obtained from the various MnRoad test sections that were constructed on I-94 beginning in 1997 through 2013. Older test sections were also obtained from Colorado and Illinois, as both of these states have constructed many SJPCP projects. A total of 30 individual sections of SJPCP were included in the calibration database. There were a total of 371 longitudinal cracking point observations over their service life. Each section was examined and a few data points were removed due to various inconsistencies over time. A summary of the design features and performance is provided in this section. More details are provided in the appendix.

MNROAD PROJECTS

Several SJPCP sections were included constructed on I-94 between 1997 and 2013 and 25 of these sections were included. These sections included both the outside (driving or truck) lanes and the inside (or passing lane). The driving lane carried 78 percent of trucks while the passing lane 22 percent, which gave a good range of traffic loadings over the same time period for identical designs. Some key information from these sections is summarized in table 5.

ILLINOIS PROJECTS

Illinois has many SJPCP projects constructed since about 2000. Two older sections near Champaign, IL were selected that included some historical data. They were both resurveyed over their entire length. The major design features are shown in Table 6. These were older sections with 14 and 15 years of service data.

Table 5. Summary of MnRoad SJPCP sections.

Section*	PCC (in)	AC (in)	Slab Size** (ft)	Years of Performance Data	Maximum Longitudinal Fatigue Cracking % Slabs***	Other Information****
Cell 60 DL	5	7	6 × 5	6.0	5.7	Sealed
Cell 60 PL	5	7	6 × 5	6.9	12.5	Sealed
Cell 61 DL	5	7	6 × 5	7.5	9.1	Unsealed
Cell 61 PL	5	7	6 × 5	6.9	6.8	Unsealed
Cell 62 DL	4	8	6 × 5	7.5	13.6	Sealed
Cell 62 PL	4	8	6 × 5	7.5	11.7	Sealed
Cell 63 DL	4	8	6 × 5	7.5	46.6	Unsealed
Cell 96 DL	6	7	6 × 5	11.7	2.8	Sealed, Fibers
Cell 96 PL	6	7	6 × 5	17.6	0.0	Sealed, Fibers
Cell 114 DL	6	5	6 x 6	7.0	11.5	1" DL, Unsealed
Cell 114 PL	6	5	6 x 6	7.0	0.0	Unsealed
Cell 214 PL	6	5	6 x 6	7.0	0.0	Unsealed
Cell 314 DL	6	6	6 x 6	3.5	17.4	1" DL, Unsealed
Cell 314PL	6	6	6 x 6	7.0	0.0	Unsealed
Cell 414 PL	6	6	6 x 6	7.0	0.0	Unsealed
Cell 514 DL	6	7	6 x 6	7.0	8.3	1" DL, Unsealed
Cell 514 PL	6	7	6 x 6	2.3	0.0	Unsealed
Cell 714 DL	6	7.5	6 x 6	7.0	0.0	1" DL, Unsealed
Cell 714PL	6	7.5	6 x 6	6.0	0.0	Unsealed
Cell 814 DL	6	8	6 x 6	7.0	12.5	Unsealed
Cell 814 PL	6	8	6 x 6	2.3	0.0	Unsealed
Cell 914 DL	6	8	6 x 6	7.0	0.0	1" DL, Unsealed
Cell 914 PL	6	8	6 x 6	2.3	0.0	Unsealed
Cell 160 PL	5	6	6 x 6	2.3	0.0	Sealed, Fibers
Cell 162 PL	4	7	6 x 6	2.3	0.0	Sealed, Fibers

*DL = Driving/Truck Lane; PL = Passing Lane
**Slab size: First value is longitudinal joint spacing, second value is transverse joint spacing.
***% slabs with longitudinal cracking at latest pavement survey.
**** Dowels, fibers PCC, sealed or unsealed, or PCC shoulder listed here.

Table 6. Summary of Illinois SJPCP sections.

Section*	PCC	AC	Slab Size** (ft)	Years of Performance Data	Maximum Longitudinal Fatigue Cracking % Slabs***	Other Information****
Highway 4- Piatt County	5 in	4 in AC 8 in PCC	5.5 × 5.5	15	1.1	Two lane county highway
Highway 2- Cumberland County	5.75 in	6.5	5.5 × 6	14	0.0	Two lane County highway

*DL = Driving/Truck Lane; PL = Passing Lane
**Slab size: First value is longitudinal joint spacing, second value is transverse joint spacing.
***% slabs with longitudinal cracking at latest pavement survey.
**** Dowels, fiber PCC, or PCC shoulder listed here.

COLORADO PROJECTS

Colorado has constructed many SJPCP projects since about 1990. Three older sections near Ft. Collins, CO were selected for inclusion in the database. They were both resurveyed over their entire length. The passing lane was also included on one of the sections. The major design features are shown in Table 7. These were older sections with 18 years of service.

Table 7. Summary of Colorado SJPCP sections.

Section*	PCC	AC	Slab Size**df	Years of Performance Data	Maximum Longitudinal Fatigue Cracking, % Slabs***	Other Information****
SH 119 DL Section 1_Slab Design 3	5	3.3	6 × 6	18	2.5	Driving Lane
SH 119 PL Section 1_Slab Design 3	5	3.3	6 × 6	18	17.3	Passing Lane. Has much more truck traffic, in urban truck area
SH 119 DL Section 1_Slab Design 4	5.1	3.3	6 × 6	18	0.0	Passing Lane

*DL = Driving/Truck Lane; PL = Passing Lane
**Slab size: First value is longitudinal joint spacing; second value is transverse joint spacing.
***% slabs with longitudinal cracking at latest pavement survey.
**** Dowels, fiber PCC, sealed, or PCC shoulder listed here.

SUMMARY OF SJPCP SECTIONS IN DATABASE

The following summarizes the key design and other features of the sections used in the calibration effort:

- Service life ranged from 2 to 18 years with a mean of 8 years.
- Total trucks carried by these sections on MnRoad I-94 typically ranged around 5 million with up to about 10 million for the oldest driving lane sections. Other sections from IL and CO received in the order of 1 to 5 million.
- There are a total of 30 SJPCP sections and all but one section has multiple distress measurement points (average of 12 points per section).
- Longitudinal cracking (percent slabs) at the last survey ranged from 0 to 46 percent with a mean of 6.3 percent.
- Slab thickness ranged from 4 to 6 in with a mean of 5.4 in.
- AC thickness ranged from 3 to 8 in with a mean of 6.5 in.
- Longitudinal joint spacing ranged from 5.5 to 6 ft.
- Transverse joint spacing ranged from 5 to 6 ft.
- Most sections were sealed with only a few unsealed. No attempt was made to include this factor into the design procedure.
- A few sections included 1 in diameter dowels in the driving lane but not in the passing lane.
- Four sections included fibers in the PCC mixture. No attempt was made to include this into the design procedure.

7 Calibration of Longitudinal Cracking Transfer Function

The damage and longitudinal cracking distress transfer functions for relatively thin bonded concrete overlays of asphalt pavements (SJPCP) were globally calibrated in this study. Joint faulting and IRI are very important to the design of SJPCP but are not included in the design procedure at the present time. They are needed before this design procedure can be considered as robust as the other conventional JPCP designs in the AASHTOWare ME. The following summarizes the methodology and mathematical models used to calibrate the longitudinal fatigue cracking.

CRITICAL BENDING STRESS FOR LONGITUDINAL SLAB CRACKING (BOTTOM-UP) – SJPCP

Bottom-up longitudinal fatigue cracking in the wheel paths is predicted as the primary structural distress. Critical bending stresses occur when the truck axle passes over the transverse joint of the slabs in both wheel paths. The wheel paths occur between the longitudinal joints (which are typically spaced as ½ of the lane width) as illustrated in Figure 16. Similar to conventional JPCP ME design, calculation of critical stresses was done using neural nets (for speed) that require the PCC slab and lower AC layer to be combined into an "equivalent slab" thickness based on equivalent stresses (load and temperature/moisture gradients), and full contact friction between slab and AC layer. This is performed monthly as the "equivalent" slab thickness varies over time.

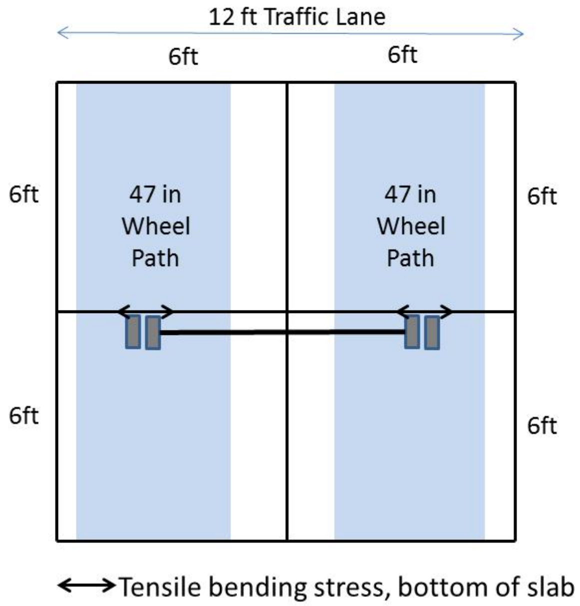


Figure 16. Illustration of proper location of longitudinal joints (approximately 1/2 lane width) to avoid corner cracking caused by overlap with truck wheel paths and the joints.

A critical tensile bending stress occurs at the bottom of the slab under the wheel load, which increases when there is a high positive temperature gradient through the slab (the top of the slab is warmer than the bottom of the slab). Repeated loadings of heavy axles under those conditions result in fatigue damage along the bottom transverse joint of the slab. Due to lateral wander of the truck axle load, different points along the transverse joint would accumulate fatigue damage at different rates. The software computes multiple points and selects the point of maximum fatigue damage for computation of longitudinal cracking. This point of maximum fatigue damage is where a longitudinal crack will initiate and then propagate to the surface of the slab and then extend along the slab.

NEURAL NET PREDICTION MODELS DEVELOPED

The rapid computation of critical bending stresses at the bottom of the PCC slab was accomplished using neural network technology (NN), similar to that used in the conventional AASHTOWare ME software for JPCP. The same ISLAB finite element model was utilized to develop the NNs. To develop the NNs for critical bending stress along the transverse joint (to predict longitudinal cracking), a matrix was designed to include the key design input variables. The following summarizes the inputs and key assumptions:

- The interface condition between the PCC and AC layers is fully bonded for the entire design life. Note that the conventional JPCP design includes an option for zero contact friction between the PCC and base layer after a specified number of months but this is not included for SJPCP.
- There is no moment transfer across the PCC transverse joints, i.e. the PCC and AC layers transfer only vertical shear.
- The AC layer is in full contact with the base/subgrade.
- PCC thickness (4 to 8 in), modulus of elasticity, and Poisson's ratio.
- AC thickness (3 to 8 in) and dynamic modulus (full undamaged and damaged range).
- Square slabs with longitudinal joint spacing of 5 to 8 ft. As mentioned elsewhere, the length of the slabs can be increased somewhat and not affect longitudinal cracking or transverse cracking.
- Transverse joint load transfer efficiency (LTE) ranging from 25 to 95 percent. All calibration done at 80 percent.
- Longitudinal joint LTE (for tied shoulder): 20 percent no tied shoulder and 40 percent tied shoulder.
- Longitudinal joints LTE was set at 50 percent.
- Range of equivalent linear temperature gradients (Due to the absence of separation between base and subgrade, the temperature stress is a linear function of temperature difference at top and bottom of slab and NNs were developed for one value equal to 10 degrees F).
- A wide range of equivalent subgrade resilient modulus, as in the conventional JPCP design, was included. The range of equivalent k-values for NNs was from 50 to 500 pci).
- Single, tandem, and tridem axle loadings (For tandem and tridem loading, an additional NN was developed using a spacing equal 51 in.)
- Single tire wheel loading on approach side of transverse joint.

- Lateral wander of the truck within traffic lane (Normal distribution, input standard deviation). NNs were developed for the set of offsets from the lane/shoulder joint starting from 0 to the lane/lane longitudinal joint. For example, in the case of 5 ft wide slabs, the offset values are equal 0, 2, 4, 6, 8, 10, … 44 in. Longitudinal cracking program includes inputs for mean wheelpath offset and standard deviation and uses this inputs and NN in the process of critical stresses calculation.
- The tire footpath width and length were fixed and the tire pressure is varied with axle load (The NN was developed for the standard tire pressure 120 psi. Due to linearity of the problem in the case of no separation of layers, critical stresses are proportional to the ratio of actual wheel load from the load spectra to a standard wheel load). The stresses from each of the dual tires were combined to produce a correct stress at the bottom of the slab.
- The ISLAB slab setup includes a total of 12 slabs to calculate the critical stress that causes longitudinal cracking in the traffic lane.
  - A single slab is defined as ranging from 5, 6, 7, and 8 ft. square.
  - There are four slabs in the longitudinal (traffic) direction so that single, tandem, and tridem axles are included.
  - There were three slabs transversely with two in the truck loading lane, and one for the outside shoulder.
  - The longitudinal lane/shoulder joint would have a constant LTE of either 20% (no tied PCC) or 40% (tied PCC).
  - The transverse joint would have an LTE ranging from 25 to 95 percent.
- The critical tensile bending stress will be at a transverse joint in the wheel path area at the bottom of the slab. Fatigue damage is accumulated at 2 in points along the transverse joint. The position of the highest damage depends on truck lateral wander and thermal stresses and may be located between the mean wheelpath point and the midpoint of the slab. For these purposes, the NN included a parameter position of analysis points on transverse joint starting from the shoulder with a 2 in increment. The longitudinal cracking program selects the location with maximum damage to predict longitudinal fatigue cracking.
- Coefficient of Thermal Expansion of PCC. Due to assumption of linearity of temperature stresses, the NNs were developed for the constant value of 4.4 degree F per in. Thus a wide range of CTE values can be utilized.
- A permanent curl/warp effective temperature difference of -10 degrees F was assumed.

