GEORGIA DOT RESEARCH PROJECT 16-01

Final Report

STUDY OF TEMPORAL PAVEMENT CRACKING IN 3D TO DETERMINE OPTIMAL TIME AND COST-EFFECTIVE TREATMENT METHODS

Georgia Department of Transportation

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16. Abstract:
The Georgia Department of Transportation (GDOT) and many of its counterparts now collect the full-extent, high-resolution 3D pavement data to provide a full coverage (or continuous) of pavement distress data on its roadways. This project focuses on exploring the potential for taking full advantage of 3D pavement data in support of using slab-level pavement distresses to forecast the performance and treatment (such as slab replacement) of jointed plain concrete pavement (JPCP). A methodology, consisting of joint/crack detection, joint/crack clustering method, crack classification, faulting computation, and slab condition criteria, was developed for effectively extracting the distresses (i.e., cracking and faulting) on each slab and classifying the slab condition based on GDOT's Jointed Plain Concrete Pavement Condition Evaluation System (JPCPACES) to support various analyses at the slab level. Six years' 3D pavement data on five test sections was processed to generate the time-series slab condition data to explore the deterioration behavior. A slab condition forecasting model was developed based on a multi-stage Markov chain modeling, which use different transition probability matrixes (TPMs) to represent the slab deterioration behavior (change in condition) in three stages defined by the slab condition. A dynamic linear regression model, coupled with the default faulting growth rate for each design category derived from CPACES, was developed for predicting faulting on Georgia's JPCP. A case study was conducted on 160 miles of I-16 (eastbound) to demonstrate the feasibility and the use of the developed models (methodology) for predicting future JPCP condition and M&R needs.

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STUDY OF TEMPORAL PAVEMENT CRACKING IN 3D TO DETERMINE OPTIMAL TIME AND COST-EFFECTIVE TREATMENT METHODS

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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EXECUTIVE SUMMARY

In recent years, 3D pavement imaging systems, which can collect high-resolution, full-coverage 3D pavement surface (depth) data at highway speeds, have become the mainstream approach for pavement distress data collection. More than 25 states, including Georgia, now use 3D pavement data for their pavement condition survey.

Currently, 3D pavement data is mainly used for reporting distress data at the segment level (e.g., 0.1 mile or 1 mile) or project level (e.g., 10 miles). However, this rich data, coupled with artificial intelligence (such as automatic crack detection), provides an innovative opportunity to extract detailed crack characteristics (including length, width, orientation, and topological patterns), which makes it feasible to closely study crack deterioration behavior. The aim of this project is to utilize 3D pavement data collected from in-service jointed plain concrete pavements (JPCPs) to better understand and model how JPCPs deteriorate in the real world and to support maintenance and rehabilitation (M&R) decisions. The outcomes of this research project are as follows:

1. A review of the JPCP distresses, M&R strategies, and forecasting models identifies there is a gap between the distresses used by agencies (for M&R decisions) and predicted by the forecasting models. The former is based on is primary determined based on the distress severity at the slab level, and the later focuses on a single indicator (e.g., percentage of transverse cracking, rating, or IRI) without the severity. There is a need for a forecasting model that can directly integrate with M&R decisions and provide more accurate estimates.

2. A review of the long-term pavement performance (LTPP) data shows that the limited cracking on the LTPP sections is not representative of the slab condition of the whole mile section. 3D pavement data collected on all in-service JPCPs on the network can be used study the JPCP performance in real world. Nevertheless, the patterns and limitations learned from the LTPP data are used in developing or defining the slab fundamentals. For instance, the number and length of cracks cannot support the slab level analysis. Moreover, cracks, especially longitudinal cracking, that do not extend to a joint or is made of short lengths (e.g., less than 1 ft.) may be map cracking, which is not considered for the deterioration or M&R.
3. A 3D slab-based methodology (3DSBM) was developed to provide an overall process that use 3D pavement data to define, analyze, model the distress (cracking and faulting) in JPCP at the slab level. The 3DSBM consists of the following components: 3D data collection, slab level fundamentals (including identification of individual slabs, classification of individual cracks, classification of individual slabs based on distress severity, and aligning/rectifying the slabs in time to measure changes in distress), and analysis and modeling (including spatial and temporal analysis for developing forecasting models).
4. Six-years of 3D pavement data on five one-mile test sections were processed to extract slab fundamentals based on 3DSBM. A multi-stage Markov chain model was developed using the data to predict the JPCP performance based on slab condition. It used different transition probability matrixes (TPMs) to represent JPCP deterioration behaviors (change in condition) in different stages. Twenty-five TPMs derived from the five test sections were categorized using a k-means

method that grouped the TPMs into three deterioration groups. The average TPM in each group was developed to represent the slab condition deterioration at the three stages without treatment. The stages are specified using the percentage of slabs in the shattered slab (SS) state and Level 2 transverse cracking (T2) (i.e., Stage 1: T2+SS < 0.05; Stage 2: 0.5<T2+SS < 0.1; Stage 3: T2+SS > 0.1). The slab condition is then predicted by the existing condition and the associated TPM based on the percentage of slabs in T2 and SS.

5. The 3DSBM was also applied for developing a faulting forecasting model. A dynamic linear regression model, coupled with the default faulting growth rate for each design category derived from CPACES, was developed for predicting faulting on Georgia's JPCP. The steps in the model are described in this report. This method takes advantage of the existing faulting observed in the field and reduces the efforts for acquiring additional data (such as traffic, drainage, etc.) that is currently not available in the CPACES database. In addition, the slab-level spatial analysis shows the faulting measured at different locations (along the joint and the distance away from the joint) is different.
6. A case study was conducted using 160 miles of JPCP on I-16 (eastbound) to demonstrate the feasibility and use of the developed methodology and forecasting models for predicting future JPCP conditions and M&R needs. The slab condition in each mile was derived using the 3D pavement data collected in 2018. There are 622 slabs of T2 and SS that can be considered as slab replacement candidates. However, the number increases to 857 slabs in 2019 and 1429 slabs in 2021. Note that many of the distressed slabs are clustered in a few sections at MP 15-20 and

MP 95-100. In a few segments, more than 10% of the slabs are cracked, and the predictions show a significant increase in the future; these segments can be further evaluated to make full-lane replacement decisions.

To ensure the implementation of the forecasting models developed using the 3DSBM, the following are recommended:

1. It has been proven that 3D pavement data can provide detail level JPCP pavement distresses; this is extremely valuable for developing a reliable JPCP performance forecasting method with the developed JPCP distress propagation model and a Markov chain deterioration model.
2. Based on the success of the feasibility study, implementing the slab condition forecasting model on I-16 is recommended. TPMs on additional sections on I-16 can be developed to cover the designs and stages on I-16.
3. It is suggested that the methodology for predicting concrete slab replacement be expanded to other JPCPs by extracting slab level fundamentals from 3D pavement data on more JPCP sections with different designs and traffic loads to establish TPMs.
4. Integrating TPMs into Georgia's pavement management system for predicting the slab condition of JPCPs is recommended. The slab condition can then be integrated into the M&R decisions for such actions as slab replacement.

It is recommended that the dynamic linear regression model, along with the default faulting deterioration rates for each design category, be integrated into Georgia's pavement management system to predict future faulting and the need for diamond grinding.

CHAPTER 1. INTRODUCTION

BACKGROUND AND RESEARCH NEEDS

The MAP-21 (the 21st Century Act) and FAST (the Fixing America's Surface Transportation Act) require state DOTs to provide a full-extent (or continuous) coverage of pavement condition data on roadways. In response to the requirement, 3D pavement imaging systems, which utilize line lasers and 3D triangulation to acquire high-resolution, full-coverage 3D pavement surface (depth) data, have become the mainstream approach for pavement condition data collection in recent years. In 2017, twenty-four states indicated they use 3D pavement data for pavement condition surveys and additional twelve states said they plan to use 3D pavement data in the next two years (Zimmerman, 2017). The Georgia Department of Transportation (GDOT) is now transitioning to a new pavement data production operation using 3D pavement data. Currently, 3D pavement data is mainly used for replacing the manual survey to provide distress data at the segment level (e.g., 0.1 mile or 1 mile) or project level (e.g., 10 miles) to support the existing operations. However, this rich data, coupled with artificial intelligence (such as automatic extraction of pavement distresses), provides great potential for closely studying the deterioration of jointed plain concrete pavement (JPCP) at a detailed, slab level.

The full-extent, high-resolution 3D pavement data can show where cracks in a slab start and how they progress, and it could show the rate of progression (Tsai, et al., 2015; Tsai and Geary, 2017). This would support more accurate predication of the JPCP slab conditions, which are directly linked with the JPCP maintenance and rehabilitation (M&R) decisions for such actions as slab replacement.

Currently, there is no method to analyze and predict JPCP performance at the slab level; thus, there is an urgent need to explore the potential for taking full advantage of this 3D pavement data to support the study of Georgia's JPCP pavement at the slab level. The challenge of 3D pavement data is managing the huge amount of data collected and turning the data into distresses and patterns that can be statistically analyzed. This study focuses on developing a methodology using 3D pavement data to study JPCP deterioration where there is crack/faulting (the predominant distresses) at both slab and segment/project level. This study is to develop more accurate deterioration forecasting models using the slab-level analysis. Slab-level analysis refers to the study of the cracking condition in each slab, and it is important for defining the severity level and adequate treatment for each slab. This is especially important when transportation agencies have limited resources and can only replace a limited number of slabs in a one-mile section.

RESEARCH OBJECTIVES AND SCOPE

The objective of this project is to develop a methodology to study JPCP at the slab-level using 3D pavement data to better support the M&R decisions. This includes
1) developing a methodology for studying the cracking and faulting at a slab level using 3D pavement data, 2) developing a JPCP forecasting model that predicts the slab condition, and 3) developing a faulting forecasting model using 3D pavement data. The outcomes include a case study with detailed steps on how to use the developed forecasting models to determine the M&R needs for JPCPs.

REPORT ORGANIZATION

This report is organized as follows:

1. CHAPTER 1 introduces the background, significance, objective, and work tasks.
2. CHAPTER 2 presents a review of JPCP distresses, M&R strategies, and forecasting models to identify any gaps between current practices and the forecasting models. In addition, LTPP data was reviewed to identify the limitations and crack characteristics, which are used to support the development of a methodology for studying JPCP at the slab level using 3D pavement data.
3. CHAPTER 3 presents a 3D slab-based methodology (3DSBM) developed to define, analyze, and model the distress (cracking and faulting) in JPCP at the slab level using 3D pavement data.
4. CHAPTER 4 presents the development and validation of a slab condition forecasting model that is based on a multi-stage Markov chain modeling. This includes the development of transition probability matrixes (TPM) using the data on the test sections, and the categorization of TPMs using a k-means method. The TPMs for each of the three stages were presented along with the criteria defining each stage.
5. CHAPTER 5 presents the development and validation of a faulting forecasting model using the faulting derived from the 3D pavement data.
6. CHAPTER 6 presents a case study using 3D pavement data collected on I-16 to demonstrate how to use the developed models to support the M&R decisions.

CHAPTER 2. REVIEW OF JPCP DISTRESSES, M&R STRATEGIES, AND FORECASTING MODELS

This chapter presents a review of the JPCP distresses, M&R strategies, forecasting models, and available JPCP data. The review focuses on how JPCP is measured and treated for deterioration by state DOTs and then looks in detail on cracking and faulting forecasting models to identify any gaps or needs for better forecasting of JPCP performance and M&R needs. In addition, the existing available data (i.e., long-term pavement performance (LTPP) data) was reviewed to discover the crack characteristics that can assist in modeling JPCP at the slab level using 3D pavement data.

REVIEW OF JPCP DISTRESSES

Jointed plain concrete pavement (JPCP) is unreinforced cast-in-place concrete pavement that uses contraction joints to control cracking. Dowel bars are often used to provide additional load transfer at the transverse joints, especially JPCPs constructed after the 1970s. Tie bars may or may not be located between adjacent lanes. Cracking and faulting are the major distresses for fatigue of JPCPs. Environmental conditions, concrete thickness, concrete slab size (length and width), and foundation stability are the major considerations of cracking and faulting in concrete pavements.

Cracking

State DOTs have been collecting pavement distress data on JPCPs since at least the 1970s. There are a variety of different distresses measured by state DOTs for JPCP, such as transverse cracking, spalled joint, shoulder drop-off, patching, etc. Although the

terminology can be different, longitudinal, transverse, corner cracking, and shattered (or divided) slabs are common cracking types collected by state DOTs, as noted in Table 2-1. In addition, cracking is defined by FHWA for Highway Performance Monitoring (HPMS) purposes as a slab cracked transversely at least half the width of the slab, but does not include longitudinal cracks or corner breaks (FHWA, 2016).

Table 2-1. Cracking distresses collected by HPMS and states.

	HPMS (2016)	OR (2019)	NC (2012)	VA (2018)	CA (2015)	IN (2010)	FL (2017)	IL (2010)	GA (2016)
Corner Break/Crack		X	X	X	X	X	X	X	X
Shattered Slab		X	X	X[1]	X[2]		X		X
Transverse Cracking	X	X	X	X	X	X	X	X	X
Longitudinal Cracking		X	X	X	X	X	X	X	X

Note: X=Identified as being collected; 1=Divided Slab; 2=3rd Stage Cracking

Almost all states report cracking distress by a number of slabs per length (e.g., 1 mile) or on a percentage of slabs basis. Also, almost all states report the highest severity cracking level in a slab. Many states (e.g., Oregon, North Carolina, Virginia, California, Florida, and Georgia) use the term divided or shattered slab to denote a slab with multiple types of different intersecting cracks. This level of distress in a slab has a higher urgency for slab replacement because multiple cracks in a single slab can lead to a variety of worsening distresses, such as spalling, differential settlement, or popouts.

Since the 1970s, GDOT has conducted an annual survey of its JPCP using its distress protocol. The latest Jointed Plain Concrete Pavement Condition Evaluation System (JPCPACES) survey consists of measuring joint faulting and counting eleven types of distresses in the outside lanes for each mile of JPCP in Georgia (GDOT, 2018). Table 2-2 lists the distress type, severity level, sample location, and measure for the

distresses in the current JPCPACES. It is noted that shattered slab and severity levels (for longitudinal and transverse cracking) are used to capture how severe the distresses are in a slab for M&R decisions.

Table 2-2. Types of distresses in CPACES (Tsai and Wu, 2019).

Distress Type	Sample Location	Severity	Report Unit
Faulting[1]	Every 8th joint	-	Faulting Index
Shattered Slab	One mile	-	# of slabs
Corner Break	One mile	-	# of slabs
Transverse cracking (Slabs with transverse cracking)	One mile	Level 1	# of slabs
		Level 2	
Longitudinal crack (Slabs with longitudinal crack)	One mile	Level 1	# of slabs
		Level 2	
Replaced slab	One mile	-	# of slabs
Failed replaced slab	One mile	-	# of slabs
Joint with spalls	One mile	-	# of joints
Joint with patched spalls	One mile	-	# of joints
Joint with failed spalls	One mile	-	# of joints
Shoulder joint distress	One mile	-	# of joints
Roughness (IRI)[2]	One mile	-	mm/km

1. Faulting is collected using a Georgia Faultmeter.
2. Roughness is collected by the Laser Profiler.

Faulting

Faulting is caused by a change in the elevation of a concrete slab near a joint. It is reported as the difference in elevation of an approach slab as compared to the elevation of a leave slab at a joint. Based on the amount of movement and type of joint, it also involves loss of aggregate interlock and/or movement or distress of dowels in the case of

doweled pavements. Faulting can be a major problem in undoweled pavements on erodible bases.

Faulting measurements have long been performed by state DOTs using manual methods such as the Georgia Faultmeter (GFM) which was first built by the Georgia DOT in 1987 (Stone, 1991). GDOT measures the faulting of every eighth joint using a GFM. Figure 2-1 shows how a faulting measurement is taken with the GFM. The legs are placed on the leave slab and the probe measures the faulting from the approach slab. The GFM reads out in positive or negative integer readings (i.e. -2, -1, 0, 1, 2) that are equivalent to 1/32 in (0.03 in or 0.8 mm). Faulting values can be reported by joint, as an average value per length or an index value. GDOT reports a faulting index, which is five times the average of "absolute" faulting readings, is reported on every mile.

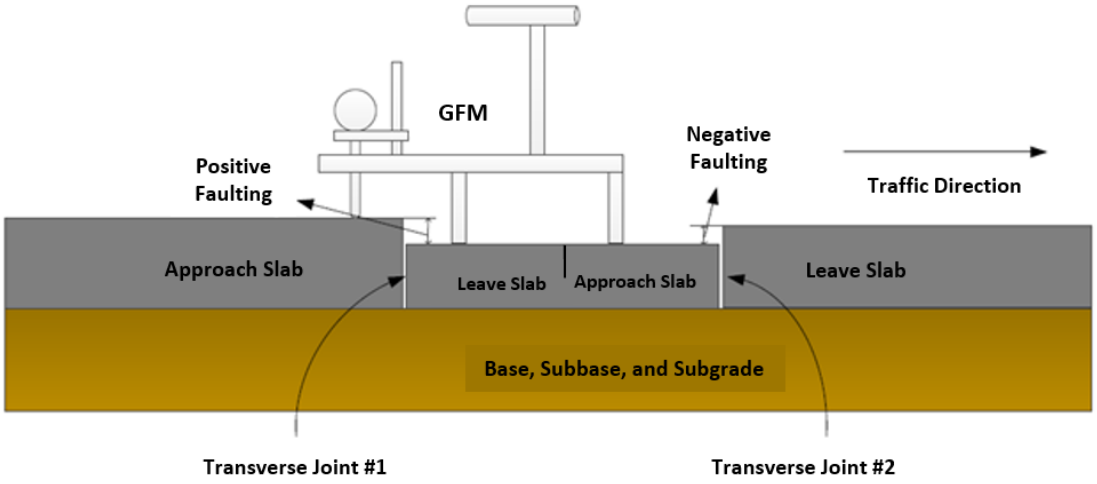


Figure 2-1. Illustration. Georgia faultmeter operation (Agurla and Lin, 2015).

AASHTO R 36, Evaluating Faulting of Concrete Pavements (AASHTO, 2017), is the current standard for faulting measurements. R 36-17 currently provides three methods to measure the faulting value: manual, automatic Method A, and automatic Method B.

The automatic methods both use one longitudinal profile from a high-speed inertial profiler (HSIP) to compute faulting. It is noted that GFM used by GDOT has a layout different from R 36-17. Preliminary studies of faulting measurements using 3D pavement data performed by Georgia Tech (Tsai et al., 2011; Tsai et al., 2012; and Geary et al., 2018) and Wang (2014) have shown potential improved results over HSIP methods.