ASSUMPTIONS IN STRESS CALCULATIONS

The following assumptions were made in the computation of the critical bottom of slab bending stresses.

- **Transverse Joint Load Transfer Efficiency (LTE).** The bending stress caused when the axle load passes over a transverse joint depends upon the aggregate interlock in the PCC slab, any mechanical device that may exist, and the underlying AC layer and sublayers. The BCOA-ME procedure assumed 90 percent LTE for the transverse joints which means that there is no reflection crack below the transverse joint in the underlying AC pavement. A similar high value of 80 percent was assumed for the implementation based on the mean of limited FWD testing data at MnRoad of SJPCP sections (about one of every four transverse joints cracked through the PCC). However, provisions are available for a seasonal LTE input if desired. The 80 percent assumption also indicates that the AC layer does not crack beneath the short spaced transverse joints. However, the LTE input can be varied from 25 to 95 percent. The 80 percent assumption was used for all sections.

- **Existing AC Layer Modulus.** Existing AC layer "damaged" modulus is a critical factor that greatly affects the critical bending stress in the PCC slab. Changing of AC stiffness leads not only to changing of effective slab stiffness but also to changing of the neutral axis position. These result in changes of the bottom of slab stresses under the wheel load and thus longitudinal cracking. As previously stated, the Level 2 input of percent area cracking was used as a calibration factor for all SJPCP sections and a constant default value of 65 percent is fixed in the software. Use of this input as a calibration constant provided a reasonable prediction of the field percent longitudinal cracking for SJPCP.

LONGITUDINAL SLAB CRACKING (BOTTOM-UP) CALIBRATION – SJPCP

Bottom-up longitudinal fatigue cracking is calculated as a percent of the total number of slabs in the wheel paths, which is the output performance criteria used for structural design. This distress is predicted using the globally calibrated Equation 1 "transfer function" for bottom-up longitudinal fatigue cracking. The two coefficients (C4, C5) were derived using non-linear regression between accumulated fatigue damage and the measured longitudinal cracking.

$$LCRK = \frac{1}{1 + 0.40\left(DI_F\right)^{-2.21}} \tag{1}$$

Where:

$LCRK$ = Predicted amount of bottom-up longitudinal fatigue cracking (percent slabs).
DI_F = Fatigue damage calculated using the procedure described in this section (Fraction from 0 to > 1) at the most critical point along the transverse joint.
C4, C5 = 0.40, -2.21 respectively derived coefficients to minimize prediction standard error.

The fatigue damage calculation is a process of summing damage over each damage increment at several critical points across the bottom of the slab along the transverse joint. The general expression for fatigue damage accumulation considering all critical factors for SJPCP longitudinal cracking is Equation 2 and referred to as Miner's hypothesis:

$$DI_F = \sum \frac{n_{i,j,k,l,m,n,o}}{N_{i,j,k,l,m,n,o}} \tag{2}$$

Where:

DI_F = Total fatigue damage (bottom-up).
$n_{i,j,k,\ldots}$ = Applied number of load applications at condition *i, j, k, l, m, n*.
$N_{i,j,k,\ldots}$ = Allowable number of load applications at condition *i, j, k, l, m, n*.
i =Age (accounts for change in PCC modulus of rupture and elasticity, slab/AC contact friction.
j = Month (accounts for change in AC dynamic modulus and dynamic subgrade K-Value).
k = Axle type (single, tandem, and tridem for bottom-up cracking).
l = Load level (incremental load for each axle type).
m = Equivalent temperature difference between top and bottom PCC surfaces.
n = Traffic offset path (normal distribution).
o = Hourly truck traffic fraction.

The applied number of load applications ($n_{i,j,k,l,m,n}$) is the actual number of axle type *k* of load level *l* that passed through traffic path *n* under each condition (age, season, and temperature difference). The allowable number of load applications (to cracking $N_{i,j,k,l,m,n}$) is) is the number of load cycles at which fatigue cracking is expected on average and is a function of the applied stress and PCC strength.

The allowable number of load applications ($N_{i,j,k,l,m,n}$) to cracking is determined using the PCC field fatigue Equation 3 which is used in the AASHTOWare Pavement ME.

$$\log\left(N_{i,j,k,l,m,n}\right) = C_1 \cdot \left(\frac{MR_i}{\sigma_{i,j,k,l,m,n}}\right)^{C_2} - 0.4371 \tag{3}$$

Where:

$N_{i,j,k,\ldots}$ = Allowable number of load applications at condition *i, j, k, l, m, n*.
M_{Ri} = PCC modulus of rupture at age *i*, psi.
$\sigma_{i,j,k,.}$ = Applied stress at condition *i, j, k, l, m, n*.
C_1 = Calibration constant, 2.0.
C_2 = Calibration constant, 1.22.

A plot of measured longitudinal cracking versus the computed fatigue damage at the bottom of the PCC slab is shown in Figure 17. This plot follows the typical S-Shaped curve transfer function between slab longitudinal fatigue cracking and cumulative fatigue damage at the bottom of the slab.

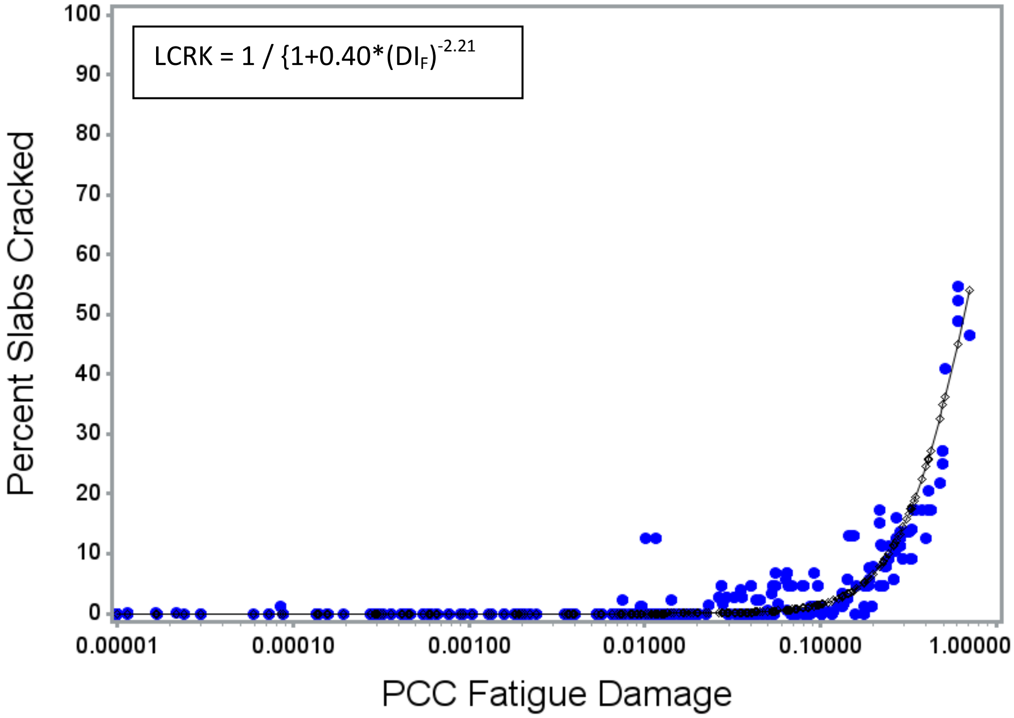


Figure 17. Measured longitudinal fatigue cracking (LCRK) versus cumulative PCC fatigue damage (DI_F) bottom of PCC slab.

Thus, using Equation 1, the results shown in table 8 illustrate the relationship between accumulated fatigue damage and longitudinal fatigue cracking. As fatigue damage approaches 1.0, the slabs cracked should be theoretically 50 percent (the calculated value is 71 percent) assuming all of the assumptions of Miner's damage model is correct as well as the stress calculation, the field PCC fatigue curve (N), the estimated truck axle loadings and weights, the lateral distribution of trucks, monthly moduli of all layers, bond or contact friction between PCC and AC layers and other factors are correct. Obviously all of these many assumptions are not exactly correct but the 71 percent result is reasonable.

Table 8. Illustration of accumulated fatigue damage at slab bottom in wheel path versus predicted longitudinal cracking.

Accumulated Fatigue Damage in Wheelpath	Predicted Longitudinal Cracking, Percent Slabs
0.00001	0.000000002%
0.001	0.00006
0.01	0.01
0.1	1.1
0.5	35
1.0	71

A plot of measured versus predicted longitudinal cracking and the statistics resulting from the global calibration process is shown in Figure 18. The goodness of fit parameters, $R^2 = 0.87$ and the standard error of the estimate was 2.87 percent suggest a good fit of the measured cracking to predicted cracking. In fact, the goodness of fit parameters are better than those for conventional JPCP transverse fatigue cracking. The total number of observations was 371. Since there were 30 total sections, this averages about 12 observations per section over time. Only one section had a single cracking observation point.

Statistical hypothesis testing at the 0.05 significance level was performed to ensure unbiased prediction:

- Hypothesis: No bias exists in prediction, meaning that the model does not consistently over or under predict cracking. One aspect of bias is indicated by the slope of the predicted versus measured cracking line. H_0: Slope = 1.0. The resulting p-value = 0.2312 (>0.05 level of significance) indicating that the Slope = 1.0 assumption cannot be rejected (no bias exists).
- Hypothesis: The intercept is zero is another aspect of bias. H_0: Difference = 0.0. The resulting p-value = 0.7869 (> 0.05), indicating that the intercept hypothesis of 0 cannot be rejected.
- Hypothesis: Another important aspect of bias is that the paired “Predicted - Measured” cracking for all sections is zero. H_0: Predicted and measured mean cracking are from the same population (paired t-test, difference =0). The resulting p-value = 0.8321 (> 0.05) indicates that the H_0 cannot be rejected, thus no bias.

The null hypothesis for all statistical tests could not be rejected indicating that the prediction model for longitudinal cracking is unbiasedly not over or under predicting cracking on average the measured longitudinal cracking in the field.

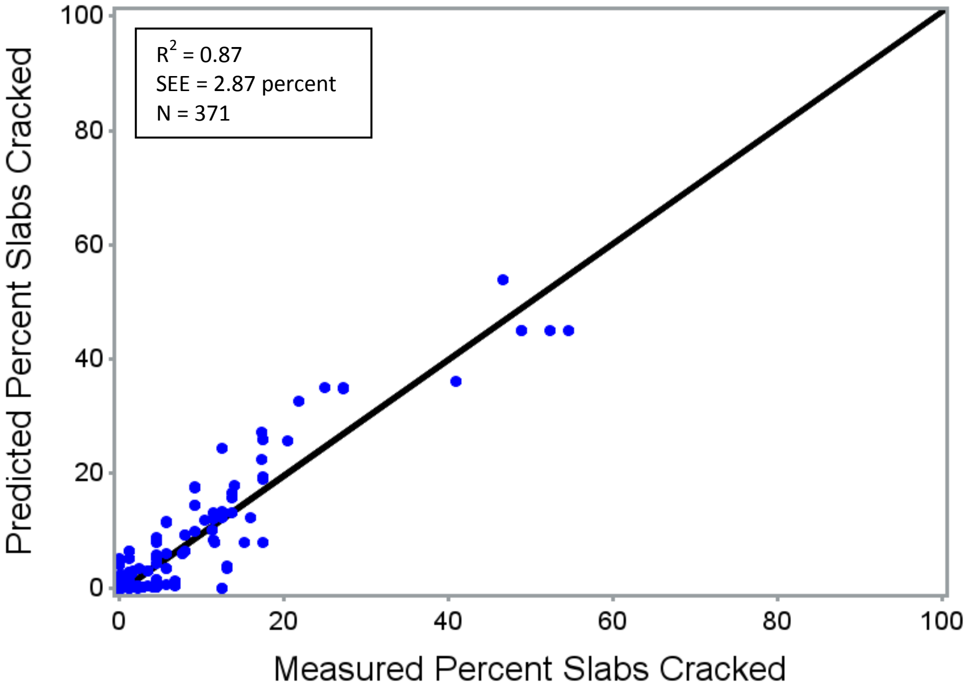


Figure 18. Comparison of measured and predicted percentage SJPCP overlay slabs longitudinally cracked resulting from global calibration process.

STANDARD ERROR OF PREDICTION

The standard error (or standard deviation of the residual error) for the percentage of slabs longitudinally cracked prediction global equation was developed similar to others in the AASHTOWare ME software and is shown in Equation 4.

$$s_{e(LCRACK)} = 3.5522 * LCRACK^{0.4315} + 0.5000 \quad (4)$$

Where:

LCRACK	= Predicted longitudinal fatigue cracking based on mean inputs (corresponding to 50% reliability), percent of cracked slabs.
$s_{e(CR)}$	= Standard error of the estimate of longitudinal fatigue cracking at the predicted level of mean longitudinal cracking.

The standard error of longitudinal cracking prediction varies with the predicted amount of cracking which is identical to all of the other AASHTOWare distresses. Table 9 shows the calculations of standard error over a range of longitudinal cracking.

Table 9. Summary of standard error of longitudinal cracking prediction over range of predicted cracking.

Predicted Longitudinal Cracking, Percent Slabs	Standard Error, Percent Slabs
0	0.5
5	7.6
10	10.1
15	11.9
20	13.4
30	15.9
50	19.7

COMPARISON OF SECTION MEASURED AND PREDICTED LONGITUDINAL CRACKING

Four sections were selected to illustrate how the AASHTOWare ME calibrated model predicts the measured longitudinal cracking for SJPCP overlays. Figures 19 through 22 show the predictions for different sections included in the database. All of these predictions look reasonable.

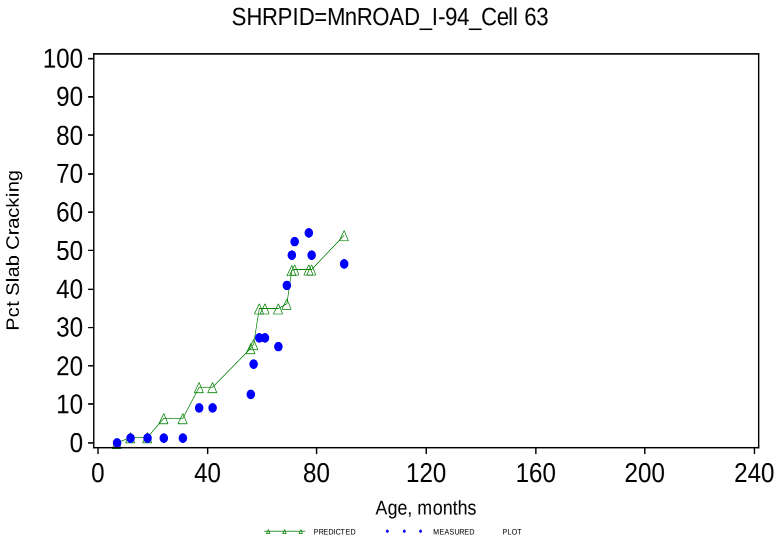


Figure 19. Predicted and measured longitudinal cracking for MnRoad 063, driving lane.

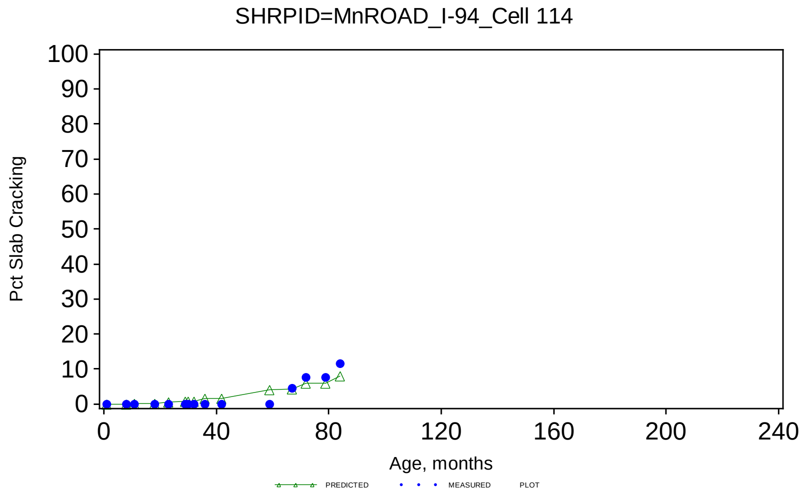


Figure 20. Predicted and measured longitudinal cracking for MnRoad 114, driving lane.

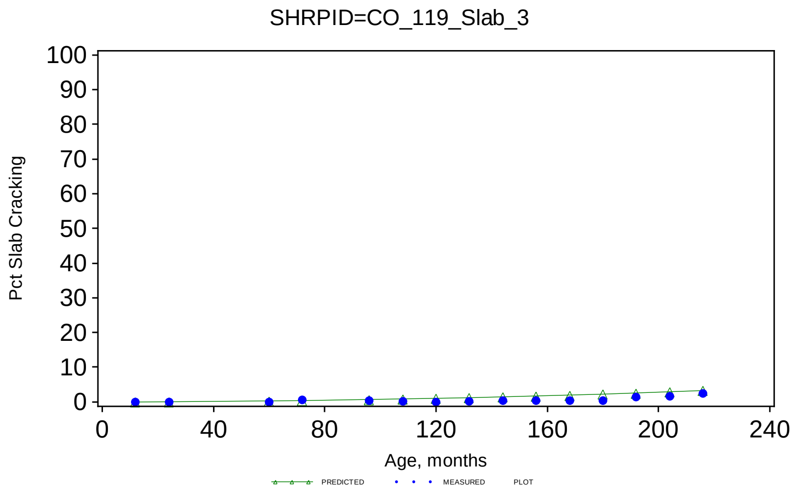


Figure 21. Predicted and measured longitudinal cracking for Colorado 119, Design 3, driving lane.

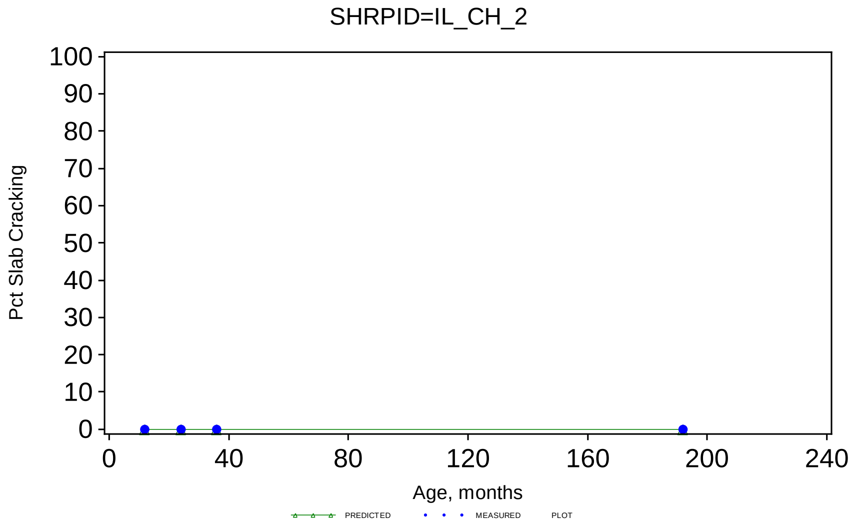


Figure 22. Predicted and measured longitudinal cracking for Illinois Highway 2.

8 Design Sensitivity Analysis of SJPCP

A design sensitivity analysis was conducted by varying several design inputs for four projects at varying locations and truck traffic level. Inputs varied include PCC thickness, AC thickness, joint spacing, shoulder type, and transverse joint LTE. Specific SJPCP projects were selected and their site conditions used in the analyses to make the sensitivity as realistic as possible.

ILLINOIS COUNTY HIGHWAY 2 (NEAR CHAMPAIGN, IL)

The initial AADTT is 500 two-way trucks. Over a design life of 20 years the project is expected to carry a total of 2.3 million trucks in the design lane. The slab is 5.75 inches thick and AC is 6.5 inches thick. The subgrade is AASHTO Class A-4 and A-6. The weather station used was Mattoon/ Charleston, IL. Lane width was 12 ft and a 6x6 ft joint spacing was selected to keep the wheelpath from coinciding with the longitudinal joint.

- **Slab and AC thicknesses.** The amount of predicted longitudinal fatigue cracking at a reliability level of 90 percent after 20 years is shown in the table below. The percent fatigue cracking in the existing AC was set at the recommended Level 2 default of 65 percent. Results in table 10 show that thicker PCC and AC result in lower amounts of longitudinal slab fatigue cracking.

Table 10. Sensitivity of AASHTOWare ME SJPCP to PCC and AC thickness for IL County Highway 2.

PCC Thickness	**20 Year Longitudinal Cracking, % Slabs**		
	AC 5 in	**AC 6 in**	**AC 7 in**
4 in	40%*	6%	1.9%
5 in	10	3.4	1.0
6 in	2.9	1.0	1.0

*Percent longitudinal fatigue cracking predicted at R = 90%.

For this county highway, a maximum of 15 percent longitudinal cracking at 90% reliability and 20 year design life is allowed and the following designs obtained.

- 4 in PCC over 6 in AC
- 5 in PCC over 5 in AC

  5.75 in PCC over 6.5 in AC (Existing Design, 0 percent cracking, 16 years)
- 6 in PCC over <5 in AC

Are these realistic design alternatives? The existing project at this site is 5.75 in PCC over 6.5 in AC and 16 years old carrying 1.7 million trucks as shown with 0 cracking. All of the designs above are slightly thinner than the existing design; however, the existing design has performed for 16 years with zero cracking so it is not known if a thinner PCC or AC layer would produce an acceptable level of longitudinal cracking. The amount of trucks over 20 years is expected to be 2.2 million and so a thinner PCC or AC layers may well still perform at this level of reliability. A photo of this project at 16 years age is shown in Figure 23.

Figure 23. Section Illinois Highway 2, Cumberland County (2016) at 16 years age.

- **Joint Spacing.** Joint spacing was varied to determine its impact on slab longitudinal fatigue cracking. The as-built joint spacing is 6x6 ft for 12 ft wide lanes. Program runs were made for 5x5, 6x6, and 7x7 ft joint spacings. Results for 20 year design are shown in table 11.

  Results show that as the longitudinal joint spacing increases, the truck lateral offset of the slab edge increases to keep the truck in the center of the lane. The predicted longitudinal fatigue cracking also significantly increases. This occurs because as the lateral offset increases, the truck wheels move closer to the center of the slab which increases the bending stress at the slab bottom along the transverse joint and fatigue damage and longitudinal cracking. This result indicates that a thicker slab may be required for longer longitudinal joint spacing if the truck stays centered in the traffic lane.

Table 11. Sensitivity of AASHTOWare ME SJPCP to joint spacing for IL County Highway 2 (truck centered in lane).

PCC Thickness	AC Thickness	Joint Spacing	Truck Lateral Offset From Edge of Slab	Longitudinal Cracking @ R=90%
5.75 in	5 in*	5x5 ft (10 ft Lane)	9	2
5.75 in	5 in*	6x6 (12 ft Lane)	21	4
5.75 in	5 in*	7x7 (14 ft Lane)	33	10

*Actual thickness was 6.5 in but only zero cracking predicted, so changed to 5 in for this sensitivity.

- **Tied PCC Shoulder.** This design had no tied shoulders and the assigned longitudinal joint LTE was 20 percent. The same design was run for a tied shoulder which provides a joint load transfer efficiency of 40 percent. Results showed the following for the 6x6 ft slab, 5.75 in PCC, and 6.5 in AC.
    - Longitudinal fatigue cracking predicted for non-tied shoulders was 1.0 percent at R = 90%.
    - Longitudinal fatigue cracking predicted for tied PCC shoulders was 1.9 percent at R = 90%.
    - Normally, for transverse cracking, the tied PCC shoulder would reduce transverse cracking. However, the geometry is completely different for longitudinal cracking. The critical stress for longitudinal cracking is along the transverse joint under the wheel load. When a tied PCC shoulder is added, this provides more restraint to the edge of the slab (the longitudinal joint load transfer efficiency is set at 40 percent). This additional restraint at the corner/edge increases the bending stress at the bottom of the slab beneath the wheel load.
    - **Effect of Transverse Joint LTE.** The LTE of transverse joints was set at 80 percent for all of the calibration sections. This example varies the LTE from 25 to 95 percent to illustrate its effect on the longitudinal fatigue cracking for this example. An LTE of less than about 50 percent would indicate that a crack in the AC layer exists beneath the transverse joint in the PCC slab. Results are shown in table 12.

Table 12. Sensitivity of AASHTOWare ME SJPCP to transverse joint LTE for IL County Highway 2.

PCC/AC Thickness	Longitudinal Fatigue Cracking, % Slabs			
	LTE 25%	LTE 50%	LTE 80%	LTE 95%
5.75 in PCC 6.5 in AC	8.4	4.2	1.0	1.0

*Percent longitudinal fatigue cracking predicted at R = 95%.

- Results show that as transverse joint LTE increases, the longitudinal PCC fatigue cracking decreases significantly. This is a logical result in that the transverse joint LTE has a major influence on bottom of slab bending stresses. If the AC layer does not crack along the transverse joint, then the LTE of the joint will be relatively high, ranging from 60 to over 90 percent with a mean of about 80 percent based on some MnRoad data measured using the FWD.
- Sections at MnRoad with conventional longer transverse joint spacings showed lower LTE values (e.g. 30-60 percent) indicating some reflection cracking in the AC layer. LTE at MnRoad did not seem to vary much across a wide range of seasons either. A mean value of 80 percent was found at MnRoad and used in the calibration of all sections. (Adams and Vandenbossche, 2013)

CO 119 COLORADO HIGHWAY (DESIGN3)

The initial AADTT is 1257 two-way truck traffic. Over the 20-year design period, the project is expected to carry a total of 5.4 million trucks in the design lane. The PCC thickness is 5 in and the AC thickness is 3.3 in. The subgrade is AASHTO Class A-1-b and the weather station used was in Ft. Collins, CO. Lane width was such that a 5x5 ft joint spacing was selected to keep the wheelpath from coinciding with the longitudinal joint.