REVIEW OF JPCP M&R STRATEGIES

M&R strategies (i.e., treatments) for JPCPs are relatively straightforward. Table 2-3 lists the individual treatment method, its use, and its expected service life. Slabs can be repaired (partial depth repair) or replaced (full depth repair or slab replacement), and faulting and/or IRI can be improved by diamond grinding. The slab replacement, joint reseal, and diamond grinding combined is the most common M&R strategy used on JPCPs. The decision on slab replacement is based on the distress severity in a slab. For example, shatter slabs typically require slab replacement.

GDOT makes its M&R decisions based on its annual survey. It typically involves repair and replacement of individual distressed slabs or portions of slabs. It considers all shattered slabs and slabs with transverse cracking Level 2 (T2) for slab replacement but decides on slabs with longitudinal cracking Level 2 (L2) on a case-by-case basis when estimating quantities per mile. In addition, diamond grinding is also used to remove surface irregularities that are often caused by faulting, curling, and warping of slabs to provide a smooth ride. IRI and/or a faulting index are used to trigger the need for diamond grinding. Since 2000, GDOT has also done a number of complete outside lane (truck lane) replacements when the number of cracked slabs needing repair exceeded

certain threshold values. This involves full lane replacement of the outside lane, including stabilizing the subgrade where necessary. Table 2-4 summarizes the M&R criteria for the typical treatments used by GDOT. Note that the decisions are based on slab-level distress conditions instead of an overall rating per mile. Thus, the capability of forecasting JPCP condition at the slab level can greatly improve the M&R planning based on the slab condition.

Table 2-3. JPCP treatment M&R strategies (Tsai et al., 2019).

M&R Strategies	**Use**	**Service Life, (Years)**
Partial Depth Repair	Used for ***spalling*** or ***corner breaks*** that do not go all the way through the slab (~ $\frac{1}{3}$ to $\frac{1}{2}$ slab thickness)	5 to 15
Slab Replacement or Full Depth Repair	Can repair ***cracked*** slabs, can reduce ***faulting*** due to cracked slabs	5 to 15
Dowel Bar Retrofit	To repair ***faulted cracks,*** or, for undoweled pavements in good condition, used to prevent/repair ***faulting***	10 to 15
Joint Reseal/Crack Seal	Protects pavement from water intrusion that can cause ***faulting*** or ***cracking***	2 to 8
Diamond Grind	Restores ride (***IRI***) and friction, need to repair any cracking or faulting first	8 to 15
Slab Stabilization/ Slab Jacking	Used to fill voids below slabs that can cause ***cracking*** or result in ***faulting***.	N/A
Rehabilitation/ Reconstruction	**Use**	
Lane Replacement	Continuous replacement of all the slabs in a lane. Can repair ***cracked*** slabs, ***faulting,*** and ride (***IRI)*** issues.	
Overlay	Asphalt or concrete overlay of existing pavement to restore ride ***(IRI).*** Some level of repair is necessary before overlaying to provide a stable base.	6 to 10

Table 2-4. Treatment criteria (GDOT, 2019).

Maintenance/Preservation			**Rehabilitation/ Reconstruction**	
Seal Cracks	**Repair Slabs (PDR/ FDR)**	**Diamond Grinding**	**Replace lane**	**Overlay**
>20% of joint seal failed	SS+T2 >10 (~5% slabs cracked)	F.I. > 20 (1/8 in) or IRI>1100	SS+T2 >33% slabs cracked	Slabs with cracks wider that ¾ in

REVIEW OF FORECASTING MODELS

This section reviews different performance or deterioration models described in the literature for JPCPs. Besides overall rating condition models, faulting and cracking models have all been developed. Overall rating condition models for concrete pavements are not as prevalent in the literature as asphalt models, potentially due to a lower volume of concrete pavements in most states' networks. The manner in which concrete pavements are maintained, such as isolated slab repair, makes overall rating models more difficult to use when measuring ratings over time. This section summarizes the review of cracking and faulting models. APPENDIX A LITERATURE REVIEW provides a more detailed review of the models.

Cracking

The most universally used mechanistic-based model for concrete pavements in the US is that used by the AASHTO PavementME Design (PMED) software, formerly known as MEPDG (mechanistic–empirical pavement design guide). The procedure uses a mechanistic-empirical approach to identify the percent of transverse slabs cracked per mile to define pavement life for cracking. The process considers both loading and thermal

(warp and curl) stresses in the pavement at the bottom and the top of the slab. Slabs are identified to crack when the ultimate tensile stress in the slab is exceeded through accumulated incremental tensile stresses based on Miners Theory (Miner, 1945). Tensile stresses from environmental and loading effects are both computed and combined. Finite element analysis and neural networks were both used to provide the necessary stresses and related deflections in a computationally efficient manner (ARA, 2004). The maximum stress theory method utilized by PMED concentrates on strength criteria such that cracking failure is identified based on the tensile and thermal properties of the concrete, with consideration of the geometry and support of the slab and the friction on the base of the slab (Huang, 1993). Properties of the concrete are based on test methods of small samples, and strength gain over time is included. This works for pavement design since ultimate conditions (cracked slabs) and not intermediate conditions (crack propagation) are being modeled. In addition, the results are empirically calibrated to full-size slabs, which should moderate size effects in the design.

The PMED does not currently predict longitudinal cracking, but the original research effort recognized “that future additions to this design procedure should fully consider” longitudinal cracking (Yu et al., 2003). Xiao and Wu (2018) developed a regression model for longitudinal cracking using Louisiana pavements that included the factors of slab geometry, base and subgrade resilient modulus, traffic, age and shoulder type. While there are many cracking models for asphalt pavement described in the literature, research on cracking models for concrete pavements is limited.

Faulting

Faulting in PMED is computed using an incremental approach. The incremental damage is a function of the type and erodibility of the base/subbase, rainfall, loading, and slab curling, which are not available for all JPCPs in Georgia. Slab curling based on environmental effects is considered as it is expected that maximum faulting would develop when the temperature differential is such that the joints are open and the slab is curled upward (ARA, 2003). Built-in slab curl or warp is not part of the analysis for either cracking or faulting. Faulting is measured as the mean faulting of all joints in inches. Faulting was also calibrated with full scale testing.

REVIEW OF LTPP DATA

While 3D pavement data can provide a wealth of information on a project level, since it is a relatively new capability, there is little historical data available. The Long Term Pavement Performance (LTPP) database is the most comprehensive information on pavement performance in the world. The LTPP database currently includes information on 2,548 pavement sections, and over 300 of these sections are JPCP (LTPP Infopave, 2018). Twenty-five sections from LTPP GPS 3 (General Pavement Studies) in the southeastern wet-no-freeze (WNF) region (where Georgia is located) were analyzed in APPENDIX A LITERATURE REVIEW. This section summarizes the limitations and discrepancies observed in the LTPP data and the review of the crack maps.

- LTPP data has been instrumental in nationally calibrating the PMED software to real world conditions. It is also used in the local calibration performed by many states to address their local conditions. However, lack of a statistically significant

number of pavement sections with appropriate distress data is still a common challenge for entities performing local calibration of PMED. Of the 8 LTPP JPCP sections in Georgia, 3 had no transverse cracking as of 2014 and 3 only had one transverse crack (4%) in the LTPP section, although their mean age was 34 years old.

- The LTPP records the number and length of different types of cracking (transverse and longitudinal cracks) with severity level (High, Medium, and Low), but it does not associate cracks with individual slabs. The PMED cracking criteria (i.e., % of transverse cracked slabs) used in national calibration uses the number of transverse cracks in a LTPP section divided by the number of slabs in the LTPP section. Therefore, if a slab had more than one transverse crack, it was actually recognized as two cracked slabs in the % of transverse cracked slabs calculation. In addition, it would require a manual review of individual distress maps to gather information at the slab level, which is time-consuming and prone to error.
- Each LTPP section covers about 500 ft (20-30 slabs). There is a question about how well it can represent the overall condition in a one-mile segment. Figure 2-2 shows transversely cracked slabs at one LTPP section (133017) in Georgia and the surrounding area (MP 150.2 – 152.2). The LTPP data shows no cracking reported at this site in 2014, which is consistent with the 3D pavement data collected in 2014. However, the 3D pavement data shows that a total of 28 slabs were identified as transversely cracked in 2014 in the 2-mile section that encompassed LTPP section 133017 (highlighted in orange squares). A field

observation of the non-cracked LTPP sites and the surrounding pavement in 2018 clearly identified slabs with transverse cracks on both sides of the LTPP sections. The continuous 3D pavement data can be used to improve the local calibration of the PMED software and to provide more intricate models of pavement performance.

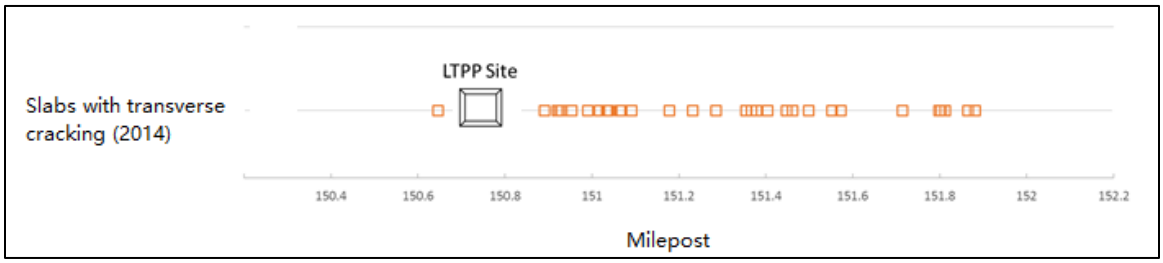


Figure 2-2. Chart. Transversely cracked slabs surrounding LTPP Section (133017)

- Analysis of the LTPP sections shows that some sections are predominately cracked longitudinally and others predominately transverse. Longitudinal cracking was more often found in consecutive slabs, while transverse cracking was more often not found in consecutive slabs. Longitudinal cracking was typically found in the wheel paths or in the center of the pavement.

A review of the LTPP cracking maps shows there are inconsistencies in the LTPP data. It was found in a number of sections (e.g., 133016, 133019, 133020) that cracking, especially longitudinal cracking, was later identified as map cracking (i.e., not longitudinal cracking). This was predominately cracking that did not extend to a joint or the cracking was made of short lengths of longitudinal cracking. Typically, short distances of longitudinal cracking in the center of a slab was later identified as map cracking. Cracks at joints appear to stay where cracks are noted in cracking maps more often; those not going to a joint later were more often noted to be map cracking.

Longitudinal cracking also disappeared without explanation much more often than transverse cracking. This could be due to misidentification as map cracking or there being maintenance of the section (diamond grinding).

SUMMARY

The review of the JPCP distresses, M&R strategies, forecasting models, and LTPP data are summarized as follows:

- Almost all states categorize cracking distresses such that the distress severities can be differentiated and report cracking distresses by a number of slabs per length (e.g., 1 mile). This is to support the M&R strategies (such as slab replacement), which are typically determined based on the distress severity in individual slabs. Therefore, a model to predict JPCP condition at the slab level is necessary to support the M&R planning.
- While longitudinal cracking is not modeled in the PMED, it is found in many of the LTPP sections. Some sections were even identified with primarily longitudinal cracking; therefore, it is an important part of cracking that needs to be considered in the models.
- The existing forecasting models (e.g., MEPDG) often predict a single indicator (such as % of transverse cracking, rating, or IRI) and do not consider different types of cracking (e.g., longitudinal and transverse cracking) or the severity. Therefore, a model that can forecast the slab condition (i.e., severity) is preferred because it provides an accurate estimate of slab replacement.

- The review of LTPP data shows continuous 3D pavement data with a large coverage can be used to improve the local calibration of the PMED software. However, the commonly used crack characteristics (the number and length of cracking) cannot support the slab-level analysis. A methodology is needed to define and extract the slab-level distress information from 3D pavement data.
- The review of LTPP data also shows the cracking, especially longitudinal cracking, that does not extend to a joint or is made of short lengths (e.g., less than 1 ft) may be later identified as map cracking or non-crack. Therefore, these cracks need to be identified and handled separately.

In summary, there is a need for a cracking model that can model JPCP at the slab level with different types of cracking and severities. It should also account for the non-linear deterioration behavior, consider the differences and randomness in the performance, and consider the existing condition on the in-serve JPCP.

CHAPTER 3. 3D SLAB-BASED METHODOLOGY

A spatial and temporal 3D slab-based methodology was developed by Geary (2018) to define, analyze, model and apply the information on the distress (cracking and faulting) state of individual slabs and slab systems in a jointed concrete pavement system using 3D pavement data. This methodology is termed the 3D Slab-Based Methodology (3DSBM) and is depicted in Figure 3-1. This chapter presents the 3DSBM, including data collection, slab level fundamentals, analysis and modeling, and applications. It is noted that while various analysis and modeling methods were discussed in this chapter, this project focuses on the forecasting model, which is discussed in CHAPTER 4.

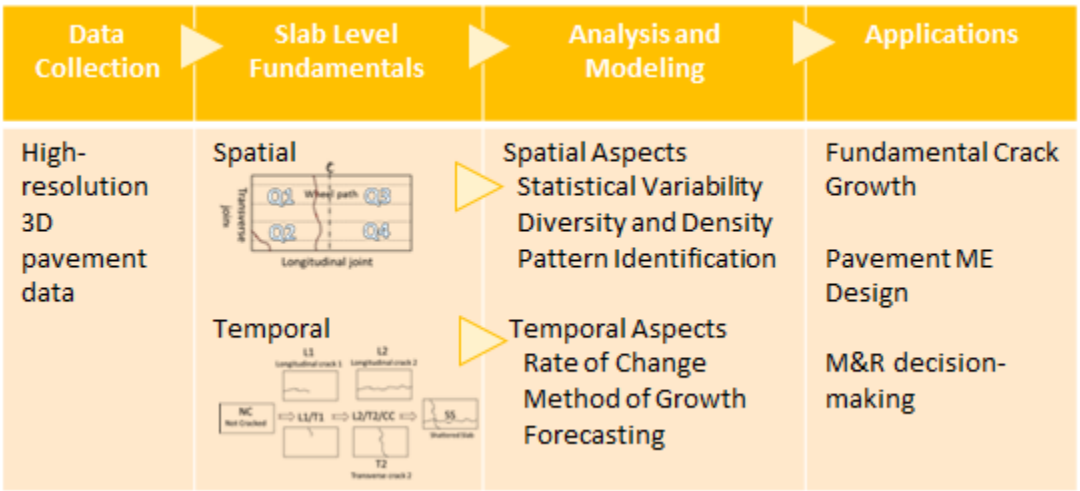
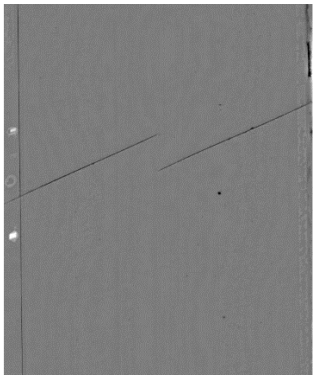


Figure 3-1. Chart. 3D slab-based methodology.

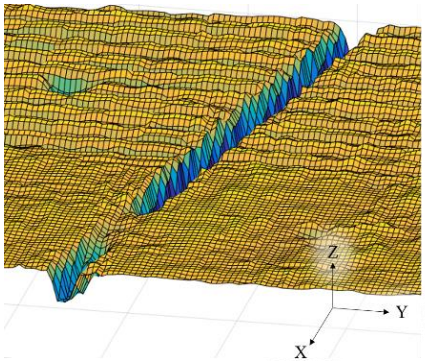
3D PAVEMENT DATA COLLECTION

The first step is to collect high-resolution 3D pavement data on JPCP, which is necessary for measuring faulting, cracking (e.g., length, type, etc.), and other surface distresses (such as rutting, raveling, and texture on asphalt pavements). With the advancement of 3D laser technology and image processing techniques, 3D pavement data can now be

collected at highway speeds. In this study, the GA Tech sensing vehicle (GTSV) was used to collect 3D pavement surface data on selected JPCP test sections at highway speeds. With a line scan rate of 5,600 profiles per second, the GTSV system can provide a resolution of 1 mm (~0.04 in) in the transverse direction and 5 mm (~0.2 in) in the longitudinal (or travel) direction at speeds up to 100 km/hr (62.5 mph) (Tsai et al., 2012). The data is stored every 5 m (i.e., 1,000 profiles), as shown in Figure 3-2 (A). On a 20-ft slab, approximately 1,200 profiles (or 5 million 3D points) can be collected to provide details (e.g., joint width, crack width, crack length, etc.) on the joint and the cracks on the slab, as shown in Figure 3-2 (B). This data is used to further process and extract the slab level fundamentals.



A. Range data collected at every 5 m



B. 3D view of the data

Figure 3-2. Photos. An example of 3D pavement data.

SLAB LEVEL FUNDAMENTALS

Slab level fundamentals is the core of the 3DSBM. It describes how the 3D pavement data is converted into slab ‘states’ as part of the 3DSBM. Figure 3-3 lists the processes involve in converting millions of 3D points (e.g., 5 million on a 20-ft slab) collected on concrete pavement surfaces into data that can support slab-level analyses.

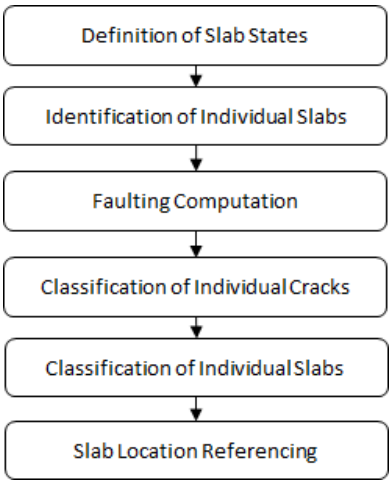


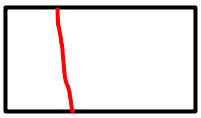
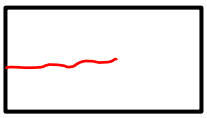
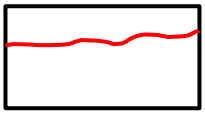
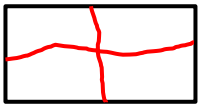
Figure 3-3. Chart. Processes in slab level fundamentals.