- **Slab and AC thicknesses.** The amount of predicted longitudinal fatigue cracking at a reliability level of 90 percent after 20 years is shown in the table below. The percent fatigue cracking of the existing AC pavement was set at the recommended default of 65 percent. Results in table 13 show that thicker PCC and AC result in lower amounts of longitudinal fatigue cracking.

Table 13. Sensitivity of AASHTOWare ME SJPCP to PCC and AC thickness for Colorado 119 (Design 3).

PCC Thickness	Longitudinal Cracking, % Slabs		
	AC 3.3 in	AC 5 in	AC 6 in
4 in	100%*	14	3.0
5 in	43	4.8	1.9
6 in	4.8	1.9	1.0

*Percent longitudinal fatigue cracking predicted at R = 90%.

For this urban highway, a maximum of 12 percent longitudinal cracking at 90% reliability and 20 year design life is specified and the following designs obtained.

- 4 in PCC over 6 in AC

(5 in PCC over 3.3 in AC Existing design, 2.4 percent, 19 years)

- 5 in PCC over 5 in AC
- 6 in PCC over 3.3 in AC

The existing project at this site is 5 in PCC over 3.3 in AC and 18 years old. The amount of measured longitudinal fatigue cracking after 18 years carrying 5.0 million trucks is 2.4 percent. The alternative designs are a little thicker than the existing design and appear to represent reasonable designs for this project.

- **Joint Spacing.** This project was also run for varying joint spacings to determine the impact on longitudinal slab fatigue cracking. Program runs were made for 5x5, 6x6, and 7x7 ft joint spacings. Results for 20 year designs are shown in table 14.

Table 14. Sensitivity of AASHTOWare ME SJPCP to joint spacing for Colorado 119 (design 3) (Truck is centered in lane).

PCC Thickness	AC Thickness	Joint Spacing (Lane Width)	Truck Lateral Offset from Edge	Longitudinal Cracking @ R=90%
5 in	3.3 in	5x5 ft (10 ft)	9 in	41%
5 in	3.3 in	6x6 ft (12 ft)	21 in	76%
5 in	3.3 in	7x7 ft (14 ft)	33 in	100%

Results show that as the joint spacing increases the truck lateral offset from the slab edge increases to keep the truck in the center of the lane. The predicted longitudinal fatigue cracking increases significantly. This occurs because as lane width increases the truck lateral offset from the slab edge increases to keep the truck centered in the lane. Thus, the truck wheels move closer to the center of the slab which increases the bending stress at the slab bottom and fatigue damage and longitudinal cracking. This result indicates that a thicker slab may be required for longer longitudinal joint spacing if the truck stays centered in the traffic lane.

- **Tied Shoulder.** The same design was run for a tied shoulder which provides a joint load transfer efficiency of 50 percent, rather than the 20 percent with no tied shoulder. Results showed the following for 6x6 ft slabs, 5 in PCC, 3.3 in AC.
    - Longitudinal fatigue cracking predicted for non-tied shoulders was 39 percent at R = 90%.
    - Longitudinal fatigue cracking predicted for tied PCC shoulders was 67 percent at R = 90% for tied PCC shoulders.
    - When a tied PCC shoulder is added, this provides more restraint to the edge of the slab (the longitudinal joint load transfer efficiency is set at 40 percent). This additional restraint at the corner/edge increases the bending stress at the bottom of the slab beneath the wheel load.

MN 63 MINNESOTA (MNROAD, I-94)

The initial AADTT is 4844 two-way truck traffic. Over the next 20 years the project is expected to carry a total of 17.7 million trucks in the outer design lane. The PCC is 4 inches and the AC is 8 in thick. The subgrade is AASHTO Class A-7-5, A-7-6, and A-6 and the weather station used was Minneapolis, MN. Lane width was 12 ft and a 6 ft longitudinal joints spacing was selected to keep the wheelpath from coinciding with the longitudinal joint.

- **Effect of PCC Slab and AC Thickness.** The predicted longitudinal cracks at a reliability level of 95 percent after 20 years are shown in the table below. The percent fatigue cracking of the existing AC pavement was set at the recommended default of 65 percent. Results in table 15 show that as PCC and or AC thickness increase the longitudinal PCC fatigue cracking decreases.

Table 15. Sensitivity of AASHTOWare ME SJPCP to AC thickness for MnRoad 63 on I-94.

PCC Thickness	**Longitudinal Cracking, % Slabs**			
	AC 6 in	**AC 7 in**	**AC 8 in**	**AC 9 in**
4 in	100%*	100	15	1.9
5 in	100	85	12.8	2.5
6 in	76	18	4.3	1.6

*Percent longitudinal fatigue cracking predicted at R = 95%.

For this Interstate highway, a maximum of 10 percent longitudinal cracking at 95% reliability and 20 year design life is specified and the following designs obtained.

- 4 in PCC over 9 in AC
  4 in PCC over 8 in AC, 7.5 years, 6 million trucks, 47 percent longitudinal cracks
- 5 in PCC over 9 in AC
- 6 in PCC over 8 in AC

The existing project at this site is 4 in PCC over 8 in AC and survived only 7.5 years carrying 6.0 million heavy trucks when it had developed 47 percent longitudinally cracked slabs. This MnRoad section developed major longitudinal cracking early on due to significant debonding. When the AC layer becomes very thick (e.g., > 8 in) the 4 in PCC slab appears to be acceptable according to the calibrated model. However, there needs to be limitations placed on the allowable thickness of AC used in design. The maximum AC layer thickness in the calibration sections was 8 in. It is recommended to limit the AC layer thickness specified in design to 8 in until additional sections with thicker than this can be included.

The only acceptable design would then be 6 in PCC over 8 in AC for this project. This design appears reasonable.

- **Joint Spacing.** This project was also run for varying joint spacings to determine the impact on longitudinal fatigue cracking. The as built joint spacing is 6x6 ft. Program runs were made for 5x5, 6x6, and 7x7 ft joint spacings. Results are shown in table 16.

Table 16. Sensitivity of AASHTOWare ME SJPCP to joint spacing for MnRoad 63 on I-94 (for each lane width the truck is centered in the lane to calculate lateral offset distance).

PCC Thickness	AC Thickness	Joint Spacing	Truck Lateral Offset Distance	Longitudinal Cracking @ R=95%
4 in	8 in	5x5 ft	9 in	7%
4 in	8 in	6x6	18 21 in	17 21
4 in	8 in	7x7	18 33 in	17 68

Results show that as the lane width varies from 10 to 14 feet, with the longitudinal joint spacing down the center of the traffic lane. The truck is offset from the outer lane edge as shown in TABLE 1 where the mean truck offset for a 12 ft lane averages about 18 inch, but as the lane gets narrower it would decrease as shown. The predicted longitudinal fatigue cracking increases from 7 to 17 percent for this design. So there is some effect on longitudinal fatigue cracking for wider traffic lanes where the longitudinal joints that are cut in the center of the lane.

- **Tied Shoulder.** The same design was run for a tied shoulder which provides a joint load transfer efficiency of 40 percent, rather than the 20 percent with no tied shoulder. Results showed the following for 6x6 ft slabs, 4 in PCC, 8 in AC.
    - Longitudinal fatigue cracking predicted with a non-tied PCC shoulder was 15 percent at R = 95%.
    - Longitudinal fatigue cracking predicted with a tied PCC shoulder was 28 percent at R = 95%.
    - When a tied PCC shoulder is added, this provides more restraint to the edge of the slab (the longitudinal joint load transfer efficiency is set at 40 percent). This additional restraint at the corner/edge increases the bending stress at the bottom of the slab beneath the wheel load.

MN 114 MINNESOTA (MNROAD, I-94 BUT INCREASED TRUCKS)

An actual MnRoad section but the initial AADTT was increased to 6000 two-way truck traffic simply to illustrate a heavier traffic design. Over the next 20 years, the project is expected to carry a total of 22 million trucks in the outer design lane. The PCC is 6 in and the AC is 5 in thick. The subgrade is AASHTO Class A-7-5, A-7-6, and A-6 and the weather station used was Minneapolis, MN. Lane width was 12 ft and a 6x6 ft joint spacing was selected to keep the wheelpath from coinciding with the longitudinal joint.

- **Effect of Slab and AC Thickness.** The predicted amount of longitudinal fatigue cracking at a reliability level of 95 percent after 20 years and 22 million trucks in design lane are shown in table 17. The percent fatigue cracking of the existing AC pavement was set at the recommended default of 65 percent and transverse joint LTE was 80 percent. Results show that as either PCC or AC thickness increases, the longitudinal PCC fatigue cracking decreases.

Table 17. Sensitivity of AASHTOWare ME SJPCP to PCC and AC thickness for MnRoad 114 on I-94 with increased trucks.

PCC Thickness	Longitudinal Fatigue Cracking, % Slabs			
	AC 5 in	AC 6 in	AC 7 in	AC 8 in
6 in	100%	52	13.6	4.8
7 in	15	6.6	3.5	1.2
8 in	3.0	1.2	1.2	1.2

*Percent longitudinal fatigue cracking predicted at R = 95%.

For this Interstate highway, a maximum of 10 percent longitudinal cracking at 95% reliability and 20 year design life (22 million trucks) is specified and the following designs obtained.

- 6 in PCC over 8 in AC
  6 in PCC over 5 in AC existing, 7 years, 6 million trucks and 11.5 percent cracking)
- 7 in PCC over 6 in AC
- 8 in PCC over 5 in AC

The existing project design at this site is 6 in PCC over 5 in AC and is 7 years old. The amount of longitudinal fatigue cracking after 7 years carrying 6.0 million trucks is 11.5 percent. The recommended designs above would increase either slab thickness or AC thickness significantly to accommodate 22 million trucks. These designs appear to be reasonable.

- **Effect of Transverse Joint LTE.** The LTE of transverse joints was set at 80 percent for all of the calibration sections. This example varies the LTE from 25 to 95 percent to illustrate its effect on the longitudinal fatigue cracking for this example as shown in table 18.

Table 18. Sensitivity of AASHTOWare ME SJPCP to transverse joint LTE for MnRoad 114 on I-94.

PCC/AC Thickness	Longitudinal Fatigue Cracking, % Slabs			
	LTE 25%	LTE 50%	LTE 80%	LTE 95%
7 in PCC **6 in AC**	88%	44	7	1

*Percent longitudinal fatigue cracking predicted at R = 95%.

Results show that as transverse joint LTE increases, the longitudinal PCC fatigue cracking decreases dramatically. This is a logical result in that the transverse joint LTE has a major influence on bottom of slab bending stresses. If the AC layer does not crack along the transverse joint above then the LTE of the joint will be relatively high, ranging from 60 to over 90 percent with a mean of about 80 percent based on some MnRoad data measured using the FWD. Sections with longer conventional joint spacings showed lower LTE values indicating some reflection cracking in the AC layer. LTE did not seem to vary much across a wide range of seasons either. A mean value of 80 percent was used in the calibration of all sections. (Adams and Vandenbossche, 2013)

COMPARISON OF BCOA-ME AND AASHTOWARE PAVEMENT ME DESIGNS

A comparison between the results obtained for these two bonded PCC overlay design procedures was made for the three designs in this section. The results are summarized in table 19. Results show fairly similar results. The databases upon which they are calibrated are similar with the SJPCP ME database including more years of performance data.

Table 19. Comparison of BCOA-ME and AASHTOWare Pavement ME SJPCP/AC.

Project	Traffic Over 20-Year Design Life	Design Reliability & Cracking	Recommend Design SJPCP/AC	Recommended Design BCOA-ME	SJPCP/AC – BCOA-ME PCC
IL CH 2	2.3 million Trucks 2.72 million ESALs	R = 90% C < 15%	4.0 PCC 6.5 AC	4.4 PCC 6.5 AC	-0.4 in
CO Design3	5.4 million Trucks 6.27 million ESALs	R = 90% C < 12%	5.5 PCC 4.0 AC	5.1 PCC 4.0 AC	+0.4 in
MN 63	17.7 million Trucks 28.8 million ESALs	R = 95% C < 10%	5.5 PCC 8.0 AC	5.9 PCC 8.0 AC	-0.4 in
Mean					-0.1 in

SUMMARY OF DESIGN THICKNESS RESULTS

The following conclusions are based on the results obtained from various sensitivity analyses for the design of SJPCP/AC overlays.