Definition of Slab States

To support slab-level analyses, the slab "states" (or condition) are first designed to represent distress condition in a slab with severities. The existing indicators (such as rating and IRI) were not used because they cannot describe the severity of cracked slabs, as discussed in CHAPTER 2. Table 3-1 lists the slab states developed by Geary (2018). The six slab states (NC, L1, L2, T1, T2, and SS) are designed to represent the common types of cracking in a slab, their severity, and the temporal progression of the distresses in a slab. Slab starts without any cracking as a NC state. Slabs with typical loading, neutral internal stresses and uniform support should suffer fatigue cracking transversely (defined as T1 or T2) near the center of the slab, as modeled in the AASHTO Pavement ME Design (PMED) software. While longitudinal cracking is not modeled in PMED, it is found in the LTPP sections and Georgia's JPCPs. Some pavements were even identified with primarily longitudinal cracking and therefore it is an important part of cracking that

needs to be considered. Longitudinal cracking also needs to be separated from transverse cracking as it tells us something about the internal stresses in the slabs (built-in curl or warp) and/or it tells us the slab is non-uniformly supported. Thus, L1 and L2 states are defined. Corner break is typically an indication of loss of support and is considered as T2. Eventually, a slab that is cracked in multiple locations and separated into 3 or more pieces is categorized as a shattered slab (SS). These slab states are expected to have a typical progression shown in Figure 3-4. A NC slab would first have cracking extend from a joint predominately in the transverse or longitudinal direction, then the crack would extend to another joint (either fully across the slab or in the case of cracks near a corner, to the adjacent corner). The addition of a different type of cracking leads to a Shattered Slab (SS). As the slab states are defined, further processes are designed to categorize slabs accordingly.

Table 3-1. Slab states.

State	State Abbr.	Description	Illustration
Not Cracked	NC	A slab with no cracking.	
Slab with transverse cracking (Levels 1 &2)	T1	A slab with transverse cracking only. Severity Level 1 is categorized as a hairline crack and a tight working crack.	
	T2	Severity Level 2 is categorized as a moving crack, which is generally wider than a hairline or tight working crack and maybe spalled. Note that corner break is considered as T2.	
Slab with longitudinal cracking (Levels 1 &2)	L1	A slab with longitudinal cracking only. Severity Level 1 is categorized as a hairline crack and a tight working crack.	
	L2	Severity Level 2 is categorized as a moving crack, which is generally wider than a hairline or tight working crack and maybe spalled.	
Shattered slab	SS	A slab that is cracked in multiple locations and separated into 3 or more pieces is categorized as a shattered slab.	

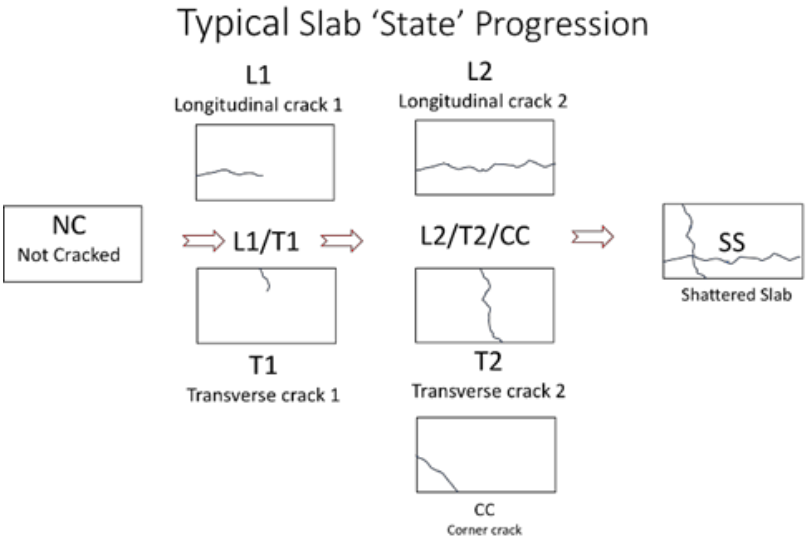


Figure 3-4. Illustration. Temporal progression of slab "states".

Identification of Individual Slabs

As described in Section 3.1, the 3D pavement data is saved in files representing a 5-m length of roadway. A slab (e.g., 20 ft.) typically spans across multiple such files. Thus, joint detected in multiple data files need to be clustered together to obtain a complete transverse joint, as illustrated in Figure 3-5. The output of this step is a list of transverse joints across the entire survey. This list of transverse joints is used to define individual slabs as the area between every consecutive pair of joints. Based on this joint list, detected cracks are also clustered together (if they span across adjacent data files) or split (if a crack goes across a transverse joint). Each crack is then assigned to a slab, as illustrated in Figure 3-5. Illustration. Joint stitching.

. Note that a slab can contain multiple cracks.

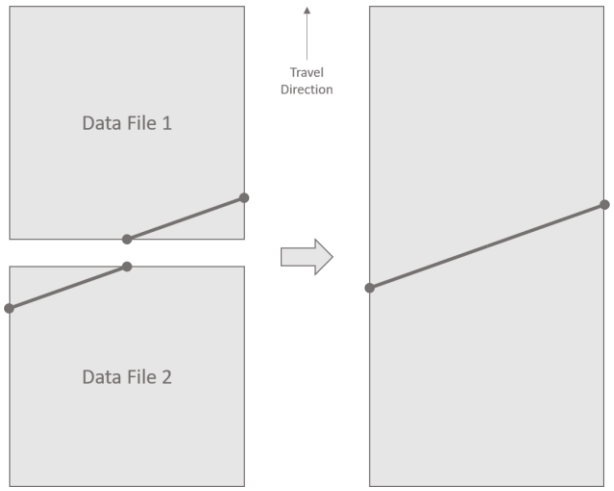


Figure 3-5. Illustration. Joint stitching.

Faulting Computation

Faulting can be computed at the joints and/or cracks using the 3D pavement data. While it is not currently used for classifying slabs or cracks, it can be used to improve the

classification and identify the problematic areas in the future. Therefore, it is included as part of the slab level fundamentals. A 2D-based faulting measurement method developed by Geary et al. (2018) is recommended for faulting computation.

Classification of Individual Cracks

In addition to the common crack properties (e.g., length, width, angle, etc.), additional properties (such as the intersection with longitudinal and/or transverse joints and the locations where a crack starts or ends in a slab, as identified in CHAPTER 2) are obtained using the fundamental crack topology available by using the 3D pavement data. These properties represent how a crack intersects with the joints. A slab is divided into four quadrants surrounded by transverse and longitudinal joints, as shown in Figure 3-6. For each crack, the quadrant in which each end point is located is identified, and whether or not the end point connects to a joint (TJ1, TJ2, LJ1, or LJ2) is determined. For example, Crack A has two end points located in the same quadrant (e.g., 1-1), and both end points connect to a joint (TJ1 and LJ1). Crack B is located in two quadrants (1-33) and connects to transverse joints (TJ1 and TJ2). These properties are used as the key factors for classifying each crack as a longitudinal crack, a transverse crack, a corner crack, or other crack based on the flowchart presented in Figure 3-7 (a). The severity level for longitudinal and transverse cracking is then determined based on the crack length and width, as show in Figure 3-7 (b). It is noted that a crack with a short length and disconnected from any joints (longitudinal or transverse) is classified as “other crack.” These cracks may be map cracks or sometimes disappear in the next year. A crack in the longitudinal direction (e.g., 1-3 or 2-4) that intersects a transverse joint is

classified as longitudinal cracking, while a crack in 1-2 or 3-4 that intersects a longitudinal joint is transverse cracking. A crack in the same quadrant is further classified by its connection to the joints. For example, a crack that is in the same quadrant and connects to both longitudinal and transverse joints is classified as a corner break. Note that with this cracking information, it is possible to derive the percentage of slabs with transverse cracks, which is one of the most important performance issues to be calibrated in the MEPDG models. As discussed in CHAPTER 2, currently, the LTPP data does provide a direct count of slabs with transverse cracking.

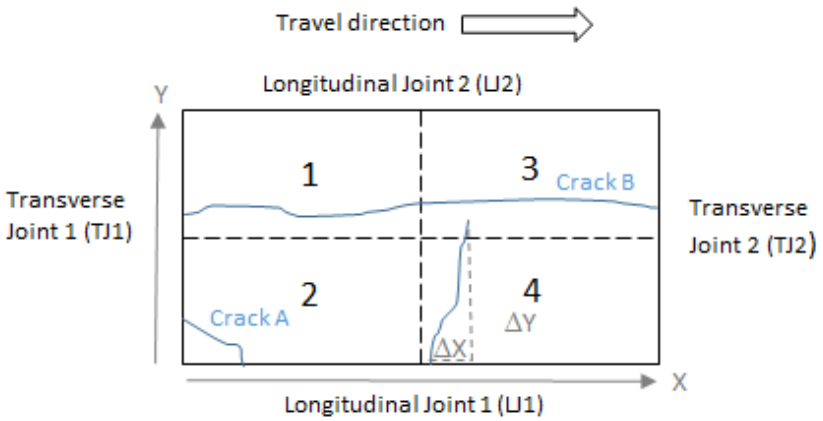


Figure 3-6. Illusration. Crack properties defining intersections with the slab and joint.

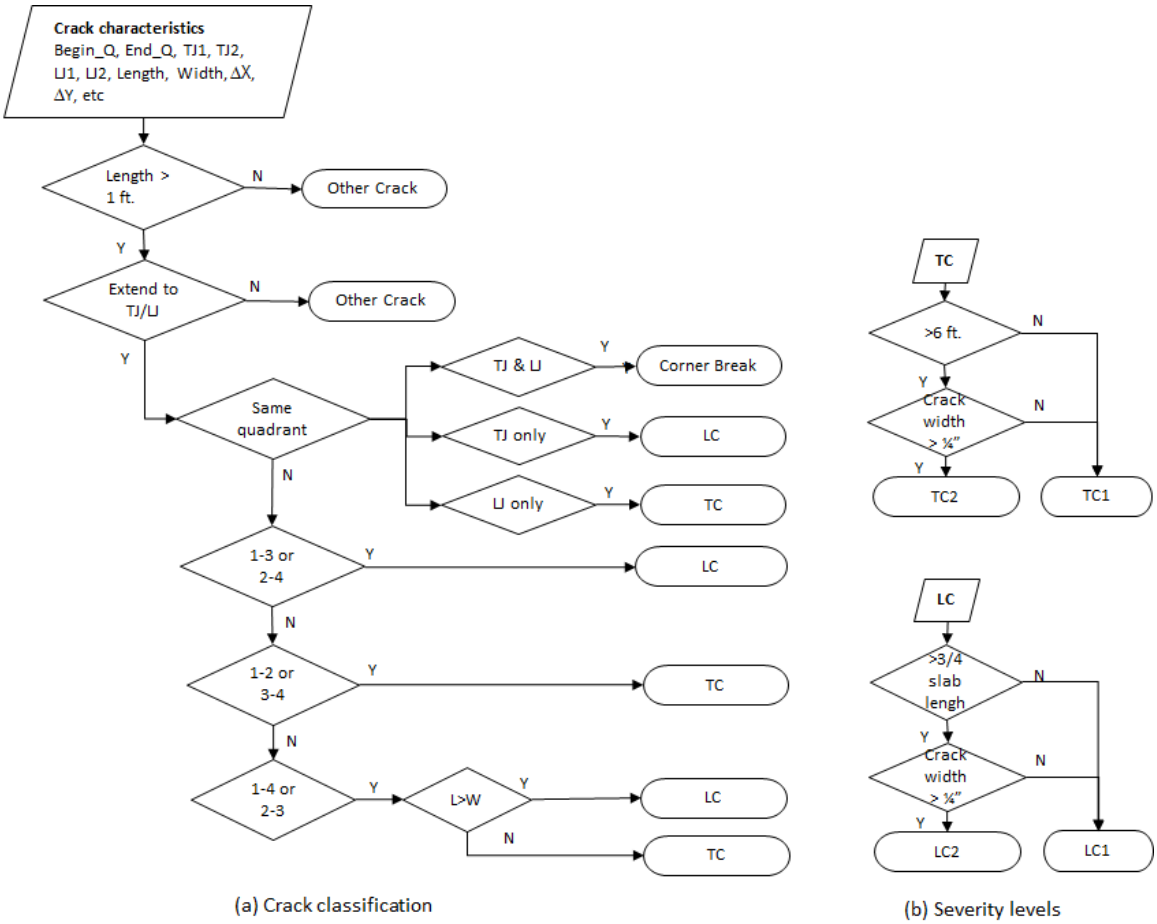


Figure 3-7. Chart. Crack classification and severity levels.

Classification of Individual Slabs

Finally, a slab is classified into one of the six states (NC, L1, L2, T1, T2, or SS) based on the most severe type of cracking in the slab. The classification is determined using the flowchart in Figure 3-8. Note that the cracks with "other" type (e.g., short crack not connecting to a joint) are not considered in the slab classification. It is noted that JPCPACES (GDOT, 2018) requires the surveyor(s) to record slab counts for different types of cracking. While there may be more than one types of cracking (e.g., longitudinal and transverse cracking) in a slab, each slab can only be counted once to avoid

duplication. This design allows GDOT to easily determine the number of slabs to be treated and also accommodates the limitations of the windshield survey. In the case that there is more than one type of cracking in a slab, the slab is classified by the most severe kind of cracking. For example, a slab with severe longitudinal and transverse cracking is counted as a shattered slab (it is neither a longitudinal cracked slab or a transverse cracked slab). While six states are used to define the slab states, 3D pavement data is capable of classifying the slab at finer categories to describe the combination of cracking in each slab (e.g., T1+L2, L2+CC, etc.).

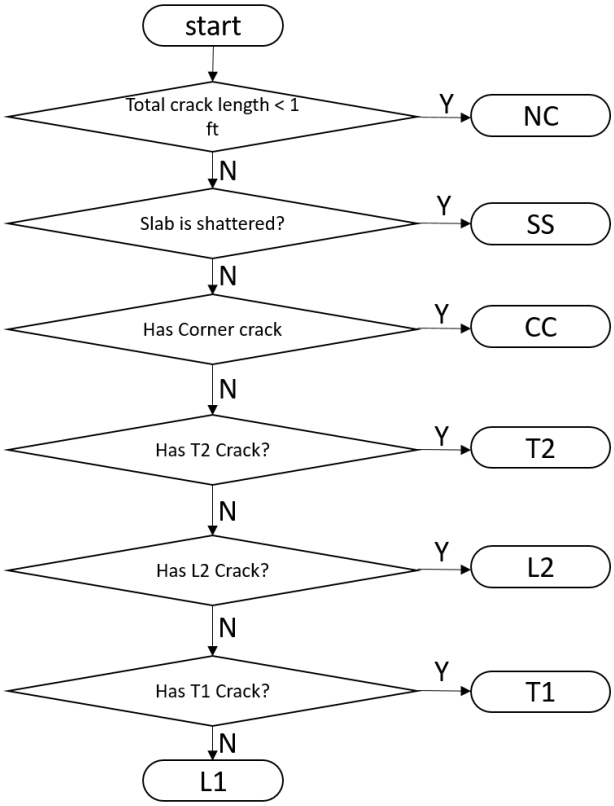


Figure 3-8. Chart. Slab classification method.

Slab Location Referencing

Each slab is referenced using a location referencing system. The location of the first and last (beginning and ending) joints are identified and referenced to the Milepost, then the location of the slabs in between are interpolated using the slab length, as shown in Figure 3-9. This can assist in aligning the slabs from different timestamps to measure changes in distress by slab.

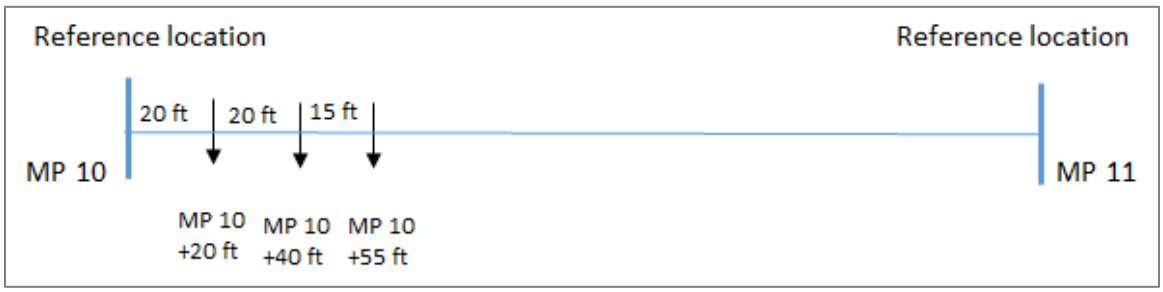


Figure 3-9. Illustration. Slab location referencing.

ANALYSIS AND MODELING

With data on each slab in a pavement section a measure of the variability and identification of patterns in multiscale is possible. Since this is a new form of data (i.e., slab level fundamentals), no standard procedures of how to utilize this data. The geospatial and computer science areas provide some suggestions. Spatial data mining includes methods of outlier detection, pattern discovery, classification and regression, clustering and hotspot analysis (Shekhar et al., 2011). Time series data can be mined to identify spatio-temporal patterns (Huang et al., 2008). This section describes the initial proposed methods that are based on modifications of these statistical and computer science methods used for other purposes. It is noted that while various methods are

described in this section, this study focuses on the predictive modeling presented in CHAPTER 4.

Spatial Aspects and Analyses

Isolated, clustered cracking should be more indicative of a construction related problem or anomaly in the foundation then a design aspect. Patterns in the location of certain cracking can also share insight into the cause of distress. Predominate longitudinal or transverse cracking also sheds information on the condition and internal stresses of the concrete pavement. Graphical representation can assist in seeing these patterns, as shown in Figure 3-10. Slabs are plotted based on their locations along the x axis with their states indicated along the y axis. Figure 3-10 shows the predominate slab state is NC (not cracked). The longitudinal cracking levels are positioned below the NC and the transverse cracking levels are above the NC. It is clear based on the number of points (slabs) aligned with L1 and L2 below the NC level, this section has predominately longitudinal cracking as compared to transverse cracking.

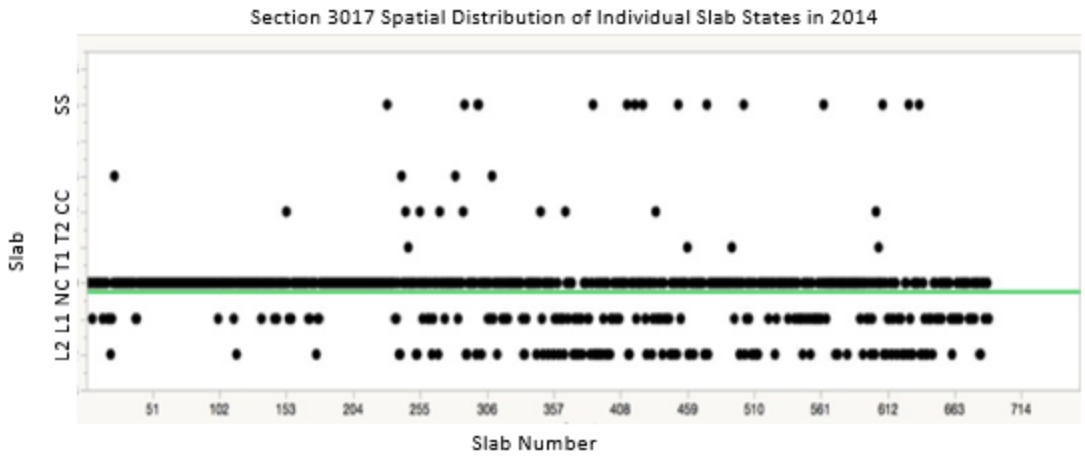


Figure 3-10. Chart. An example of spatial distribution of slab states.