- **As PCC thickness increases, the predicted amount of longitudinal PCC fatigue cracking decreases greatly.** This is caused by an increase in the "equivalent" PCC slab thickness resulting in reduced bending stress at the bottom of the slab.
- **As existing AC thickness increases, the predicted amount of longitudinal PCC fatigue cracking decreases greatly.** This is caused by the increase in the "equivalent" PCC slab thickness resulting in a decrease in the bending stress at the bottom of the equivalent slab layer. This effect diminishes greatly as AC thickness increases.
- **Joint spacing that varies from 5x5 to 7x7 ft shows a predicted significant effect.** Unfortunately, there were no 7 or 8 ft joint spacings in the calibration database. For all of the design examples analyzed, as the longitudinal joint spacing increased from 5 to 7 ft, the amount of longitudinal fatigue cracking increases significantly. This implies that a thicker slab will be required for longer longitudinal joint spacing. As joint spacing increases, the truck wheel is moved more towards the center of the slab width which results in higher bending stress at slab bottom and increased fatigue damage and longitudinal cracking.
- **Adding tied PCC shoulders showed an increase prediction of longitudinal PCC fatigue cracking over a non-tied/other shoulder.** When a tied PCC shoulder is added, this provides more restraint to the longitudinal edge of the slab (the longitudinal joint load transfer efficiency (LTE) is set at 50 percent). This additional restraint at the corner/edge increases the bending stress at the bottom of the slab beneath the wheel load. However, tied PCC shoulders may still be very beneficial in reducing slab edge and corner deflections and critical stresses.
- **Transverse joint Load Transfer Efficiency (LTE) showed a very significant effect on predicted longitudinal PCC fatigue cracking.** The higher the LTE the lower the predicted longitudinal cracking. FWD testing has shown that the LTE is typically in the range of 60 to 90 percent with an average of 80 percent which was used in the calibration of all sections. (Adams and Vandenbossche, 2013)
- **Thickness designs of four projects ranging from low volume to high volume indicated that reasonable results** shown in table 20 can be obtained using the calibrated models. However, the criticality of the level of design reliability and maximum longitudinal cracking criteria must be emphasized. These values require implementing agency review and revision as needed.

Table 20. Comparison of existing PCC/AC designs with 20-year recommended redesigns.

Project	Existing Age & Trucks	Measured Cracking	Existing Design	Recommend Design**	Cracking & Trucks 20 Yrs	Design Reliability & Cracking
IL CH 2	16 years 1.7 million	0.0 %	5.75 PCC 6.5 AC	4.0 PCC 6.0 AC	6%* 2.3 million	R = 90% C < 15%
CO Design3	19 years 5 million	2.4%	5.0 PCC 3.3 AC	6.0 PCC 3.3 AC	4.8 % 5.4 million	R = 90% C < 12%
MN 63	7.5 years 6 million	47%	4.0 PCC 8.0 AC	6.0 PCC 8.0 AC	4.3% 18 million	R = 95% C < 10%
MN 114	7 years 6 million	11.5%	6.0 PCC 5.0 AC	8.0 PCC 5.0 AC	3% 22 million	R = 95% C <10%

*Percent longitudinal fatigue cracking predicted at design reliability.
**Redesign of the project using existing site conditions but over 20 years of traffic.

- **A comparison** of the BCOA-ME thickness results with the AASHTOWare Pavement ME SJPCP results indicated no significant difference in PCC overlay thickness for three designs in Minnesota, Illinois, and Colorado. The calibration databases were fairly similar; however, the more recent SJPCP included several additional years of performance data. However, this was only a three project comparison and there may be greater differences over a wider design factor space. Also, a comparative sensitivity analysis of the impact of some key design variables such as joint spacing, AC thickness, and other climate zones would also be interesting.

9 Summary of Implementation

The following points summarize the key aspects regarding the implementation of a portion of the BCOA-ME (University of Pittsburgh) design procedure into the AASHTOWare Pavement ME software.

- A portion of the BCOA-ME was implemented into the AASHTOWare Pavement ME software maintaining as many of the fundamental concepts as possible. These include the following:
    - The SJPCP PCC/AC interface used full contact friction and bond between the layers throughout the design life. This is not the case for the BCOA ME where the stress was reduced to account for debonding. Both procedures recognized

  that this bond is very often lost over time due to stripping and erosion at the PCC/AC interface.
  - Longitudinal fatigue cracking initiates at the transverse joints in the wheel paths at the slab bottom for slabs with longitudinal joints roughly placed between the truck wheel paths (e.g., a 12 ft lane would have 6 ft longitudinal joints). The critical bending stress was calculated at this point beneath the truck wheel loads.
  - The fatigue damage was calculated at close intervals across the transverse joints to identify the point of maximum fatigue damage which was used to predict longitudinal cracking in the calibration.
  - Traffic lateral wander according to the Normal distribution was assumed with variable input standard deviation. Mean truck offset from the slab is an important design input and varies with lane width. For a normal 12 ft wide traffic lane, this mean lateral offset should be set at 18 in as per conventional design. For narrower and wider traffic lanes, it is recommended to either measure the mean offset in the field or to simply calculate an offset that maintains the truck in the center of the traffic lane on average.
  - A relatively high amount of load transfer at the transverse joints (due to the uncracked and bonded AC below the joint) used in the development of the BCOA-ME procedure was maintained in the AASHTOWare ME procedure (80 percent) but this is an input that can be varied.
- Slab thickness ranging from 4 to 8 in PCC was included. The BCOA-ME was 3 to 6.5 in.
- Existing AC layer ranging from 3 to 8 in was included, with a recommended cap of 8 in so that the PCC layer would be unrealistically thin.
- Joint spacings from 5 to 8 ft were also included. The very short slabs, e.g., <4.5 ft., were not included in the implementation due to the obvious overlap of truck wheelpaths and the shorter spaced longitudinal joints which results in very poor performance with corner cracks and debonding beneath the corners that evolves out of that configuration. In addition, shorter joint spacing requires significant increase in construction cost due to many more joints to saw and seal and a thicker slab to control the corner cracking as opposed to longitudinal cracking.
- Longer more conventional bonded PCC overlays (thickness of 6 in and higher and joint spacings 10 ft and higher with full lane with slabs) of asphalt pavement are already included in the AASHTOWare Pavement ME software.
- Other differences in implementation mostly include those required to match the computational procedures of the AASHTOWare Pavement ME.
  - **Traffic loadings** were modeled the same as the AASHTOWare Pavement ME with full spectral axle loads and lateral variation of trucks as opposed to ESALs.

  - **Climate** was modeled the same as the AASHTOWare Pavement ME with full use of the weather stations and hourly climatic data.
  - **Unbound materials** were modeled the same as the AASHTOWare Pavement ME with changing monthly modulus values over time.
  - **PCC materials** were modeled the same as the AASHTOWare Pavement ME with changing monthly strength and modulus rather than a single 28-day value.
  - **AC materials** were modeled the same as the AASHTOWare Pavement ME with the dynamic modulus changing monthly over time. In addition, the monthly "damaged" dynamic modulus values over time were included based on the percent of fatigue cracking in the AC layer (Level 2).
  - **Unbound materials** (base, subbase, subgrade) were modeled the same as the AASHTOWare Pavement ME with the resilient modulus changing monthly over time.
  - **Condition of existing AC pavement.** The condition assessment Level 2 method was used to consider "damaged" modulus through fatigue cracking of the AC layer. Consideration of the impact of the "damaged" AC modulus on field longitudinal cracking led to the selection of a constant value of 65 percent fatigue cracking area. This value appeared to provide the vast majority of sections with a good unbiased calibration fit. This approach results in a reduction in the "equivalent" PCC thickness due to a loss of modulus of the AC layer.
  - **The transverse joint load transfer efficiency (LTE)** was set at 80 percent for calibration (similar to the 90 percent used in the BCOA-ME) which represented the typical LTE measurements from MnRoad.
- **Longitudinal Joint spacing design (or slab size)** allowed considers two key items: performance and construction cost.
  - **Performance of various longitudinal joint spacings** has shown the following (which is the approach taken by the BCOA ME procedure developers):
    - **Very Short jointed** bonded concrete overlays of asphalt with <4.5 ft longitudinal joint spacing have developed corner cracking over time as the predominant distress on many projects. This is due to the wheel loads on either side of the truck repeatedly loading the slab corners inducing high deflections and bending stresses leading to fatigue damage and corner cracking. Design for this slab size and joint spacing must directly consider corner stresses (which are much higher than edge stresses) to predict fatigue corner cracking. This is the approach taken in the BCOA ME procedure for < 4.5 ft joint spacing. The capability to

        design for corner stresses and <4.5 ft joint spacing is not included in the implementation.
        - **Short jointed** bonded concrete overlays of asphalt (e.g. 5 ft to 8 ft) where the joint spacing is approximately ½ lane width have developed predominantly longitudinal cracking over time on projects. This is due to the wheel loads centered on the middle portion of the slabs causing a repeated bending stress at the bottom of the slab leading to fatigue damage and longitudinal cracking. Design of these slabs must directly consider longitudinal cracking. This is the approach taken in the BCOA ME procedure for >4.5 to 7 ft joint spacing.
        - **Shape and length of slabs are important to performance and cost.** Most agencies construct square slabs (e.g. 4x4 or 6x6 ft) because it's a simple construction concept, but there may be a significant advantage to increasing the length a small amount when mechanical load transfer devices are specified to control faulting. A slight lengthening of the slabs would provide longer joint spacing where some type of joint load transfer mechanism could be considered more economically (dowels, plate dowels, fibers). Slab size aspect ratios should be respected however where the length to width ratio would be a maximum of 1.25. Thus a 6 ft wide slab could have a length up to 7.5 ft as an example. As the slab becomes longer, the potential for transverse fatigue cracking increases but not significantly within this relatively short slab narrow range.
            - Thermal and moisture curling of the small slabs (5 to 8 ft) are not very significant for the critical bending stresses.
            - Slab thickness required is greater for shorter longitudinal joints (< 4.5 ft) than for longer longitudinal joints (5 to 7 ft) using the BCOA ME design procedure due to higher critical stresses (approximately 40 percent).
    - **Construction cost includes joint forming and sealing (if used) and slab thickness** since both are influenced by joint spacing. Both of these costs are reduced by selecting a longitudinal joint design that is centered in the traffic lane with spacing of approximately ½ lane-width. Any additional longitudinal joints would add significantly to the cost of the pavement due to additional sawing and sealing cost as well as a thicker slab to prevent corner cracking due to many more truck wheel loads on the slab corners and higher stresses involved.
- **The optimum longitudinal joint spacing for SJPCP appears to be a longitudinal joint centered across the traffic lane.** This design would effectively minimize the chance of either wheel loading the corners of the slabs. Thus, a lane width of 12 ft would have a 6

ft longitudinal joint spacing. A 10 ft traffic lane would have a 5 ft joint spacing. A 16 ft wide ramp would have an 8 ft joint spacing.

- **Joint sealant** significantly affected the performance of a few direct comparisons at MnRoad. The 4.5 in PCC section with no sealant developed significantly more cracking than the section with joint sealant/filler. The 5.5 in PCC sections showed a lesser difference. The calibrated model for longitudinal cracking uses data from a large number of sections at MnRoad that included sealed and unsealed joints. However, in lower precipitation areas such as some of the western US, sealing may not be beneficial. The impact of sealing was not considered in the implementation.
- **Structural Fibers (Polyolefin) in PCC** were included in MnRoad Cell 95 but this cell did not meet the thickness criteria for inclusion but performed well. Many other sections in Illinois include a structural fiber and reportedly show improved performance in holding cracks tighter and perhaps increase the LTE of the joints. One main advantage may be in reducing the amount of joint faulting. However, they may also help hold fatigue cracks together over time. There is no calibrated modification to this SJPCP design for use of structural fibers even though evidence indicates that they are beneficial.
- Longitudinal fatigue cracking, initiating at the bottom of the PCC slab, is the only performance characteristic considered in this design procedure. **Joint faulting** is developing on some of the SJPCP test sections under heavy Interstate traffic. Before this design procedure can be considered robust, there needs to be faulting models as well as IRI models added to provide a robust SJPCP design.

10 References

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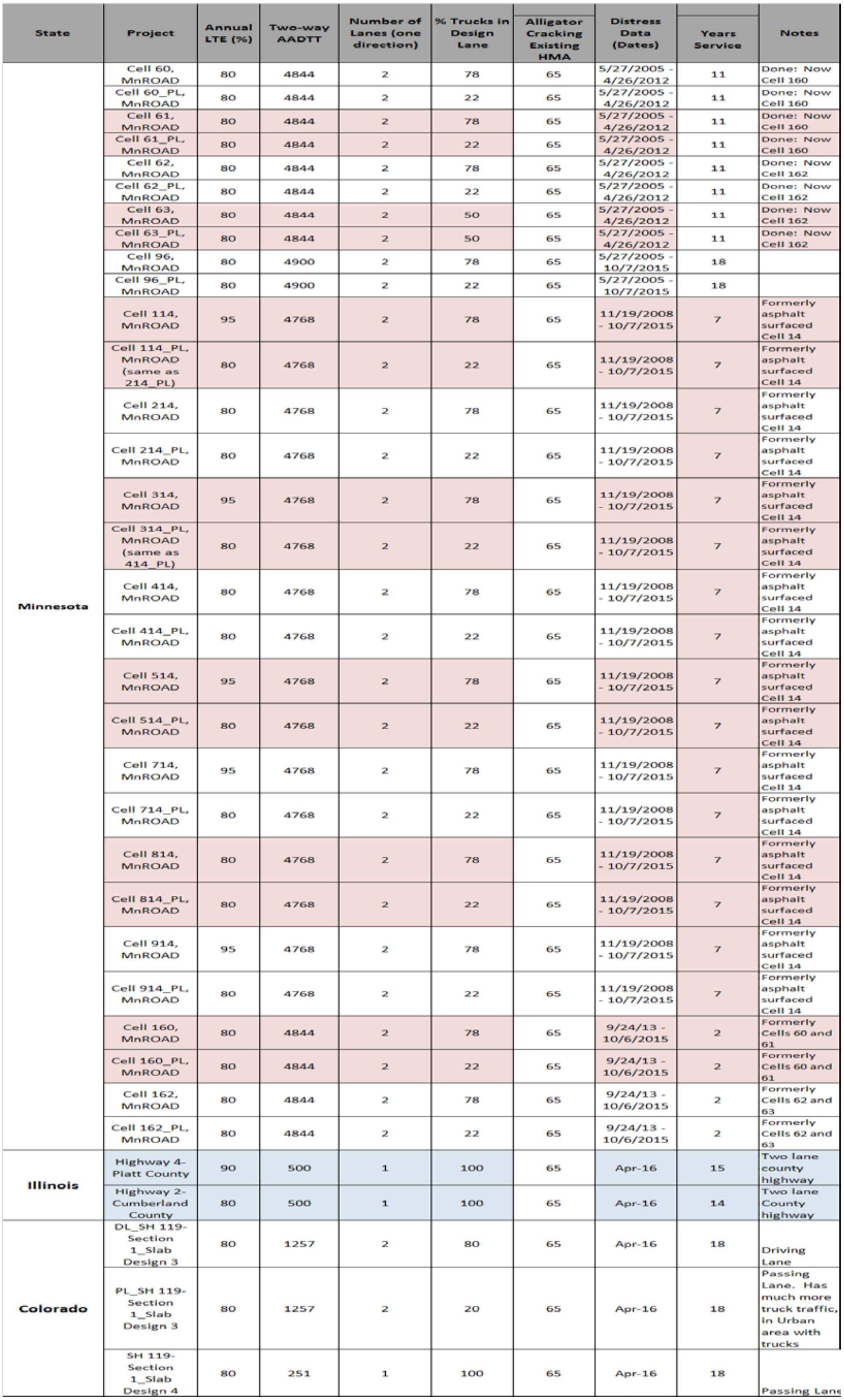
Appendix A Database of Inputs for Calibration of AASHTOWare ME SJPCP