The following are some that would be beneficial to measure in concrete pavements. They can be further explored in future study.

- predominate patterns in cracking type and location (a method to identify patterns in the predominate cracking type of a pavement)
- measures of uniformity (a method to measure uniformity at different scales)
    - identification of anomalies
    - uniformity at different scales (cluster analysis)
- pattern recognition
    - identification of patterns
    - comparison to no pattern conditions (i.e. random walk)

Temporal Aspects and Models

Temporal aspects provide the ability to look at rate of deterioration along with the variability of deterioration. Figure 3-11 shows a progression of an individual slab from a T2 state to a SS state. Not every slab will move from a T2 to a SS

state at the same time, since a number of factors are involved, that is where statistics and probabilistic methods succeed, therefore other existing probabilistic measures can be modified to use with slab states in the 3DSBM. Time series analysis such as autocorrelation and Augmented Dickey-Fuller (ADF) tests can be investigated to quantify time-based patterns and compare any patterns found to what should be expected if the changes were totally random. This will allow the changes in time, as shown in Figure 3-12, to be mathematically defined.

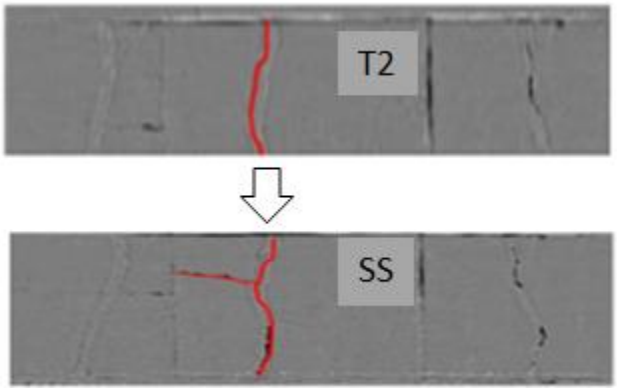


Figure 3-11. Illustration. An example of individual slab state change.

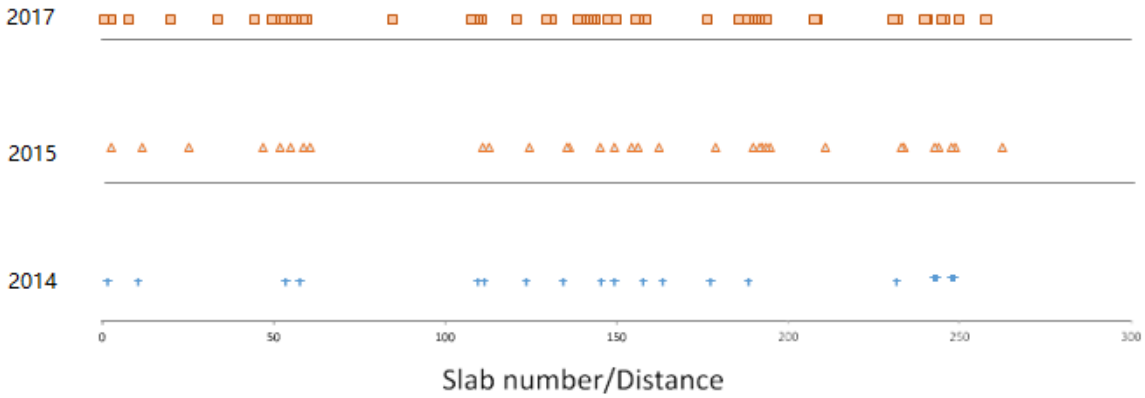


Figure 3-12. Chart. An example of change in slab states over time (MP 17).

The following are some that would be beneficial to measure in concrete pavements. Note that a forecasting model is discussed in CHAPTER 4. The other methods/models can be further explored in future study.

- rate of cracking growth
  - compare to expected or average behavior
  - local anomalies in cracking growth rates (hot spots)
- forecasting model(s)

APPLICATIONS

This section discussed some potential applications.

- Improve slab replacement quantity estimation

  Identifying, classifying and categorizing individual slabs lends itself to development and use of individual slab replacement planning tools. 3D pavement data also provides the benefit of being able to identify the most economical repair strategies based on probabilities of stable or unstable future slab states, such that the slabs most in need of repair are targeted first.
- Improve future slab replacement planning

  The slab-level forecasting model (e.g., Markov chain derived TPMs) can be used to predict future slab replacement needs based on predicted slab conditions.
- Improve the local calibration of the Pavement ME Design

  The 3DSBM can be used now to improve pavement design capabilities of existing methods, like AASHTO Pavement ME, through more detailed calibration information, and, in the future for providing needed

understanding on types of distress not now modeled, like longitudinal cracking. Using 3D pavement data of the entire mile that the LTPP section is located can provide some probability of cracking for the LTPP section for calibration purposes, instead of trying to calibrate based on zero cracking.

- Improve M&R decision-making (slab replacement vs. full lane replacement)

The 3DSBM as a decision tool in long-term life cycle rehabilitation decisions by incorporating distress level of the pavement with rate of change of distress in the pavement. The models developed based on this new 3D Slab-based Methodology will aid in managing pavement assets through regular slab replacement and complete life cycle cost analysis of pavement rehabilitation.

CHAPTER 4. DEVELOPMENT OF SLAB CONDITION FORECASTING MODEL

This chapter presents the development and validation of a slab condition prediction model, which is to support the maintenance and rehabilitation (M&R) decisions, especially full-depth slab replacement. The condition of in-service JPCP (i.e., slab states/conditions), is predicted based on the existing condition using a Markov chain modeling approach. The results of the prediction models include the number of slabs in each condition, which can be directly used to determine the need for M&R (e.g., full slab replacement).

DATA DESCRIPTION

3D pavement data on selected test sections were processed to extract slab-level information based on the 3D slab-based methodology. Table 4-1 lists the selected sites. The initial effort focused on pavement sections that included the highest identified cracking (broken slabs) in the historical concrete pavement condition evaluation data (CPACES). This included a three-mile section of I-16 near MP 17 Westbound, separated into MP 17 to MP 16, MP 16 to 15, and MP 15 to 14. Construction of these three one-mile sections on I-16, under the same contract with the same pavement design, displayed very different distress behavior. The other two Georgia sites involve about 2 miles of pavement each which include the LTPP locations (133015 and 133017). These two sections (noted as 133015 and 133017) have very different designs (doweled vs undoweled, asphalt vs cement treated base) but same design thickness (10 inches) and

similar truck traffic levels, and are located on Interstate 16 and Interstate 20, respectively. Construction of these pavements were originally between 1968 and 1978. 3D pavement data from six consecutive yearly assessments (years 2013 to 2018) was analyzed for the majority of the sections.

Table 4-1. Test sites.

Test Site	Slabs/Length	Bridge
I-16 WB MP17-16	265 slabs/ 4,878 ft	Over Flat Creek 300 ft
I-16 WB MP16-15	281 slabs/ 4,722 ft	Over Bond Road 269 ft
I-16 WB MP15-14	267 slabs/ 5,240 ft	None
I-16 EB MP 104-106	530 slabs/ 10,560 ft	
I-20 EB MP 130-132	526 slabs/ 10,520 ft	

PROPOSED SLAB CONDITION FORECASTING MODEL

Any pavement management system requires an accurate, efficient, and reliable pavement performance forecasting model to estimate future pavement performance and determine M&R needs. In this study, a JPCP performance forecasting model is proposed to predict the need for slab replacement, which is the most common treatment applied on JPCP. A multi-stage Markov chain model is proposed to predict future slab states (or conditions) based on their existing states. A Markov chain is a stochastic model describing a sequence of possible events in which the probability of each event depends only on the event attained in the previous event. Probabilistic model (i.e., transition probability matrix) is used to model the change of a pavement from a given condition (or state) to another condition (or state) in one cycle period (e.g., one year). The benefits of the Markov chain model include the following:

- Being able to model and predict pavement performance based on "state," which can be defined based on the severity (i.e., GDOT's distress protocol);
- Being able to account for the randomness in the pavement performance and predict the dependent variable with certain probability;
- Being able to the predict future condition based on the existing condition;
- Being able to develop the model with a minimum of two years of data;
- Having the ability to treat data with stochastic tools, including Bayesian processes.

Figure 4-1 illustrates the multi-stage Markov chain modeling on JPCP deterioration; different Markov chain models are used for different pavement "stages" for different pavement design categories. The assumptions are 1) pavements with different designs perform differently, and 2) pavements at different "stages" perform differently. Thus, different Markov chain models can be developed for different pavement design categories in different stages, as illustrated in Figure 4-1.

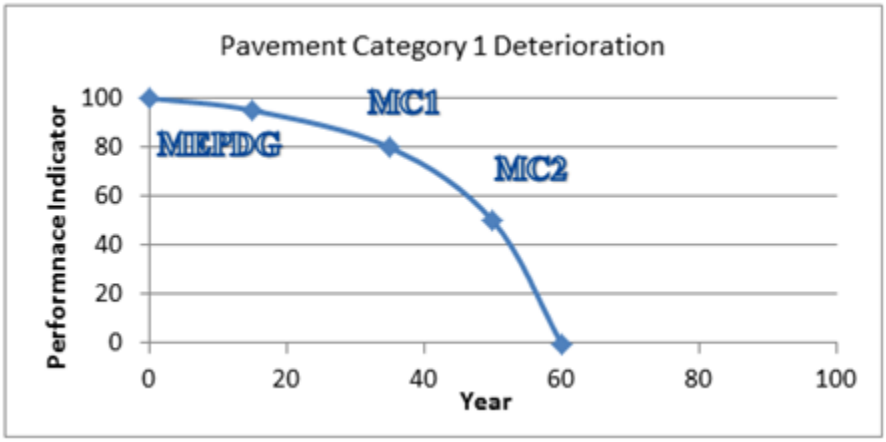


Figure 4-1. Illustration. Deterioration based on pavement category.

The rate of deterioration is expected to be the lowest in the first period and can be modeled using mechanistic methods (i.e. PavementME). The mechanistic methods can

provide an estimated time to first cracking, or start of fatigue failure. The second and third periods are modeled using probabilistic methods based on a near constant rate of distress. The rate of distress in the early life of the pavement will be less than in the later life; therefore, the rate for MC1 would be different than the rate of MC2, and two Markov Chains are needed to model this section of the pavement's life. At a point (shown as year 50 in Figure 4-1) the pavement becomes distressed to the point that further deterioration is exponential to the end of pavement life, shown as age 60 in Figure 4-1. This multi-stage Markov chain approach was designed to develop prediction models for different pavement stages with limited data. It would require a substantial amount of data (i.e., condition data over a long period of time) to develop a non-homogeneous Markov chain model to capture the change of deterioration rate through a pavement's life.

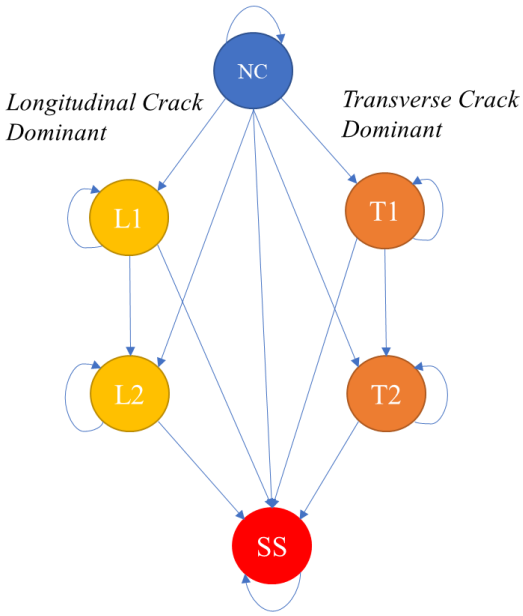
This section describes the modeling of JPCP deterioration behavior using the multi-stage Markov chain processes. Markov chain modeling starts with defining the states that define the transition probability matrix (TPM). Next, TPMs are developed using the data from different timestamps. A TPM represents the probability of a pavement in its current pavement state as it transitions to the next state in a time cycle (one year). Finally, the TPMs are categorized based on their similarity to represent the deterioration behavior in each stage. Previous studies used bands or ranges of values, such as IRI (e.g., Good = 0 to 70.87 in/mile; Fair = 70.87-106.30 in/mile; etc. in Porras-Alvarado et al., 2014), pavement rating, or percent of transverse cracking in the case of asphalt pavements (Mills et al., 2012), to define "states." In this study, the slab states (NC, L1, L2, T1, T2, and SS) defined in CHAPTER 3 are used as the states in Markov chain, as they are designed to capture the progression of the cracking a slab.

Developing Transition Probability Matrixes (TPMs)

A DTMC (discrete-time Markov chain) is used to model the probability of a current pavement condition transitioning to the next state in a time cycle (one year). Based on the six states defined in previous section, a TPM with a dimension of 6x6 is used to model the probability of change in the states. In pavement application, many cells in the TPM can be zero based on assumptions about the deterioration behavior. Figure 4-2 depicts the state representing the slab condition and its deterioration behavior. The nodes represent the states; links represent the probability of a slab moving from one state to another state. The TPM is a collection of the probabilities of the links, as shown in Figure 4-2. In this matrix, p(ij) is the probability that a slab will move from State i to State j. The following assumptions were made for the deterioration behavior:

- Without M&R, a slab can only stay in the same state or deteriorates (move to worse state) over a cycle time. Thus, TPMs are strictly upper triangle matrices. The non-zero values are in upper triangle cells, and lower triangle cells are assigned to zero.
- A slab can deteriorate into more than one state (i.e., not restricted to the adjacent state like many previous studies). An NC (not cracked) slab can move to T1, T2, L1, L2, or SS with different probabilities.
- However, the movement between transverse cracking and longitudinal cracking are prohibited by design. Thus, certain cells (e.g., p_{23}, p_{34}, p_{45}, and p_{25}) have a value of zero.

- The SS state is the absorbing (or final state) without M&R. Thus, a slab in the SS state can only remain SS with a probability of 1 (i.e., p_{66} =1).



	NC (1)	L1 (2)	T1 (3)	L2 (4)	T2 (5)	SS (6)
NC (1)	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{16}
L1 (2)	0	P_{22}	0	P_{24}	0	P_{26}
T1 (3)	0	0	P_{33}	0	P_{35}	P_{36}
L2 (4)	0	0	0	P_{44}	0	P_{46}
T2 (4)	0	0	0	0	P_{55}	P_{56}
SS (6)	0	0	0	0	0	P_{66}

Figure 4-2. Illustration. Transition probability matrix.

The transition probabilities, P_{ij} (P_{12}, P_{23}, P_{34}, P_{45}), indicate the probability of the portion of the network in condition i moving to condition j in one duty cycle. The transition probabilities P_{ii} (P_{11}, P_{22}, P_{33}, P_{44}) indicate the proportion of the network staying in condition i in one duty cycle. The conditions of Markov chain modeling that apply to the process of developing a TPM when used to simulate pavement deterioration are as follows:

- All entries should be nonnegative.
- A segment is not allowed to deteriorate by more than one state in one duty cycle. Hence, P_{13}, P_{14}, P_{15}, P_{24}, P_{25}, and P_{35} are zeros. Practically, only two values need to be determined to define the entire TPM, P_{ii}, and P_{ij} .
- The sum of the entries in each row should be equal to 1.

- $P_{ij} = 0$ for $i > j$, signifying the belief that road condition cannot improve without treatment. Hence P_{21}, P_{31}, P_{32}, and so forth are zeros.
- The entry of 1 in the last row of the TPM, that is, $P_{66} = 1$, signifies a holding or absorbing state. It implies that pavements have reached their worst condition and cannot transition from this state without a reconstruction.

Using the data on the test sections, a total of 20 TPMs were developed. Table 4-2 (A and B) shows an example TPM on two 1-mile segment (MP 17-16 and MP 15-14 on I-16 (westbound)) derived from using data from 2017 and 2018. It is noted these two miles are from the same project (i.e., with the same design); however, the deterioration behaviors are different. The probability of a slab in the T2 state moving to the SS state is 17.67% on MP 17-16, higher than the 0% on MP 15-14. In addition, the probability of an NC slab developed with any cracking is also higher on MP 17-16. This indicates this segment (MP 17-16) deteriorates at a faster rate compared to MP 15-14. The TPMs will be categorized in the subsequent section.

Table 4-2. TPM example for two 1-mile segments on I-16

A. TPM of MP 17-16

	NC	L1	T1	L2	T2	SS
NC	0.926136	0.017045	0.022727	0.005682	0.028409	0
L1	0	0.458333	0	0.208333	0	0.333333
T1	0	0	0.190476	0	0.809524	0
L2	0	0	0	0.833333	0	0.166667
T2	0	0	0	0	0.823529	0.176471
SS	0	0	0	0	0	1

B. TPM of MP 15-14

	NC	L1	T1	L2	T2	SS
NC	0.96748	0.00813	0.00813	0	0.01626	0
L1	0	0.75	0	0	0	0.25
T1	0	0	0	0	1	0
L2	0	0	0	0.666667	0	0.333333
T2	0	0	0	0	1	0
SS	0	0	0	0	0	1

Categorizing Transition Probability Matrixes (TPMs)

Pavement deterioration rates are affected by complicated external and internal factors, such as, material, traffic volume, weather, construction quality, the pavement's current condition, etc. Therefore, a pavement deterioration category should first be defined based on the deterioration rate. Then, different TPMs could be developed corresponding to certain deterioration categories using available historical data. When performing pavement condition forecasting, candidate pavement sections would first be identified by which category the section belongs to; then, this would be the criteria to justify TPM should be adopted to perform the forecasting in the next time period. Through the entire pavement life, the above procedure is repeated to update forecasting results.

In order to categorize pavement sections into different groups, the K-means clustering method is adopted to categorize each one-mile pavement section. The algorithm is formulated as

$$\underset{C}{\operatorname{argmin}} \sum_{x \epsilon C_i} \sum_{i=1}^{k} \|x - \mu_i\|^2$$

Where x represents data points of interest, and μ_i is the corresponding centroids. Since the objective is to group pavement sections with similar trends, elements of transition probability matrices are selected to group different categories.

The derived TPMs are categorized into 3 categories. To identify the characteristics of each category, the TPMs in each category were carefully reviewed. It was observed that that TPMs in Category 1 are those with lightest distresses (TC2 + SS < 0.05); TPMs in Category 3 are under very bad condition (TC2 + SS > 0.1); Category 2 is in between (0.05 < TC2 + SS < 0.1). These criteria can be used to determine which category of TPM to use based on the existing condition. The TPMs in each category were averaged to obtain an overall TPM for each category. Tables 4-3 to 4-5 list the TPM for each category.