State	Project	h_{PCC}, in	PCC 28-Day Strength		PCC Modulus (psi)	PCC Poisson's Ratio	PCC CTE/F	W/C	Cementitious Material
			Compressive Strength (psi)	Flexural Strenght (psi)					
Minnesota	Cell 60, MnROAD	5	4161	Calc	Calc	0.2	4.10	0.40	400.00
	Cell 60_PL, MnROAD	5	4161	Calc	Calc	0.2	4.10	0.40	400.00
	Cell 61, MnROAD	5	3659	Calc	Calc	0.2	4.10	0.40	400.00
	Cell 61_PL, MnROAD	5	3659	Calc	Calc	0.2	4.10	0.40	400.00
	Cell 62, MnROAD	4	3998	Calc	Calc	0.2	3.80	0.40	400.00
	Cell 62_PL, MnROAD	4	3998	Calc	Calc	0.2	3.80	0.40	400.00
	Cell 63, MnROAD	4	4520	Calc	Calc	0.2	4.10	0.40	400.00
	Cell 63_PL, MnROAD	4	4520	Calc	Calc	0.2	4.10	0.40	400.00
	Cell 96, MnROAD	6	6200	Calc	Calc	0.2	5.50	0.40	550.00
	Cell 96_PL, MnROAD	6	6200	Calc	Calc	0.2	5.50	0.40	550.00
	Cell 114, MnROAD	6	5030	Calc	Calc	0.2	4.90	0.40	600.00
	Cell 114_PL, MnROAD (same as 214_PL)	6	5030	Calc	Calc	0.2	4.90	0.40	600.00
	Cell 214, MnROAD	6	5030	Calc	Calc	0.2	4.90	0.40	600.00
	Cell 214_PL, MnROAD	6	5030	Calc	Calc	0.2	4.90	0.40	600.00
	Cell 314, MnROAD	6	5030	Calc	Calc	0.2	4.90	0.42	600.00
	Cell 314_PL, MnROAD (same as 414_PL)	6	5030	Calc	Calc	0.2	4.90	0.42	600.00
	Cell 414, MnROAD	6	5030	Calc	Calc	0.2	4.90	0.42	600.00
	Cell 414_PL, MnROAD	6	5030	Calc	Calc	0.2	4.90	0.42	600.00
	Cell 514, MnROAD	6	5030	Calc	Calc	0.2	4.90	0.42	600.00
	Cell 514_PL, MnROAD	6	5030	Calc	Calc	0.2	4.90	0.42	600.00
	Cell 714, MnROAD	6	5030	Calc	Calc	0.2	4.90	0.42	600.00
	Cell 714_PL, MnROAD	6	5030	Calc	Calc	0.2	4.90	0.42	600.00
	Cell 814, MnROAD	6	5030	Calc	Calc	0.2	4.90	0.42	600.00
	Cell 814_PL, MnROAD	6	5030	Calc	Calc	0.2	4.90	0.42	600.00
	Cell 914, MnROAD	6	5030	Calc	Calc	0.2	4.90	0.42	600.00
	Cell 914_PL, MnROAD	6	5030	Calc	Calc	0.2	4.90	0.42	600.00
	Cell 160, MnROAD	5	4470	Calc	Calc	0.19	4.00	0.40	400.00
	Cell 160_PL, MnROAD	5	4470	Calc	Calc	0.19	4.00	0.40	400.00
	Cell 162, MnROAD	4	4470	Calc	Calc	0.19	4.00	0.40	400.00
	Cell 162_PL, MnROAD	4	4470	Calc	Calc	0.19	4.00	0.40	400.00
Illinois	Highway 4-Piatt County	5	5200	Calc	Calc	0.2	4.90	0.42	600.00
	Highway 2-Cumberland County	5.75	5200	Calc	Calc	0.2	4.90	0.42	600.00
Colorado	DL_SH 119-Section 1_Slab Design 3	5	5000	Calc	Calc	0.2	4.80	0.43	600.00
	PL_SH 119-Section 1_Slab Design 3	5	5000	Calc	Calc	0.2	4.80	0.43	600.00
	SH 119-Section 1_Slab Design 4	5.1	5000	Calc	Calc	0.2	4.80	0.43	600.00

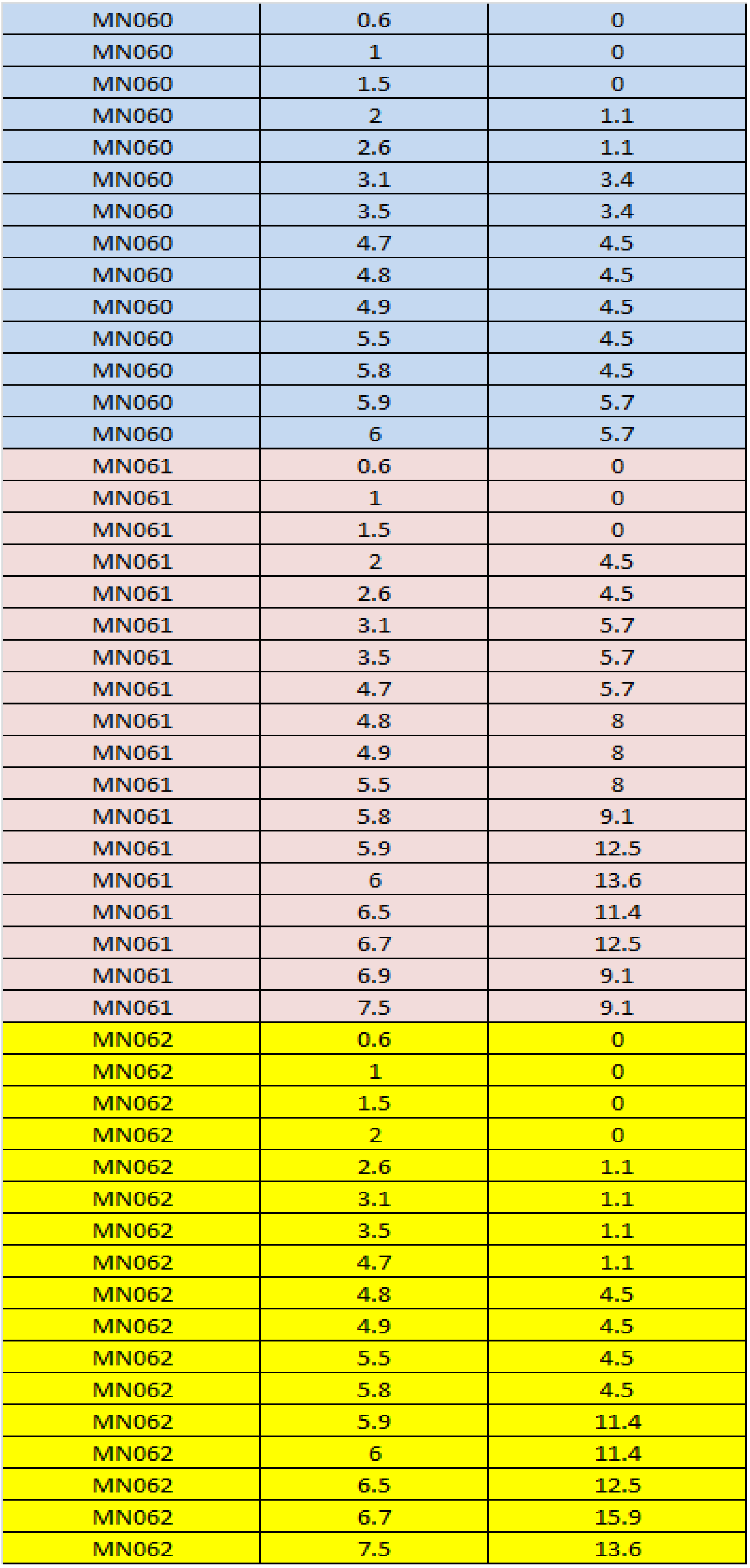
State	Project	h_{HMA}, in	HMA Asphalt Binder	Base Thickness, in	Slab size, ft × ft	Original HMA Constructio	PCC Overlay Constructio	Dowels
Minnesota	Cell 60, MnROAD	7	PG 58-28	None	6 × 5	1993	Oct-04	None
	Cell 60_PL, MnROAD	7	PG 58-28	None	6 × 5	1993	Oct-04	None
	Cell 61, MnROAD	7	PG 58-28	None	6 × 5	1993	Oct-04	None
	Cell 61_PL, MnROAD	7	PG 58-28	None	6 × 5	1993	Oct-04	None
	Cell 62, MnROAD	8	PG 58-28	None	6 × 5	1993	Oct-04	None
	Cell 62_PL, MnROAD	8	PG 58-28	None	6 × 5	1993	Oct-04	None
	Cell 63, MnROAD	8	PG 58-28	None	6 × 5	1993	Oct-04	None
	Cell 63_PL, MnROAD	8	PG 58-28	None	6 × 5	1993	Oct-04	None
	Cell 96, MnROAD	7	PG 58-28	None	6 × 5	1993	Oct-97	None
	Cell 96_PL, MnROAD	7	PG 58-28	None	6 × 5	1993	Oct-97	None
	Cell 114, MnROAD	5	PG 58-28	None	6 x 6	1993	Oct-08	1", driving lane only
	Cell 114_PL, MnROAD (same as 214_PL)	5	PG 58-28	None	6 x 6	1993	Oct-08	None
	Cell 214, MnROAD	5	PG 58-28	None	6 x 6	1993	Oct-08	None
	Cell 214_PL, MnROAD	5	PG 58-28	None	6 x 6	1993	Oct-08	None
	Cell 314, MnROAD	6	PG 58-28	None	6 x 6	1993	Oct-08	1", driving lane only
	Cell 314_PL, MnROAD (same as 414_PL)	6	PG 58-28	None	6 x 6	1993	Oct-08	None
	Cell 414, MnROAD	6	PG 58-28	None	6 x 6	1993	Oct-08	None
	Cell 414_PL, MnROAD	6	PG 58-28	None	6 x 6	1993	Oct-08	None
	Cell 514, MnROAD	7	PG 58-28	None	6 x 6	1993	Oct-08	1", driving lane only
	Cell 514_PL, MnROAD	7	PG 58-28	None	6 x 6	1993	Oct-08	None
	Cell 714, MnROAD	7.5	PG 58-28	None	6 x 6	1993	Oct-08	1", driving lane only
	Cell 714_PL, MnROAD	7.5	PG 58-28	None	6 x 6	1993	Oct-08	None
	Cell 814, MnROAD	8	PG 58-28	None	6 x 6	1993	Oct-08	None
	Cell 814_PL, MnROAD	8	PG 58-28	None	6 x 6	1993	Oct-08	None
	Cell 914, MnROAD	8	PG 58-28	None	6 x 6	1993	Oct-08	1", driving lane only
	Cell 914_PL, MnROAD	8	PG 58-28	None	6 x 6	1993	Oct-08	None
	Cell 160, MnROAD	6	PG 58-28	None	6 x 6	1993	Jul-13	None
	Cell 160_PL, MnROAD	6	PG 58-28	None	6 x 6	1993	Jul-13	None
	Cell 162, MnROAD	7	PG 58-28	None	6 x 6	1993	Jul-13	None
	Cell 162_PL, MnROAD	7	PG 58-28	None	6 x 6	1993	Jul-13	None
Illinois	Highway 4-Piatt County	4+8 PCC	PG 64-22	CTB, t=8in	5.5 × 5.5	1987	Fall 2000	None
	Highway 2-Cumberland County	6.5	PG 64-22	10" Aggregate	5.5 × 6	1987	Fall 2001	None
Colorado	DL_SH 119-Section 1_Slab Design 3	3.3	Pen Grade 85-100	8" Aggregate	6 × 6	1970	May-97	None
	PL_SH 119-Section 1_Slab Design 3	3.3	Pen Grade 85-100	8" Aggregate	6 × 6	1970	May-97	None
	SH 119-Section 1_Slab Design 4	3.3	Pen Grade 85-100	8" Aggregate	6 × 6	1970	May-97	None



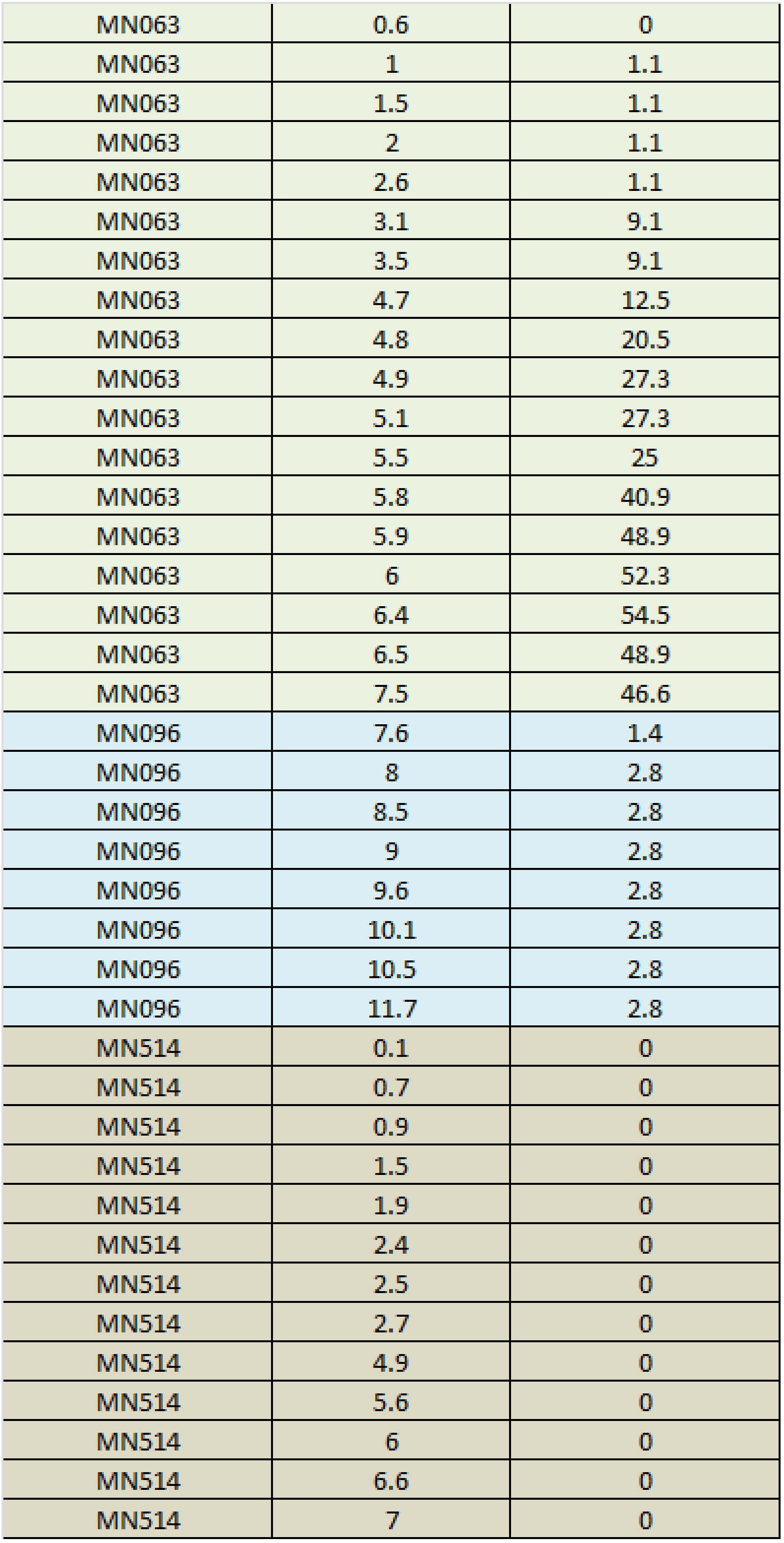
State	Project	Annual LTE (%)	Two-way AADTT	Number of Lanes (one direction)	% Trucks in Design Lane	Alligator Cracking Existing HMA	Distress Data (Dates)	Years Service	Notes
Minnesota	Cell 60, MnROAD	80	4844	2	78	65	5/27/2005 - 4/26/2012	11	Done: Now Cell 160
	Cell 60_PL, MnROAD	80	4844	2	22	65	5/27/2005 - 4/26/2012	11	Done: Now Cell 160
	Cell 61, MnROAD	80	4844	2	78	65	5/27/2005 - 4/26/2012	11	Done: Now Cell 160
	Cell 61_PL, MnROAD	80	4844	2	22	65	5/27/2005 - 4/26/2012	11	Done: Now Cell 160
	Cell 62, MnROAD	80	4844	2	78	65	5/27/2005 - 4/26/2012	11	Done: Now Cell 162
	Cell 62_PL, MnROAD	80	4844	2	22	65	5/27/2005 - 4/26/2012	11	Done: Now Cell 162
	Cell 63, MnROAD	80	4844	2	50	65	5/27/2005 - 4/26/2012	11	Done: Now Cell 162
	Cell 63_PL, MnROAD	80	4844	2	50	65	5/27/2005 - 4/26/2012	11	Done: Now Cell 162
	Cell 96, MnROAD	80	4900	2	78	65	5/27/2005 - 10/7/2015	18	
	Cell 96_PL, MnROAD	80	4900	2	22	65	5/27/2005 - 10/7/2015	18	
	Cell 114, MnROAD	95	4768	2	78	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 114_PL, MnROAD (same as 214_PL)	80	4768	2	22	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 214, MnROAD	80	4768	2	78	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 214_PL, MnROAD	80	4768	2	22	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 314, MnROAD	95	4768	2	78	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 314_PL, MnROAD (same as 414_PL)	80	4768	2	22	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 414, MnROAD	80	4768	2	78	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 414_PL, MnROAD	80	4768	2	22	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 514, MnROAD	95	4768	2	78	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 514_PL, MnROAD	80	4768	2	22	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 714, MnROAD	95	4768	2	78	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 714_PL, MnROAD	80	4768	2	22	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 814, MnROAD	80	4768	2	78	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 814_PL, MnROAD	80	4768	2	22	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 914, MnROAD	95	4768	2	78	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 914_PL, MnROAD	80	4768	2	22	65	11/19/2008 - 10/7/2015	7	Formerly asphalt surfaced Cell 14
	Cell 160, MnROAD	80	4844	2	78	65	9/24/13 - 10/6/2015	2	Formerly Cells 60 and 61
	Cell 160_PL, MnROAD	80	4844	2	22	65	9/24/13 - 10/6/2015	2	Formerly Cells 60 and 61
	Cell 162, MnROAD	80	4844	2	78	65	9/24/13 - 10/6/2015	2	Formerly Cells 62 and 63
	Cell 162_PL, MnROAD	80	4844	2	22	65	9/24/13 - 10/6/2015	2	Formerly Cells 62 and 63
Illinois	Highway 4-Piatt County	90	500	1	100	65	Apr-16	15	Two lane county highway
	Highway 2-Cumberland County	80	500	1	100	65	Apr-16	14	Two lane County highway
Colorado	DL_SH 119-Section 1_Slab Design 3	80	1257	2	80	65	Apr-16	18	Driving Lane
	PL_SH 119-Section 1_Slab Design 3	80	1257	2	20	65	Apr-16	18	Passing Lane. Has much more truck traffic, in Urban area with trucks
	SH 119-Section 1_Slab Design 4	80	251	1	100	65	Apr-16	18	Passing Lane

Appendix B Database of Age and Longitudinal Cracking for Calibration of AASHTOWare ME SJPCP

Database for ME Calibration File Name	Pavement Age	Measured Long. Cracking % Slabs
CO119-3	1	0
CO119-3	2	0
CO119-3	3	1.7
CO119-3	4	4.0
CO119-3	5	0
CO119-3	6	0.6
CO119-3	7	1.6
CO119-3	8	0.5
CO119-3	9	0.1
CO119-3	10	0
CO119-3	11	0.2
CO119-3	12	0.3
CO119-3	13	0.3
CO119-3	14	0.4
CO119-3	15	0.3
CO119-3	16	1.5
CO119-3	17	1.6
CO119-3	18	2.4
CO119-3_PL	10	11.4
CO119-3_PL	11	11.3
CO119-3_PL	12	10.4
CO119-3_PL	14	13.6
CO119-3_PL	15	14
CO119-3_PL	17	17.3
CO119-3_PL	18	17.3
CO119-4	18	0



MN060	0.6	0
MN060	1	0
MN060	1.5	0
MN060	2	1.1
MN060	2.6	1.1
MN060	3.1	3.4
MN060	3.5	3.4
MN060	4.7	4.5
MN060	4.8	4.5
MN060	4.9	4.5
MN060	5.5	4.5
MN060	5.8	4.5
MN060	5.9	5.7
MN060	6	5.7
MN061	0.6	0
MN061	1	0
MN061	1.5	0
MN061	2	4.5
MN061	2.6	4.5
MN061	3.1	5.7
MN061	3.5	5.7
MN061	4.7	5.7
MN061	4.8	8
MN061	4.9	8
MN061	5.5	8
MN061	5.8	9.1
MN061	5.9	12.5
MN061	6	13.6
MN061	6.5	11.4
MN061	6.7	12.5
MN061	6.9	9.1
MN061	7.5	9.1
MN062	0.6	0
MN062	1	0
MN062	1.5	0
MN062	2	0
MN062	2.6	1.1
MN062	3.1	1.1
MN062	3.5	1.1
MN062	4.7	1.1
MN062	4.8	4.5
MN062	4.9	4.5
MN062	5.5	4.5
MN062	5.8	4.5
MN062	5.9	11.4
MN062	6	11.4
MN062	6.5	12.5
MN062	6.7	15.9
MN062	7.5	13.6



MN063	0.6	0
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MN063	1.5	1.1
MN063	2	1.1
MN063	2.6	1.1
MN063	3.1	9.1
MN063	3.5	9.1
MN063	4.7	12.5
MN063	4.8	20.5
MN063	4.9	27.3
MN063	5.1	27.3
MN063	5.5	25
MN063	5.8	40.9
MN063	5.9	48.9
MN063	6	52.3
MN063	6.4	54.5
MN063	6.5	48.9
MN063	7.5	46.6
MN096	7.6	1.4
MN096	8	2.8
MN096	8.5	2.8
MN096	9	2.8
MN096	9.6	2.8
MN096	10.1	2.8
MN096	10.5	2.8
MN096	11.7	2.8
MN514	0.1	0
MN514	0.7	0
MN514	0.9	0
MN514	1.5	0
MN514	1.9	0
MN514	2.4	0
MN514	2.5	0
MN514	2.7	0
MN514	4.9	0
MN514	5.6	0
MN514	6	0
MN514	6.6	0
MN514	7	0

MN714	0.1	0
MN714	0.7	0
MN714	0.9	0
MN714	1.5	0
MN714	1.9	0
MN714	2.4	0
MN714	2.5	0
MN714	2.7	0
MN714	3	0
MN714	3.5	0
MN714	4.9	0
MN714	5.6	0
MN714	6	0
MN714	6.6	0
MN714	7	0
MN814	0.1	0
MN814	0.7	0
MN814	0.9	0
MN814	1.5	0
MN814	1.9	0
MN814	2.4	0
MN814	2.5	0
MN814	2.7	0
MN814	3	0
MN814	3.5	0
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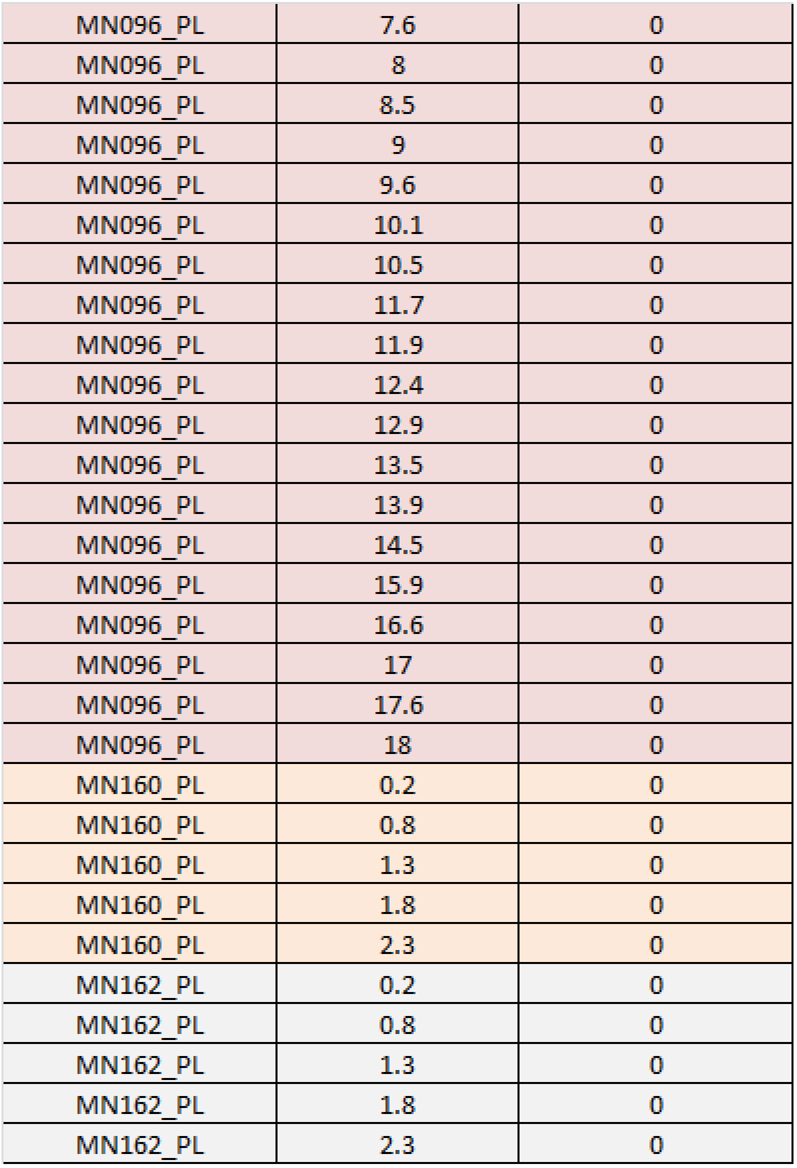
MN814	5.6	0
MN814	6	0
MN814	6.6	12.5
MN814	7.0	12.5
MN914	0.1	0
MN914	0.7	0
MN914	0.9	0
MN914	1.5	0
MN914	1.9	0
MN914	2.4	0
MN914	2.5	0
MN914	2.7	0
MN914	3	0
MN914	4.9	0
MN914	5.6	0
MN914	6	0
MN914	6.6	0
MN914	7	0