Table 4-3. TPM for category 1.

0.9889	0.0069	0.0018	0	0.0015	0.0009
0	0.83	0	0.0628	0.0584	0.0489
0	0	0.9167	0	0.0476	0.0357
0	0	0	0.9266	0	0.0734
0	0	0	0	0.9751	0.0249
0	0	0	0	0	1

Table 4-4. TPM for category 2.

0.9159	0.0267	0.0268	0.0095	0.0127	0.0084
0	0.6577	0	0.1976	0.0241	0.1205
0	0	0.4302	0.0506	0.3708	0.1485
0	0	0	0.8505	0.0013	0.1482
0	0	0	0	0.8319	0.1681
0	0	0	0	0	1

Table 4-5. TPM for category 3.

0.9764	0.0054	0.0081	0	0.0102	0
0	0.9136	0	0.0364	0	0.05
0	0	0	0	0.9	0.1
0	0	0	0.9179	0	0.0821
0	0	0	0	0.7535	0.2465
0	0	0	0	0	1

VALIDATION OF THE PROPOSED MODELS

The TPMs were validated using two segments (MP 15-14 and MP 17-16 on I-16 westbound). State distribution in 2013 was set to be the initial condition. Then, based on the criteria (T2+SS), a TPM (category 1, 2, or 3) was determined for predicting the next year's condition. This process was repeated to predict the pavement condition from 2014-2018, and the results were compared to the actual condition.

- Case 1: I-16 MP 15-14 (westbound)

  Segment MP 15-14 on I-16 (westbound) is categorized by the proposed criteria. Figure 4-3 shows the actual and predicted number of slabs in each state are fairly close. Table 4-6 lists the actual and predicted number of slabs in each state; the differences are within 4 slabs.

Table 4-6. Actual vs. predicted slabs by state.

	2014		2015		2016	
	Actual	Predicted	Actual	Predicted	Actual	Predicted
NC	246	244	238	238	236	233
L1	4	4	5	5	7	6
T1	1	2	2	2	0	2
L2	3	4	2	4	2	4
T2	0	3	5	7	5	9
SS	13	10	15	11	17	14

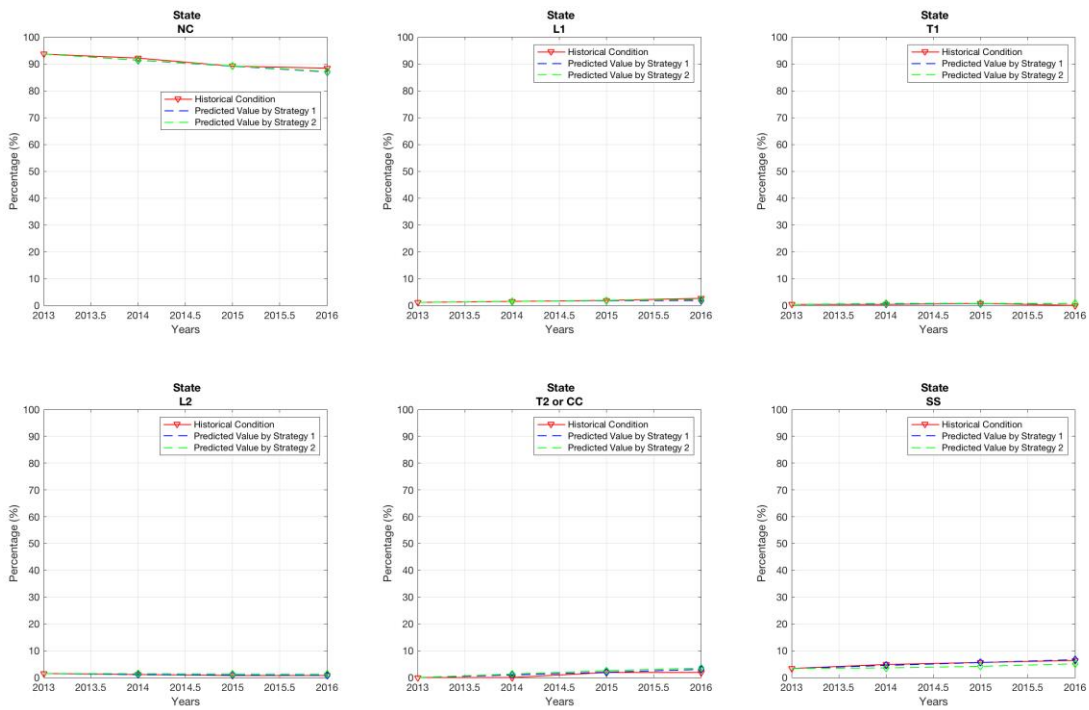


Figure 4-3. Charts. Prediction vs. actual (MP 15-14).

- Case 2: I-16 MP 17-16 (westbound)

  Segment MP 17~16 on I16 (westbound) was under poor condition and belongs to Category 3. Again, Figure 4-4 shows the predicted values are close to the actual values. The differences are within 5 slabs. The model predicts more SS slabs than the actual in five years and under predicts in T2. However, the total T2+SS are

very close to the actual condition. If both T2 and SS slabs will be replaced, the prediction results can provide a good estimate for the slab replacement need.

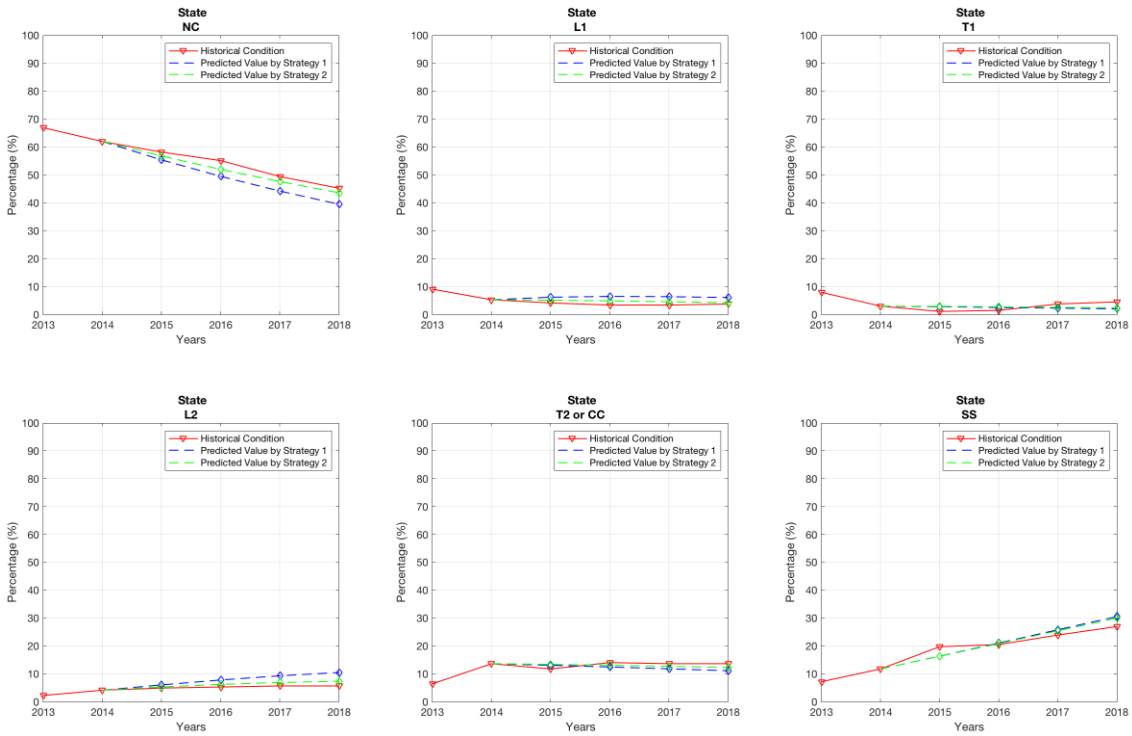


Figure 4-4. Charts. Prediction vs. actual (MP 17-16).

SUMMARY

A multi-stage Markov chain model was developed to capture the deterioration behaviors of a slab in different stages. A total of 20 TPMs were derived using the sensing data, and a k-means method was used to categorize the TPMs based on their similarity. A TPM was obtained for each of the three categories that represent the JPCP stages based on the current pavement condition. The categorization criteria is based on the percentage of slabs in T2 and SS. Category 1 (T2+SS < 0.05) represents the pavement in good condition with mild deterioration; Category 3 (T2+SS > 0.1) represents the pavement in poor condition with more rapid deterioration; Category 2 (0.5<T2+SS < 0.1) represents

the pavement condition in between with a deterioration rate in between. A case study on two 1-mile segments with different conditions shows promising results; the multi-stage TPMs can reasonably predict the future JPCP slab condition with an error within 5%. The TPM models can be implemented in the PMS to predict the future slab condition on JPCP to estimate the need for slab replacement.

CHAPTER 5. DEVELOPMENT OF A FAULTING FORECASTING MODEL

Faulting is defined as the elevation difference between two slab edges across a transverse joint. It is one of the important performance indicators for JPCP and, also, used for triggering maintenance, rehabilitation, and reconstruction (MR&R) such as diamond grinding. Therefore, it is necessary to predict future faulting to support MR&R planning and programming, such as making plans for diamond grinding. This chapter presents the analyses of faulting using the LTPP, CPACES and 3D pavement data; it also discusses the development and validation of a faulting forecast based on segment-level dynamic linear regression.

ANALYSIS OF FAULTING DATA

In this section, faulting data from the LTPP, CPACES, and 3D sensing data were studied to address: 1) what the faulting distribution along a transverse joint is, and 2) how the faulting increases over time.

Spatial Aspects

As discussed in CHAPTER 2, faulting can be measured at different locations on a slab using a Georgia Faultmeter or 3D pavement data. As shown in Figure 5-1, faulting can be measured at different distances away from the joint (highlighted in blue) and different locations along the joint (highlight in brown). Due to the factors such as curling/warping, vibration, etc., faulting values measured at different locations can be different. Therefore,

in this section, faulting values measured at different locations were compared to understand the impact of the locations.

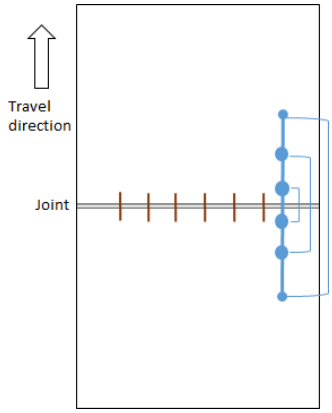


Figure 5-1. Illustration. Faulting measured at different locations on a slab.

Faulting along the joint

Figure 5-2 shows faulting computed at multiple locations along a transverse joint using 3D pavement data. The two slabs are located on I-16 (westbound, MP 17-16). The y-axis represents the faulting values in mm and the x-axis indicates the distance from the left lane marking. As the distance increases, it is closer to the right lane marking (i.e., outside lane marking). As shown in Figure 5-2, faulting values increase as the measurement is taken closer to outside slab edge (or outside pavement marking). This would tend to indicate that measuring faulting closer to the joint should provide more conservative faulting values (i.e., larger values). Thus, it is suggested that faulting be reported at 1 ft. from the outside pavement marking.

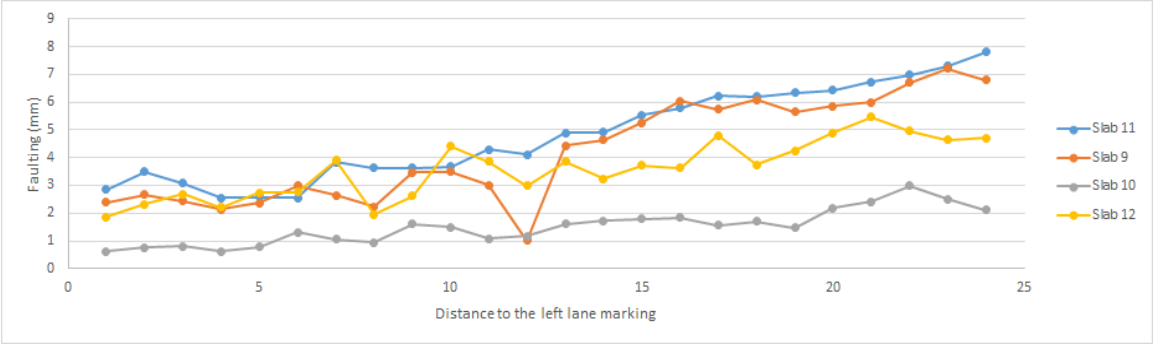


Figure 5-2. Graph. Faulting at different locations along a transverse joint.

Faulting at different distances from the joint

Figure 5-3 shows faulting values at different distances away from a transverse joint using 3D pavement data. Changes in faulting values related to distance from the joint can come from curl and warp of the slabs, profile elevation changes or cracking of the slabs. Figure 5-3 shows faulting values computed at different distances from the joint (e.g., 40 mm, 60 mm, 100 mm, and 300 mm) on 19 joints on I-16. It shows an almost consistent trend of the faulting values becoming smaller as the measurement is taken further from the joint. Once again, this would tend to indicate that measuring faulting closer to the joint should provide more conservative faulting values.

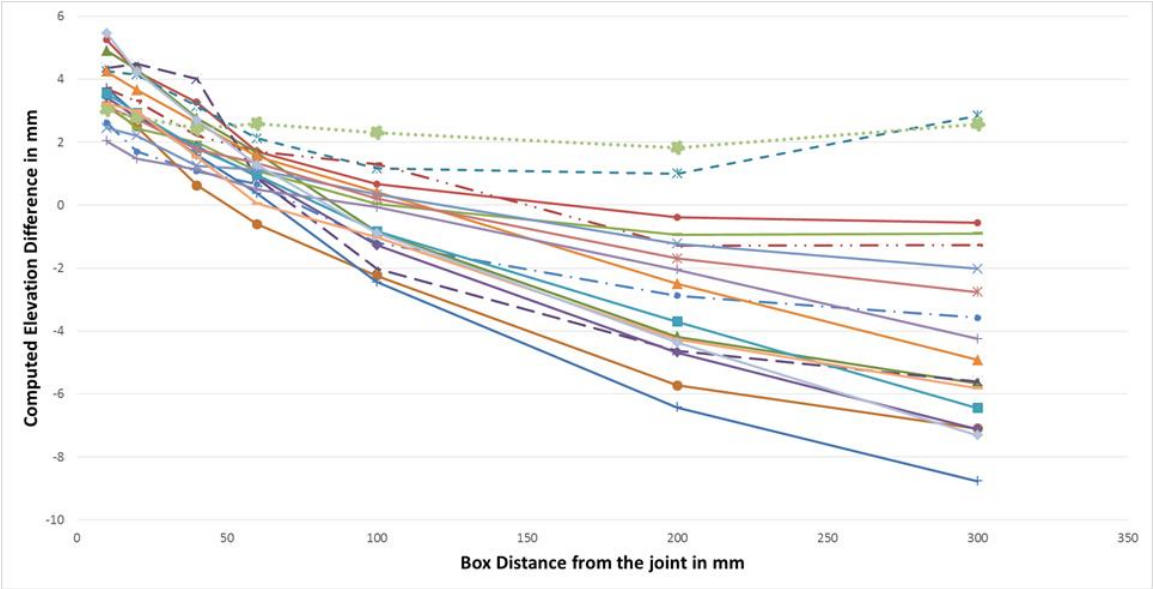


Figure 5-3. Graph. Faulting at different distances away from a transverse joint.

Temporal Aspects

Faulting is expected to increase slowly over years, especially with the use of dowels. As shown in Figure 5-4, a faulting of 0.07 in (1.8 mm) and 0.02 in (0.5 mm) was predicted by the MEPDG at the end of 20 years on two sections on I-16 and I-75. The rate of faulting increase per year is very small (less than 1/32 in as measured by the Georgia Faultmeter); it would take a long period of time (e.g., 5-10 years) to observe the faulting increase trend. Therefore, the LTPP data and CPACES data, which are comprised of faulting data collected over a long period time, were studied to provide insights on the faulting trend on Georgia's JPCP

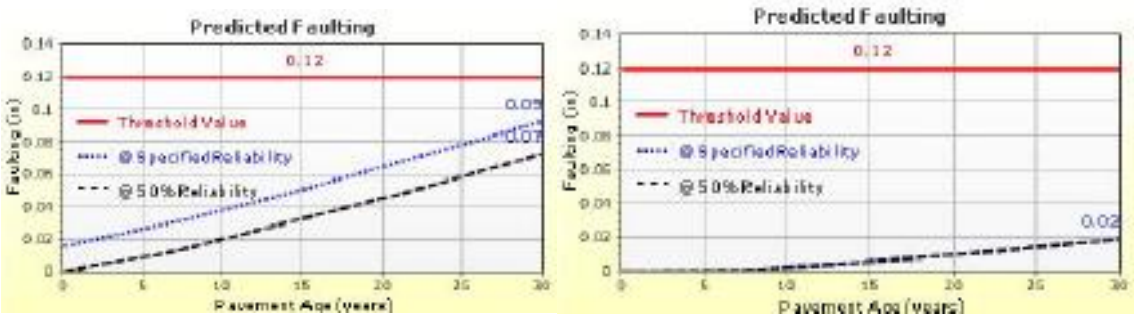


Figure 5-4. Graphs. Faulting predicted on two sections (I-16 and I-75) using the MEPDG.

Faulting measured on the LTPP sections in Georgia was analyzed to reveal the trend of faulting change over time. Figure 5-5 shows the faulting measured at different ages based on the LTPP data. Note that the faulting values were converted into faulting index (i.e., average faulting in 1/32-in unit multiplied by 5) used in GDOT's CPACES database. Overall, the faulting on the eight LTPP sections shows an increasing trend with some fluctuations. The faulting values can be affected by various factors, including curl and warp of the slabs, where the faulting was measured, profile elevation change, or cracking of the slabs. Thus, certain fluctuations are considered reasonable. As expected, the magnitude of the faulting is generally low with only one section exceeding a faulting index of 20 (average faulting of 1/8 in) after 25 years. There are limited faulting values recorded in the first ten years. The faulting index showed a consistent increase trend after 10 years at an average rate of 0.6 per year. The low faulting may be attributed to the stabilization of the base and the standard practice by GDOT to use dowel and edge drain on many projects. It is also observed that the rate of faulting increase varies by section (or segment). Section 3015 exhibits a relative high rate of faulting increase compared to other sections; Section 3018 shows a very slow, almost flat, increase in faulting.

Therefore, it is suggested to use the rate of increase in faulting index on individual segments for prediction to reflect the characteristics on the segment (e.g., pavement design, traffic, environment conditions, etc.).