MN060_PL	0.6	0
MN060_PL	1	0
MN060_PL	1.5	0
MN060_PL	2	0
MN060_PL	2.6	0
MN060_PL	3.1	0
MN060_PL	3.5	0
MN060_PL	4.7	2.3
MN060_PL	4.8	2.3
MN060_PL	4.9	3.4
MN060_PL	5.5	4.5
MN060_PL	5.8	6.8
MN060_PL	5.9	5.7
MN060_PL	6	6.8
MN060_PL	6.5	6.8
MN061_PL	0.6	0
MN061_PL	1	0
MN061_PL	1.5	2.3
MN061_PL	2	4.5
MN061_PL	2.6	4.5
MN061_PL	3.1	4.5
MN061_PL	3.5	4.5
MN061_PL	4.7	4.5
MN061_PL	4.8	4.5
MN061_PL	4.9	4.5
MN061_PL	5.5	4.5
MN061_PL	5.8	4.5
MN061_PL	5.9	4.5
MN061_PL	6.5	4.5
MN061_PL	6.7	4.5
MN061_PL	6.9	6.8
MN062_PL	0.6	0
MN062_PL	1	0
MN062_PL	1.5	0
MN062_PL	2	0
MN062_PL	2.6	0
MN062_PL	3.1	0
MN062_PL	3.5	0
MN062_PL	4.7	2.3
MN062_PL	4.8	0
MN062_PL	4.9	0
MN062_PL	5.5	1.1
MN062_PL	5.8	1.1
MN062_PL	5.9	0
MN062_PL	6	0
MN062_PL	6.5	0
MN062_PL	6.7	0



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MN096_PL	9	0
MN096_PL	9.6	0
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MN096_PL	10.5	0
MN096_PL	11.7	0
MN096_PL	11.9	0
MN096_PL	12.4	0
MN096_PL	12.9	0
MN096_PL	13.5	0
MN096_PL	13.9	0
MN096_PL	14.5	0
MN096_PL	15.9	0
MN096_PL	16.6	0
MN096_PL	17	0
MN096_PL	17.6	0
MN096_PL	18	0
MN160_PL	0.2	0
MN160_PL	0.8	0
MN160_PL	1.3	0
MN160_PL	1.8	0
MN160_PL	2.3	0
MN162_PL	0.2	0
MN162_PL	0.8	0
MN162_PL	1.3	0
MN162_PL	1.8	0
MN162_PL	2.3	0

MN214_PL	0.1	0
MN214_PL	0.7	0
MN214_PL	0.9	0
MN214_PL	1.5	0
MN214_PL	1.9	0
MN214_PL	2.4	0
MN214_PL	2.5	0
MN214_PL	2.7	0
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MN214_PL	5.6	0
MN214_PL	6	0
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MN214_PL	7	0
MN414_PL	0.1	0
MN414_PL	0.7	0
MN414_PL	0.9	0
MN414_PL	1.5	0
MN414_PL	1.9	0
MN414_PL	2.4	0
MN414_PL	2.5	0
MN414_PL	2.7	0
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MN414_PL	5.6	0
MN414_PL	6	0
MN414_PL	6.6	0
MN414_PL	7	0
MN514_PL	0.1	0
MN514_PL	0.7	0
MN514_PL	0.9	0
MN514_PL	1.5	0
MN514_PL	1.9	0
MN514_PL	2.4	0
MN514_PL	2.5	0
MN514_PL	2.7	0
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MN514_PL	5.6	0
MN514_PL	6	0
MN514_PL	6.6	0
MN514_PL	7	0

MN714_PL	0.1	0
MN714_PL	0.7	0
MN714_PL	0.9	0
MN714_PL	1.5	0
MN714_PL	1.9	0
MN714_PL	2.4	0
MN714_PL	2.5	0
MN714_PL	2.7	0
MN714_PL	3	0
MN714_PL	3.5	0
MN714_PL	4.9	0
MN714_PL	5.6	0
MN714_PL	6	0
MN814_PL	0.2	0
MN814_PL	0.8	0
MN814_PL	1.3	0
MN814_PL	1.8	0
MN814_PL	2.3	0
MN914_PL	0.2	0
MN914_PL	0.8	0
MN914_PL	1.3	0
MN914_PL	1.8	0
MN914_PL	2.3	0
MN114	0.1	0
MN114	0.7	0
MN114	0.9	0
MN114	1.5	0
MN114	1.9	0
MN114	2.4	0
MN114	2.5	0
MN114	2.7	0
MN114	3	0
MN114	3.5	0
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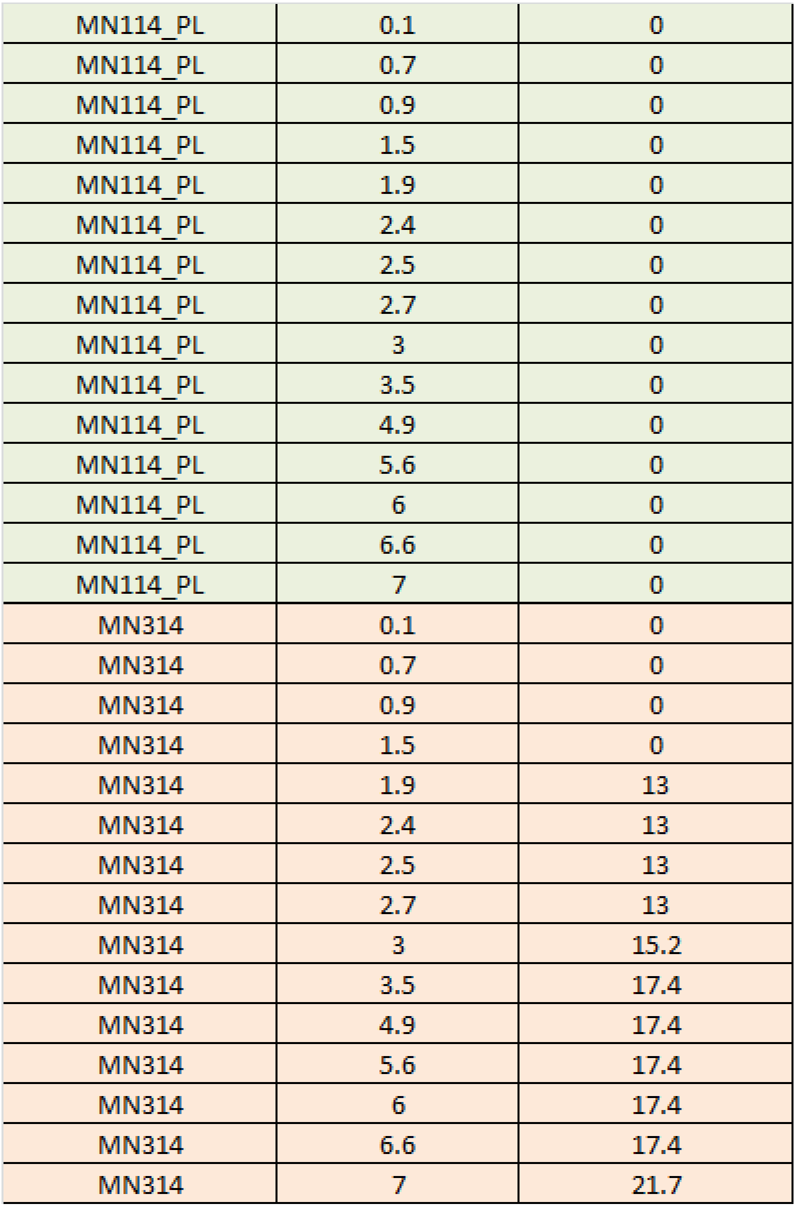
MN114	6	7.7
MN114	6.6	7.7
MN114	7	11.5



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MN114_PL	0.7	0
MN114_PL	0.9	0
MN114_PL	1.5	0
MN114_PL	1.9	0
MN114_PL	2.4	0
MN114_PL	2.5	0
MN114_PL	2.7	0
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MN114_PL	5.6	0
MN114_PL	6	0
MN114_PL	6.6	0
MN114_PL	7	0
MN314	0.1	0
MN314	0.7	0
MN314	0.9	0
MN314	1.5	0
MN314	1.9	13
MN314	2.4	13
MN314	2.5	13
MN314	2.7	13
MN314	3	15.2
MN314	3.5	17.4
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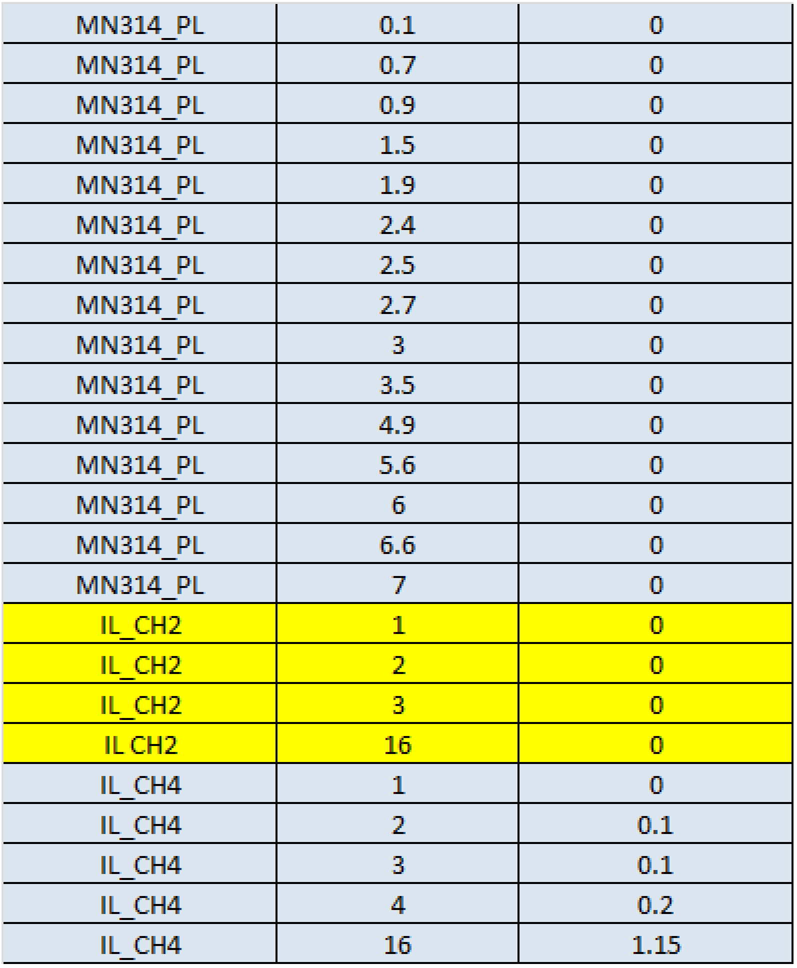
MN314	5.6	17.4
MN314	6	17.4
MN314	6.6	17.4
MN314	7	21.7



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MN314_PL	0.7	0
MN314_PL	0.9	0
MN314_PL	1.5	0
MN314_PL	1.9	0
MN314_PL	2.4	0
MN314_PL	2.5	0
MN314_PL	2.7	0
MN314_PL	3	0
MN314_PL	3.5	0
MN314_PL	4.9	0
MN314_PL	5.6	0
MN314_PL	6	0
MN314_PL	6.6	0
MN314_PL	7	0
IL_CH2	1	0
IL_CH2	2	0
IL_CH2	3	0
IL CH2	16	0
IL_CH4	1	0
IL_CH4	2	0.1
IL_CH4	3	0.1
IL_CH4	4	0.2
IL_CH4	16	1.15