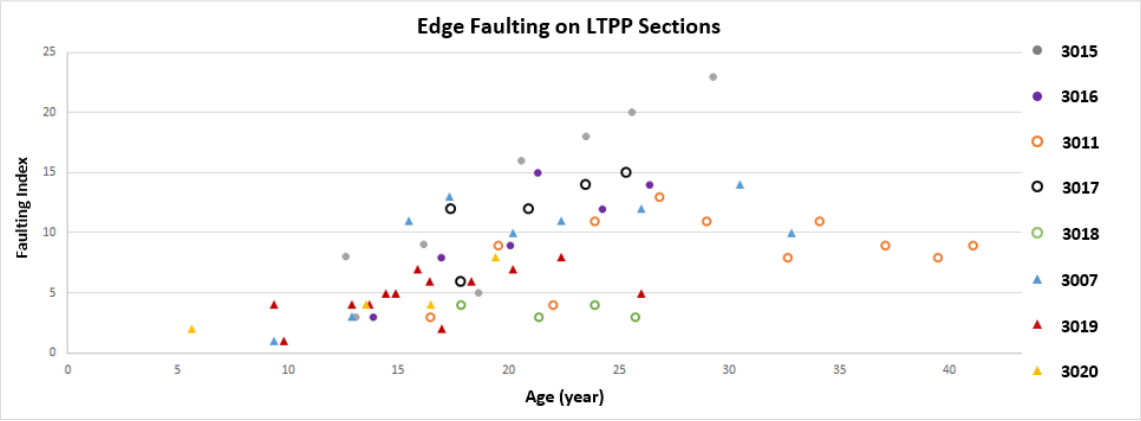


Figure 5-5. Graph. Faulting measured on 8 LTPP sections.

PROPOSED FAULTING FORECASTING MODEL

As discussed in a previous section, faulting increases at a slow and linear trend, and the rate varies by the pavement design, especially the use of dowel bars. Thus, a dynamic linear regression model, combined with the default deterioration rates for design categories, was proposed to predict segment-level faulting. This model utilizes the historical faulting index of a segment in the CPACES database to develop a linear regression equation and uses it to forecast the next year's faulting index for the segment. It takes advantage of the existing faulting observed in the field and reduces the efforts necessary for acquiring additional data, such as traffic, drainage, etc., which is currently not available in the CPACES database. In addition, historical CPACES data was analyzed to obtain the default rate of increase in faulting index for different pavement design

categories. These default values are used when the linear regression cannot be performed due to data issues.

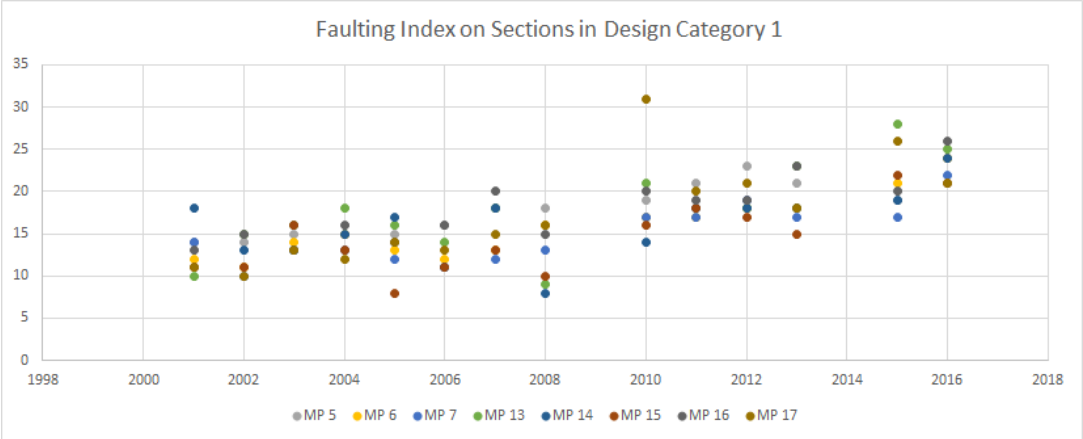
Default rate of increase in faulting index

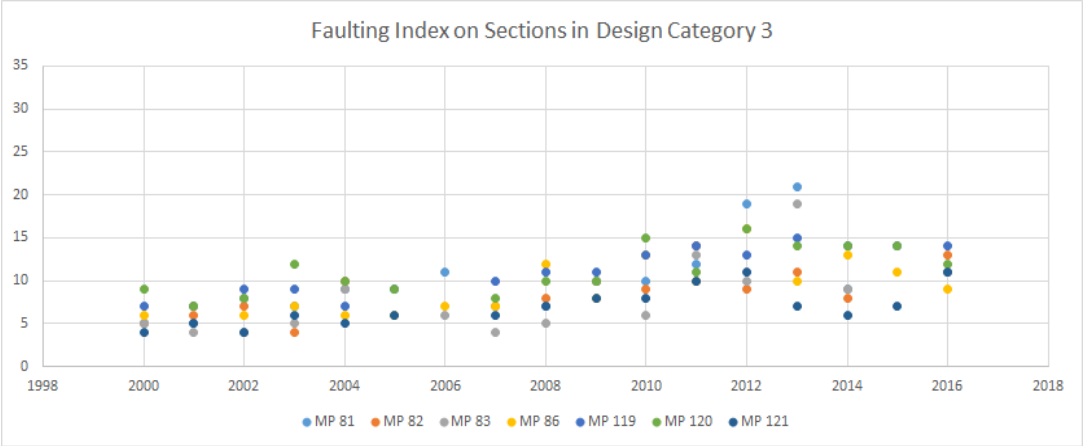
Since 1970s, GDOT has implemented various designs (e.g., different joint spacing, dowel bars, drainage, etc.) of JPCP to improve its performance. In a previous study (Tsai et al., 2010), various designs of JPCPs in Georgia were categorized into four categories by key design features, including load transfer, base type, and edge support, which also reflect major improvements in GDOT's concrete pavement design. In this study, the increases in faulting index was analyzed for three design categories. These three categories are as follows:

- Category 1 includes the non-doweled JPCP with no edge support on a soil or soil cement base, which were considered as the state-of-art JPCP design in the 1960s. These designs often had a 9 or 10-in thickness, a 30-ft joint spacing, and an asphalt shoulder. Edge support, which was not used in this design category, can be tied concrete shoulders or a wide lane (greater than 12-ft).
- Category 2 includes the non-doweled JPCP with no edge support on an improved base, which were introduced in the early 1970s to address such issues as faulting and base erosion observed in the field. Graded aggregate base (GAB) or cement stabilized GAB in conjunction with an asphalt interlayer was used to provide a non-erodible base and good support. Along with the improvements in the base, a variation of joint spacing (e.g. random) and joint orientation (e.g. skewed) was used to address the faulting issue. An asphalt shoulder was still in use.

- Category 3 includes doweled-JPCP with edge support (e.g., tied concrete shoulder) on an improved base (e.g., GAB). Doweled JPCP was first constructed in Georgia in the mid-1970s and has become a standard in the concrete pavement design since the 1980s.
- Category 4 refers to the latest concrete pavement design, which consists of doweled-JPCP, a short joint spacing (15-ft), edge support (a 13-ft wide lane), and an asphalt interlayer and a GAB base. It is noted that no sufficient data was available to support an analysis of long-term performance for Category 4 pavements.

Figure 5-6 shows the faulting indexes on selected segments for each design category. It shows despite some outliers, the faulting index in general increased steadily, It is clear that the segments in Design Category 1 exhibited a faster increase in faulting index compared to the other two Design Categories (2 and 3). After removing the outliers, a rate of increase in faulting index for each design category was obtained. Table 5-1 lists the default value for each of the three design categories. It is noted that the rates are similar for Design Categories 2 and 3.





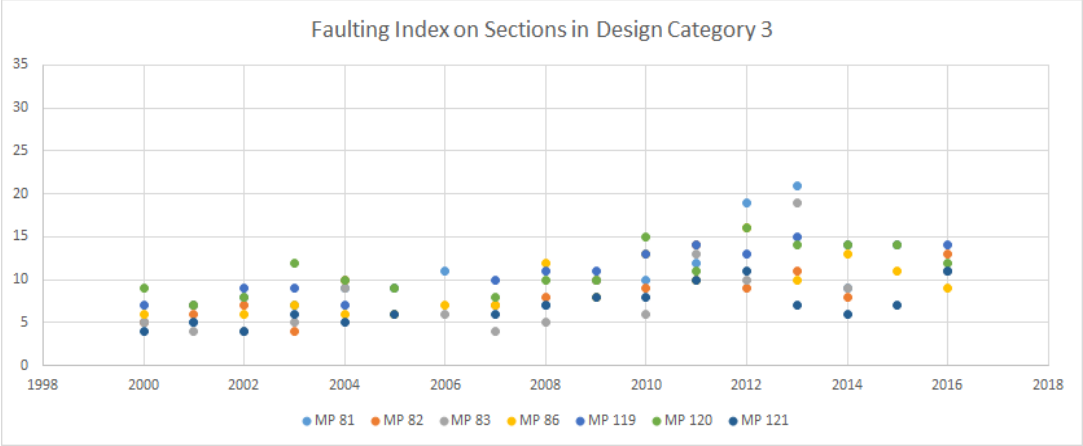


Figure 5-6. Graphs. Faulting index for different design categories (1, 2, and 3).

Table 5-1. Default faulting increase rates for different categories.

Design	Rate of Increase in faulting index
Design Category 1	0.70 per year
Design Category 2	0.45 per year
Design Category 3	0.40 per year

Dynamic Linear Regression Model

Figure 5-7 depicts the detailed steps for the segment-level dynamic regression model. Each step is discussed below.

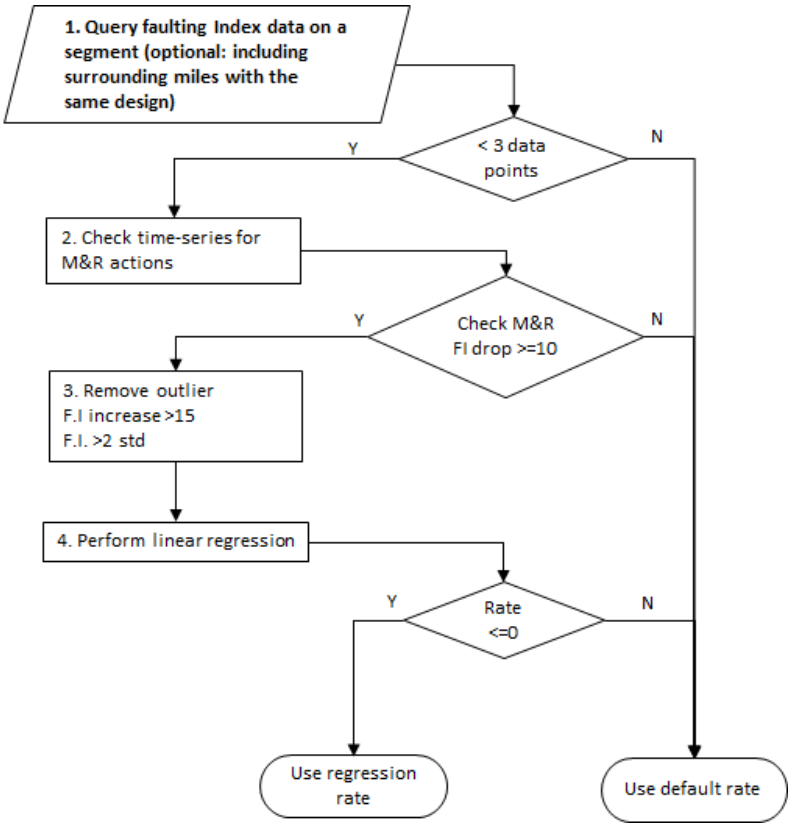


Figure 5-7. Chart. Segment-level dynamic regression model.

- Query faulting index

  A data search is first performed to find the time-series faulting index based on a combination of route number, route suffix, county, direction, milepost-from, and milepost-to to uniquely identify a segment. Data within recent eight years will be queried from CPACES for further processing. In addition, if the design information is available, the surrounding segments (e.g., two miles on each side of the segment) with the same design can also be queried. The number of the faulting index is checked to ensure the data is sufficient (i.e., at least three faulting indexes) for performing further analysis. If the total number of faulting index points is less than three, a default rate will be used.

- Check time-series data for M&R actions

  This step is to ensure that no MR&R has been applied on the segment. It was observed in the CPACES data that the faulting index in a certain year is abruptly decreased, most likely due to the M&R actions. For example, diamond grinding will remove faulting and restore the ride, and a significant drop in the faulting index is anticipated after diamond grinding. Thus, there is a need to identify any MR&R actions within three years. Therefore, the faulting index is checked to determine if MR&R actions have been applied within three years. A significant drop in the faulting index is anticipated when M&R actions, such as diamond grinding and lane replacement, are applied. A previous study (Tsai et al., 2012) found an increase of 10 in the faulting index indicates an MR&R action may have been applied on the segment. This value (10) is used as the threshold for determining if MR&R has been applied.

- Remove outliers

  While the faulting index is expected to increase in time, fluctuation (increase and decrease) was observed in the faulting index reported in the CPACES data. Significant increase of faulting index was observed in the CPACES data from time to time. A review of these significant increases found they often due to recording error or other errors (as faulting index often dropped significantly in the next year). Thus, the faulting index outside the 66% confidence level will be removed.

- Perform linear regression

  In this step, linear regression is applied to estimate the deterioration rate of the faulting index. A positive (or increasing) rate is expected for the faulting index, which deteriorates without M&R action. Therefore, only a positive rate can be used for predicting the future faulting index. If a negative rate is reported in the linear regression equation, a default value will be used to ensure the predicted faulting follows the right trend.

- Predicting faulting

  The faulting index is predicted using the linear regression equation if a valid rate is available from the linear regression equation. Otherwise, default faulting deterioration rates are in Table 5-1 used for the segments with M&R actions, missing data, or insufficient data.

VALIDATION OF THE FAULTING FORECASTING MODEL

A case study was conducted using CPACES data on a 1-mile segment on I-16 (eastbound, MP 12) to demonstrate the use of the proposed method for predicting

faulting. The segment on the eastbound lane at MP 12-13 was built in 1968 with non-doweled JPCP, a 30-ft joint spacing, 9 in of PCC on top of a 10-in stabilized cement base. Figure 5-8 shows the measured and predicted faulting index from 2000 to 2016. The faulting index measured on this segment is relatively high compared to the average faulting index of 10 at the network level in 2016. The faulting index was predicted using the default deterioration rate of 0.7 per year because no sufficient data was available for establishing the linear regression equation. The linear regression was used from 2012 to 2016, and the deterioration rate was updated each year as new data was collected. The differences between the measured and predicted faulting indexes range from 0 to 6. The maximum difference occurs in 2015 when the measured faulting increased significantly. However, it dropped to 19 in 2016. This case illustrates it is feasible to predict the faulting index using the proposed method, which is based on the historical CPACES data.

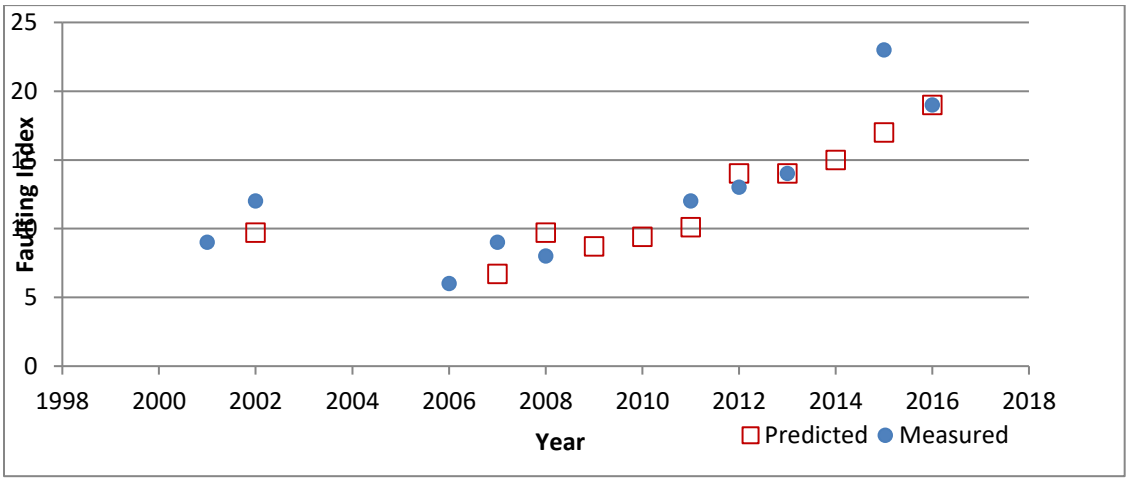


Figure 5-8. Example of predicted and measured faulting index.

SUMMARY

In this chapter, the faulting from the LTPP, CPACES, and 3D pavement data were examined to determine the faulting distribution along a joint and its time-series trend. It was found that faulting measured closely to the outside pavement marking is typically higher than the faulting measured from other locations. Thus, it would provide a more conservative measurement for determining the M&R needs. The faulting data shows some fluctuation due to the curling and warping of slabs, the location of the faulting measured, the cracking of slabs, etc. Despite the fluctuation, it shows a slow steady increase trend. However, the magnitude of faulting is low; it is limited only to a section that reached 1/8 in (3.125 mm) in 25 years. This means the change per year is very small (less than 1/32 in as measured by a Georgia Faultmeter). It would require several years' data (e.g., 5 -10 years) to identify the rate of faulting increase. In addition, review of CPACES data shows the project with the same design typically performs in a similar trend (i.e., increase rate), though with some differences. Also, the projects with different designs (e.g., Categories 1, 2, and 3) show different rates of increase in faulting. Thus, a dynamic linear regression model combined with a default rate for each design category was developed for predicting the faulting on Georgia's JPCPs using CPACES data. A case study was conducted on a 1-mile segment to demonstrate the feasibility of the proposed method. The results show the method is promising; it predicts with a variation of 5 points in the faulting index. Compared with the other models, the segment-based dynamic linear regression model has the advantage of considering the specific characteristics of each individual project in forecasting its future year pavement deterioration rates. Also, the model automatically incorporates the most recent

performance rating data available for the project as they are available from the CPACES survey for developing the regression equation. Limitations of the model do exist. Not every segment has valid historical faulting index information. For those segments, the default deterioration rate for each design category can be used for forecasting a future faulting index.

CHAPTER 6. A CASE STUDY ON I-16

This chapter provides instructions on how to utilize the developed forecasting models to estimate the M&R needs in the near future (e.g., 3 years), in terms of slab replacement. First, the steps for predicting the JPCP condition using the developed TPMs are described. A case study on 160 miles of I-16 (eastbound) was conducted to show the implementation of steps and demonstrate the capability of estimating future M&R needs.

INSTRUCTIONS ON PREDICTING JPCP PAVEMENT CONDITION

Figure 6-1 shows the flow chart for predicting future JPCP conditions using the existing pavement condition and developed TPMs. These steps can be integrated into Georgia's pavement management system. Essentially, the future JPCP condition is determined by multiplying the existing condition (state vector) and the appropriated TPM determined based on the pavement condition category criteria.

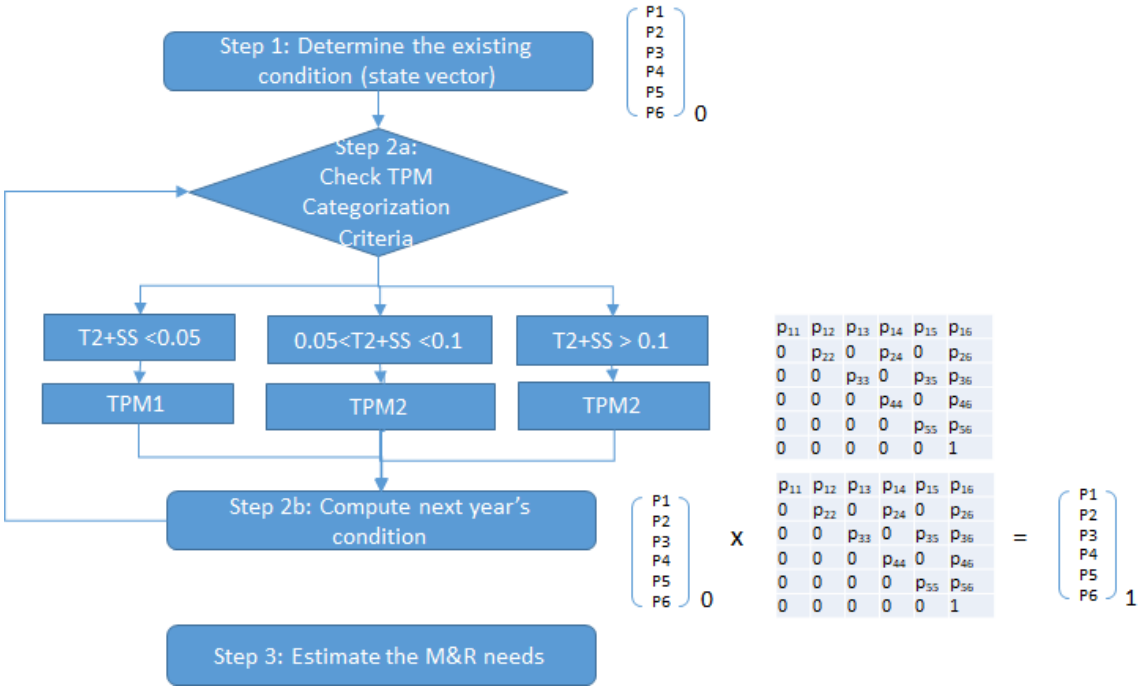


Figure 6-1. Chart. Steps for predicting future pavement condition using developed TPMs.

- Step 1: Determine the initial (or existing) pavement condition for each mile by converting the annual pavement condition evaluation data into the state distribution (or state vector). As described in CHAPTER 4, the six states are not-cracked (NC), longitudinal cracking Level 1 (L1), longitudinal cracking Level 2 (L2), transverse cracking Level 1 (T1), T2 (including corner break), and SS. The percentage of slabs in each state is computed by the number of slabs in each state and divided by the total number of slabs in each mile.

$$Pi = pi / \sum pi$$

- Step 2: Compute the future pavement condition. First, determine the appropriated TMP to use based on the TMP categorization criteria, which is based on the percentage of T2 and SS combined. If the percentage is less than 0.05, a Category 1TPM is used. If the percentage is greater than 0.1, a Category 3 TPM is used. If

the percentage is in between, a Category 2 TPM is used. Then, the future pavement condition (i.e., the percentage of slabs in each state) is computed by multiplying the state vector (from Step 1) and the TPM (from Step 2a).

- Step 3: Determine the needs for slab replacement based on the predicted pavement condition. Currently, T2 and SS are considered for slab replacement. In addition, the rate of the increase in T2 and SS can be reviewed to determine if slab replacement is an adequate treatment or if a full-lane replacement should be considered.

CASE STUDY

A case study was conducted on 160 miles of I-16 (eastbound) to show the implementation of steps and demonstrate the capability of estimating future M&R needs. I-16 is a 160-mile-long, east–west, interstate highway located entirely within Georgia. It travels from Macon to Savannah, via Dublin, Metter and Pooler. It was built in the 1960s with non-doweled JPCP, a long joint spacing (20-30 ft.), 9-11 in of PCC on stabilized cement base. There are random skewed joints and squared joints with slab lengths ranging from 20 ft. to 30 ft. There had been little maintenance applied until 2010; since 2010, there have been some rehabilitation actions on certain sections. Figure 6-2 shows the pavement structure design on a LTPP section (133015) around MP 105.2.

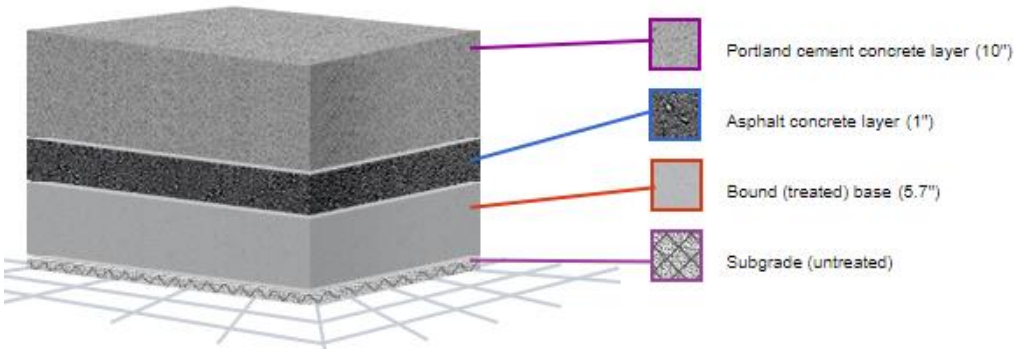


Figure 6-2. Illustration. Pavement design on LTPP section 133015 (~MP 105.2).

The major M&R projects on I-16 are as follows:

- The outside lane between MP 23 to MP 72 was replaced with 11-in of doweled JPCP (full-lane replacement) around 2012.
- In recent years, there were several slab replacement projects in recent years. These include the slab replacement on MP 95-104, MP a-b, and MP c-d. These slab replacement projects also included diamond grinding and joint reseal.

Data Preparation

The first step was to collect high-resolution 3D laser data, which are necessary for extracting slab level information. The GA Tech Sensing Vehicle (GTSV), described previously in CHAPTER 3, was used to collect the data in 2018. With a line scan rate of 5,600 profiles per second, approximately 7.3 million 3D points can be collected on a 30-ft slab at a speed up to 62.5 mph (100 km/hr) (Tsai et al., 2015). The data was processed using the process described in CHAPTER 3. Joint and cracking data were extracted from the 3D pavement data, and the condition of each slab was assigned based on the cracking. The data was then aggregated into every 1 mile based on the six states.

Table 6-1 shows an example of the data for each mile. A total of 40,000 files covering the 1605 miles were processed, and the condition on 39,459 slabs was determined. The slab level data was aggregated by 1 mile.

Existing Pavement Condition in 2018

Of the 39,459 slabs surveyed in 160 survey-miles (eastbound), the majority (97.1%) are under good condition (NC), as shown in Table 6-1. The slabs in L2, T2, and SS are approximately 0.62%, 1.1%, and 0.49%, respectively. Figure 6-3 shows the spatial distribution of the distressed slabs. It is noted that there are no distresses reported between MP 23 and MP 72, as it was reconstructed in 2012. There are three clusters with more distressed slabs (MP 10-20, MP 90-110, and MP 150-160). In general, transverse cracking (in green) is more common compared to longitudinal cracking (in blue). The sections with the most severe distressed slabs are located at MP 10~20. On average, 8% of SS was reported in these sections, and approximately 32% of the slabs were reported with cracking (L1, L2, T1, T2, or SS). The sections between MP 140-160 were also reported with some slabs in the SS state. The percentage of cracked slabs ranges from 5% to 20% with an average of 11%. The sections between MP 90-110 were reported with mostly Level 2 longitudinal and transverse cracking. Figure 6-4 is map showing the percentage of T2+SS slabs of the different segments on I-16.

Table 6-1. Current slab state distribution.

	NC	L1	T1	L2	T2	SS
Number of Slabs	38341	132	119	245	428	194
Percentage (%)	97.17	0.33	0.30	0.62	1.08	0.49

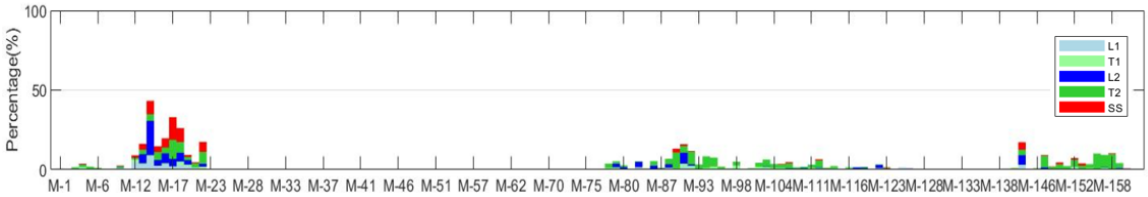


Figure 6-3. Chart. Current slab state distribution for each mile.

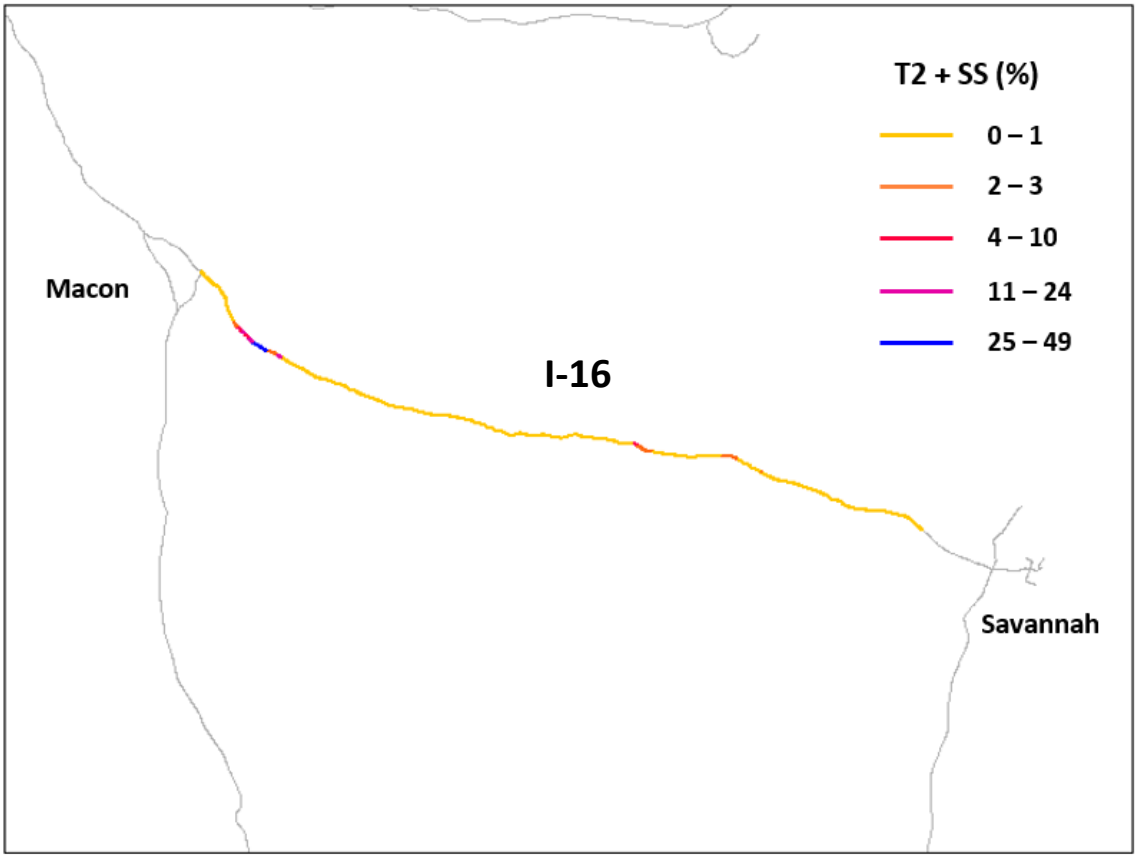


Figure 6-4. Map. Spatial distribution of T2+SS slabs on I-16 in 2018.

Predicted Pavement Condition on I-16

Following Step 2 in Section 6.1, the JPCP condition (i.e., percentage of slabs in each state) for each mile in the next year (2019) was estimated. It is noted there is no TPM applied to Sections MP 23-71 because it was reconstructed in 2012. According to the

Pavement ME prediction, there would be no cracking in the first 10 years. The prediction results in terms of slab state distribution for all the I-16 sections are shown Table 6-2; Figure 6-5 shows the change of each state over five years. The number of NC slabs decreases as expected (assuming no treatment). About 5% of the slabs without cracking turn into L1 or T1 after 5 years of deterioration. There is a significant increase in the SS slabs; it almost tripled in 5 years (from 371 to 1205). Other distressed slabs (L1, L2, T1, and T2) also increased (about doubled in five years).

Table 6-2. Forecasting of total number of slabs in different state.

	NC	L1	T1	L2	T2	SS
2019	37792	389	175	246	486	371
2020	37214	589	265	259	582	550
2021	36596	804	336	294	689	740
2022	35984	943	385	406	808	933
2023	35389	1047	426	453	939	1205

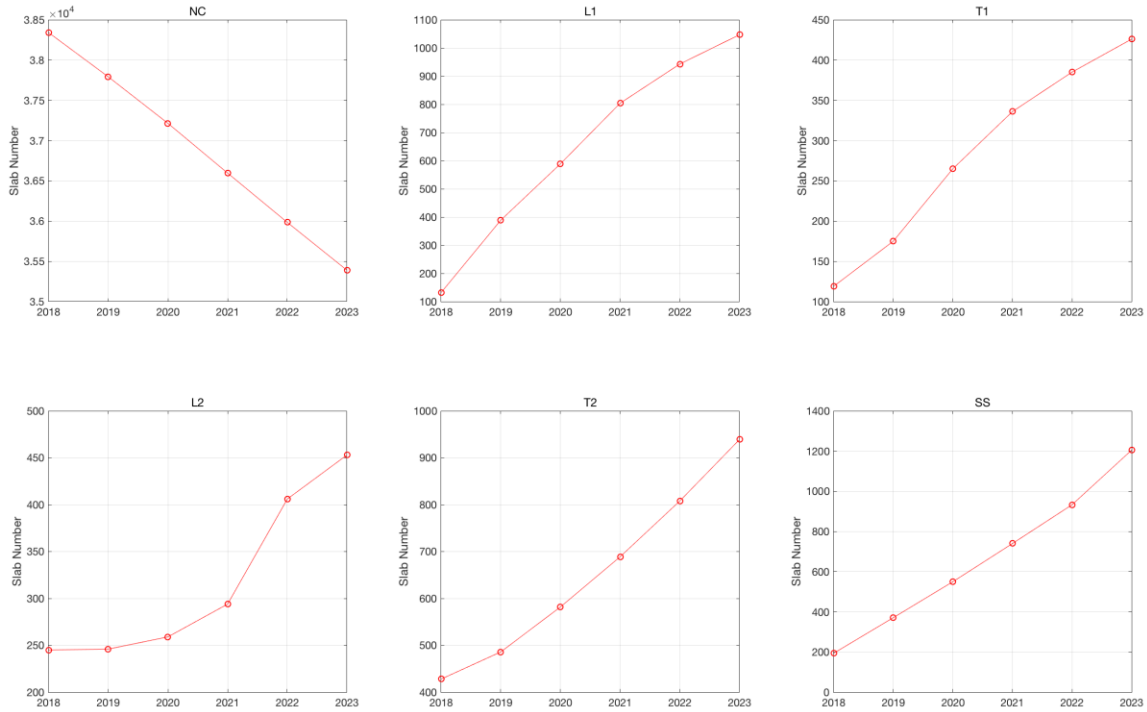
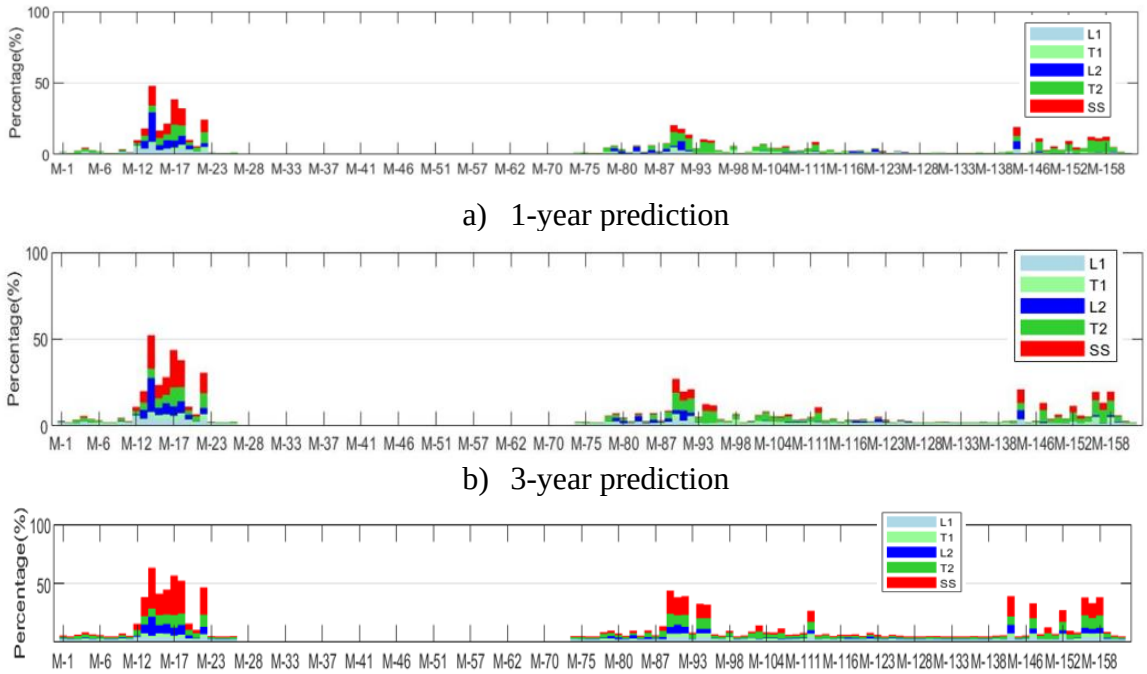


Figure 6-5. Charts. Slab states predictions.

Figure 6-6 show the slab state distribution for each mile in coming 1, 3, and 5 years. A significant increase in the number of shattered slabs can be observed between MP 10 -20. In addition, a large portion of slabs with transverse crack have developed into shattered slabs between MP 90-110. Milepost 115-116 also demonstrates a sharp increase in the number of shattered slabs.



a) 1-year prediction

b) 3-year prediction

c) 5-year prediction

Figure 6-6. Charts. Predicted slab state distribution for each mile.

Estimated Slab Replacement Need on I-16

Based on the predicted pavement condition and GDOT's slab replacement criteria, the estimated slab replacement need for the coming five years can be determined. In addition, because of their rapid deterioration field investigation is recommended for the following sections.

- Slab replacement was performed on the Sections MP 90-110 and MP 140-150 in 2015; however, significant SS slabs were reported on some segments in 2018, just two years after the slab replacement. This can be due to 1) the failure on the replaced slabs and/or 2) the rapid deterioration of other slabs. A field investigation is recommended to identify the issues.
- Significant SS slabs were reported and predicted on the sections at MP 17-12 (especially MP 17-16). Because 40% of the slabs are cracked and 15% are SS, it is recommended the M&R strategy be thoroughly evaluated, including the full-lane replacement. Otherwise, GDOT may need to go back to the same section to perform slab replacement in a few years.

CONCLUSIONS AND RECOMMENDATIONS

The Georgia Department of Transportation (GDOT) is currently transitioning to a new pavement data production operation that deriving its pavement distresses using 3D pavement data. While this full-extent, high-resolution 3D data, coupled with artificial intelligence, such as automatic extraction of pavement distresses, allows researchers and agencies to closely study the insights of jointed plain concrete pavement (JPCP) deterioration behavior at a detailed, slab level, there is an urgent need to explore the potential of taking full advantage of this 3D pavement data (that becomes popular in the future) in support of the forecasting of Georgia's JPCP pavement performance and treatment, such as slab replacement, using the slab level pavement distresses. This project focuses on 1) developing a methodology for effectively extracting pavement distress data for JPCP at slab level using the 3D pavement data to support various analyses, and 2) developing models to more accurately predict JPCP condition at slab level to better support the maintenance and rehabilitation (M&R) decisions (such as slab replacement and diamond grinding), which is based on the detailed level of slab condition. The outcomes of this research project are the following:

1. A review of the JPCP distresses, M&R methods, and forecasting models shows the common M&R action (such as slab replacement) is determined based on the distress severity at the slab level and the pavement condition survey often designed to capture the severely distressed slabs (e.g., shattered slab) to support the M&R decision. However, the existing forecasting models focus on single indicator (e.g., % of transverse cracking, rating, or IRI) without addressing the severity. There is a need for a forecasting model that agency's typically classify

and record slab condition and are often based on the . However, the forecasting models,

2. A review of slab condition data derived from the 3D pavement data shows that the limited cracking on the LTPP sections is not representative of the slab condition of the whole mile section. Nevertheless, the patterns and limitations learnt from the LTPP data are used in developing or defining the slab fundamentals. These include 1) the number and length of cracks cannot support the slab level analysis, 2) some cracks with a short length (e.g., less than 1 ft) can be map cracking that is not considered as pavement structure failure, 3) some tight cracks can
3. A 3D slab-based methodology (3DSBM) was developed provide overall processes to define, analyze, model the distress (cracking and faulting) in JPCP at the slab level using 3D pavement data. It consists of three steps: 3D data collection, extraction of slab level fundamentals (including identification of individual slabs, classification of individual cracks, classification of individual slabs based on cracking within the slab, and aligning/rectifying the slabs in time to measure changes in distress), and analysis and modeling (including spatial and temporal analysis for developing forecasting models).
4. Six-years of 3D pavement data on five one-mile test sections were processed to extract slab fundamentals based on 3DSBM. A multi-stage Markov chain model was developed using the data to predict the JPCP performance based on slab condition. It used different transition probability matrixes (TPMs) to represent the slab deterioration behaviors (change in condition) in different stages. Twenty-five TPMs derived from the five test sections were categorized

using a k-means method that grouped the TPMs into three deterioration groups. The average TPM in each group was developed to represent the slab condition deterioration at the three stages without treatment. The stages are specified using the percentage of slabs in shattered slab (SS) and Level 2 transverse cracking (T2) (i.e., Stage 1: T2+SS < 0.05; Stage 2: 0.5<T2+SS < 0.1; Stage 3: T2+SS > 0.1). Slab condition is then predicted by the existing condition and the associated TPM based on the percentage of slabs in T2 and SS.

5. The 3DSBM was also applied for developing a faulting forecasting model. A dynamic linear regression model, coupled with the default faulting growth rate for each design category derived from CPACES, was developed for predicting faulting on Georgia's JPCP. The steps in the model were described in this report. This method takes advantage of the existing faulting observed in the field and reduces the efforts for acquiring additional data (such as traffic, drainage, etc.) that is currently not available in the CPACES database. In addition, the slab-level spatial analysis shows the faulting measured at different locations (along the joint and the distance away from the joint) is different.
6. A case study was conducted on 160 miles of I-16 (eastbound) to demonstrate the feasibility and the use of the developed methodology and forecasting models for predicting future JPCP conditions and M&R needs. The slab condition in each mile was derived using the 3D pavement data collected in 2018. There are 622 slabs of T2 and SS that can be considered as slab

replacement candidates. However, the number increases to 857 slabs and 1429 slabs in 2019 and 2021. Note that many of the distressed slabs are clustered in a few sections; MP 20-15 and MP 95-100. In a few segments, more than 10% of the slabs are cracked and the predictions show a significant increase in the future; these segments can be evaluated further to make full-lane replacement decisions.

To ensure the implementation of the forecasting models developed using the 3DSBM, the following are recommendations:

1. It has been proven that 3D pavement data can provide detailed level JCPC pavement distresses; this is extremely valuable for developing a reliable JCPC performance forecasting method with the developed JCPC distress propagation model and a Markov chain deterioration model.
2. Based on the success of the feasibility study, implementing the slab condition forecasting model on I-16 is recommended. TPMs on additional sections on I-16 can be developed to cover the designs and stages on that interstate route.
3. It is suggested that the methodology for predicting the concrete slab replacement be expanded onto the other JPCPs by extracting slab level fundamentals from 3D pavement data on more JPCP sections with different designs and traffics to establish TPMs.
4. Integrating TPMs into Georgia's pavement management system for predicting the slab condition of JPCPs is recommended. The slab condition can then be integrated into the M&R decisions on such actions slab replacement.
5. It is recommended that the dynamic linear regression model along with the

default faulting deterioration rates for each design category be integrated into Georgia's pavement management system to predict future faulting and the need for diamond grinding.

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APPENDIX A LITERATURE REVIEW

JPCP Deterioration Mechanisms

In jointed plain concrete pavements (JPCP) crack initiation occurs shortly after the pavement is placed due to the (expected) shrinkage of the concrete as it hardens. If joints are properly and timely made (sawed) those cracks are initiated at the end of the 'notched' saw cuts and propagate downward through the concrete pavement to the base rather quickly as shown below in Figure A-1.

Figure A-1. Illustration. Cracking below a notched joint in JPCP (taken at Illinois Tollway, 2015)

Pavements are jointed to address this expected shrinkage related to concrete hardening. Preferably, these would be the only cracks in jointed concrete pavements. Instead, due to a number of different possible factors as noted below, cracks are initiated in other areas of concrete pavements. Crack initiation in concrete is typically considered a result of excessive tensile force on the concrete, since concrete tensile strength is typically around 10 times less than its compressive strength. Crack initiation in concrete pavements can occur due to:

- shrinkage or other material related stresses,
- thermal expansion/contraction stresses,

- loading stresses,
- stress in the slab due to loss of support, or,
- any combination of these.

Shrinkage was noted previously and is controlled by jointing the pavement. Materials related stresses including D-cracking, alkali-silica reaction and others can contribute to or cause cracking and/or spalling, but these types of distresses are outside the purview of this effort, which is intended to focus on fatigue related cracking. Environmental, loading and support conditions have the most effect on fatigue related cracking.

Curling and warping of concrete pavements is a known source of environmental stress in pavement slabs. Curling and warping are due to the top and bottom of the slab experiencing different temperature or moisture conditions, respectively. This can occur for temperature when the surface is exposed to a hot sunny day, while the bottom is in contact with a cooler subgrade. In this case, the slab would contract more on the top and cause the slab to curl up, with the center above the edges, as shown in Figure A-2. Warping can affect the slab similarly, when the dryer side of the slab is in contact with the subgrade and the surface is wetter as shown in Figure A-3. Curling and warping work independently but can have additive effects or offset each other. Cool, dry nights with wet, warm subgrade conditions are the most typical additive condition and so can be the most detrimental, where the stresses are compounded like shown in Figure A-4 (Taylor, 2006].

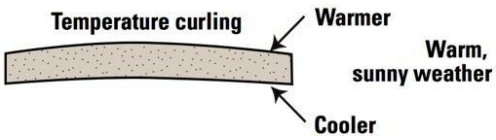

Figure A-2. Illustration. Curling due to temperature.

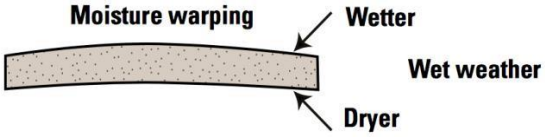

Figure A-3. Illustration. Warping due to temperature.

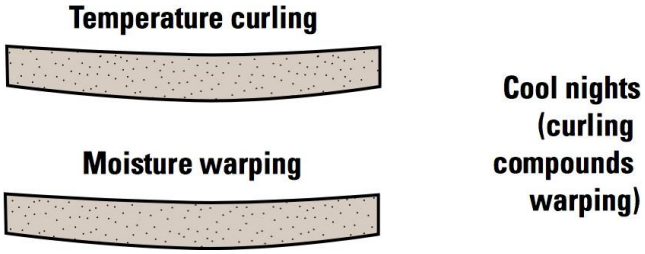

Figure A-4. Illustration. Additive effects of curling and warping (Taylor, 2006).

Different levels of curl and warp can be built into a pavement depending upon the condition at time of construction. Some efforts to measure built-in curl and warp of pavements have been made but they are not standardized, and they typically involve making measurements at different temperatures and environmental conditions (Chang et al., 2008 and Ceylan et al., 2007). Built in curl and warp have been identified as having an effect on performance of jointed plain concrete pavements, especially in the measurement of smoothness (IRI) measurements (Yu et al., 1998). Built-in curl and warp has also been linked to increased longitudinal cracking (Signore et al., 2012).

Fundamental Cracking Models

Concrete used in jointed plain concrete pavements is non-reinforced concrete. Concrete at its most basic is composed of cement, water and aggregates (fine and coarse). The cement and the water chemically react to create the binder that holds the aggregates together. For the purposes of this discussion on cracking, the chemistry involved will not be discussed since information on it can be found in any Concrete textbook. What is important is that different reactions occur at different times and at different levels and due to that, and the composites that make up concrete, it is not a homogeneous material at the macro or micro level. Recent advances in scanning electron microscopy (SEM) have provided additional information on the structure of concrete at a nanoscale but much is still unknown (Birgisson et al., 2012). As shown in Figure A-5 it is non-homogeneous even at a nanoscale.

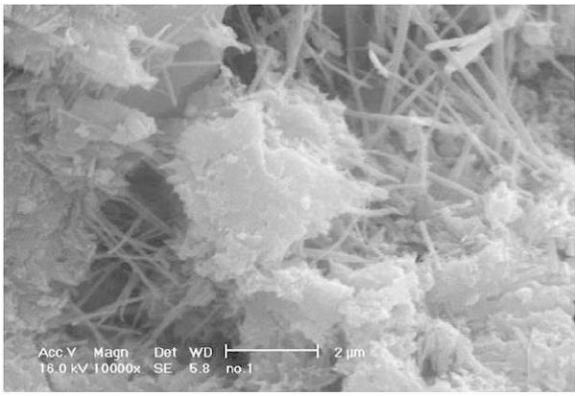

Figure A-5. Photo. SEM picture of concrete structure at nanoscale (Li and Liang, 2011).

Fracture mechanics is the study of how materials fracture or break. It recognizes that materials do not always exhibit their theoretical strength levels due to inherent flaws in the material. Primarily used in metals and glass, it has recently (starting in the 1980s)

been expanded to concrete materials. The challenges for using in concrete are the non-homogeneity of concrete that was discussed earlier. No material is purely homogeneous, but steels and glass are much more so than concrete.

The basics of fracture mechanics is that cracking requires energy both to initiate and to propagate. Larger structures have more energy available to feed the propagation of a crack and, based on Weibull Theory, the larger the volume associated with a material/structure the higher probability of weak areas/flaws/microcracks. Isenberg noted in a 1968 American Concrete Institute (ACI) document on 'Cracking in Concrete' that "strength and stiffness" of concrete "are not permanent properties, but change as microcracking develops" (Isenberg, 1968). These considerations are why failure or fracture of a structure cannot be based solely on the theoretical strength (i.e. tensile strength) of a material. In addition, these materials have inherent cracks/flaws that also affect the energy and propagation of the crack. Each crack has a crack tip which is under stress (stress intensity factor, KI) and a zone in front of the crack tip (fracture process zone, FPZ). KI is proportional to the load applied and is related to the crack length and the geometry of the specimen, so it changes with movement of the crack and different size specimens. The material resists cracking based on its fracture toughness, KIc, which is the critical value of KI. Propagation of the crack relies on the fracture energy, G where the critical crack energy is termed Gf. The crack propagates only if G reaches Gf. G and KIc are basic material properties. The fracture toughness and the critical crack energy are related by Youngs Modulus, E, and the Poisson ratio, ν, of the material as shown in Equation 1.

$$KIc = GfE' \quad \text{where} \quad E' = \quad E \qquad (1)$$

Fracture Mechanics looks at three Modes of loading as shown in Figure A-6. Since Mode I is related to tensile loading, and concrete has a low tensile strength, this is the Mode most considered in concrete (Bazant, 1999).

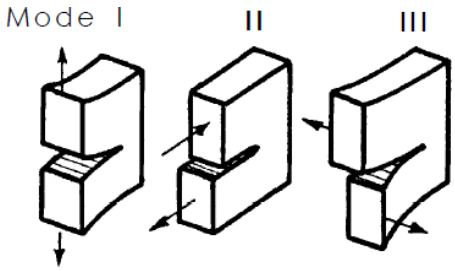

Figure A-6. Illustration. Elementary cracking modes (Bazant, 1999).

Flaws cause failure (act as stress concentrators since load cannot be carried over cracks) and larger samples have more flaws, therefore size matters in crack propagation. It has also been shown through round robin testing by RILEM that the same concrete mix tested with different sample sizes will provide different values of Gf. The research reported this was related to changes in micocracking due to differences in curing based on the size of the specimen (Karihaloo and Nallathambi, 1991).

S-N curves are empirical measures of fatigue. For laboratory specimens they are developed using notched samples that are subjected to cyclic loading until failure. The disagreement between the S-N relationship between laboratory beams and full scale concrete pavements in the field due to the specimen size effect is well known (Ioannides, 1997). The definition of failure also contributes to the differences. In a laboratory beam, failure is the partially supported beam breaking in two. In the field different values have been used to define failure. As shown in Figure A-7, noted in the 1999 TRB paper, the S- N relationship differences shown in the figure were also due to differences in the experiments definition of failure (Roesler and Barenberg, 1999). The Corp of Engineers data (identified as Field Slabs-Darter) was based on 50% of slabs exhibiting cracking

while the AASHO Road Test (Field Slabs-Vesic and Saxena) used present serviceability index (PSI), a ride comfort based criteria.

Recent research performed at the University of Illinois advanced the correlation between small-scale properties and flexural capacity and crack propagation of full-scale pavements, but they also recognized that to apply this tool to pavement practitioners "other important effects, such as load transfer between slabs, base type, and slab temperature or moisture curling must be addressed" (Gaedicke and Roesler, 2009).

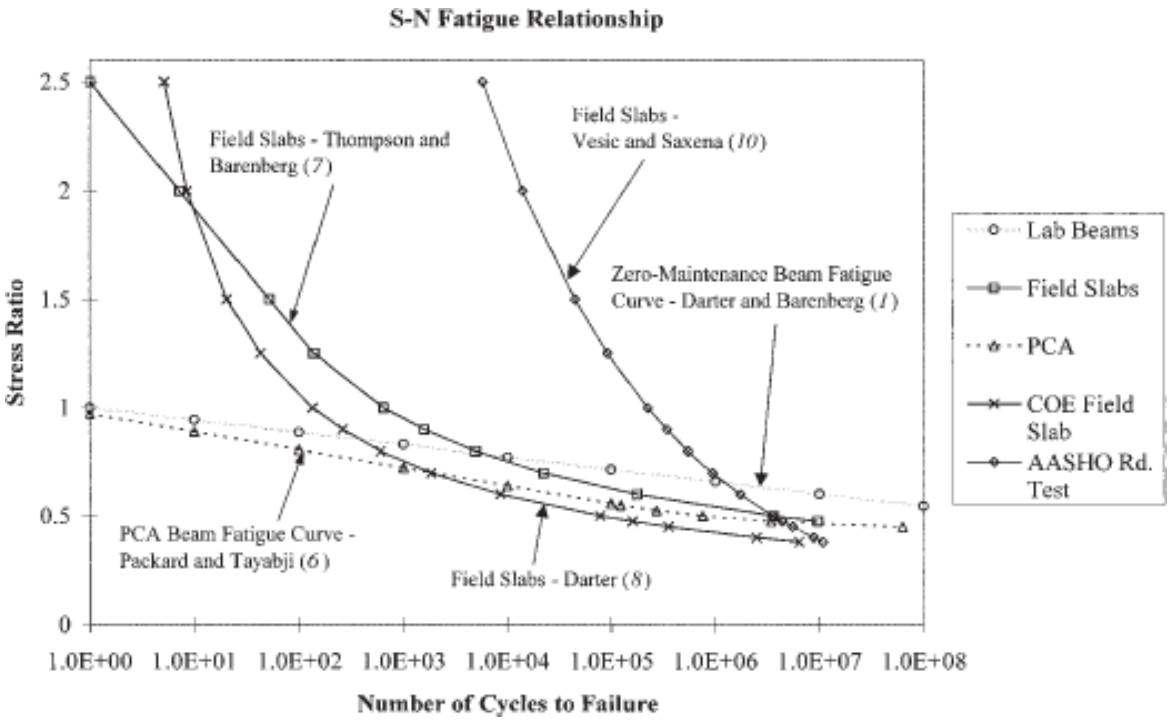

Figure A-7. Graph. Fatigue relationship based on failure definition (Roesler and Barenberg, 1999).

Cracking and Faulting Models in AASHTO Pavement ME

The most universally used mechanistic based model for concrete pavements in the US is that used by the AASHTO PavementME Design (PMED) procedure, formerly known as MEPDG (mechanistic –empirical pavement design guide). The procedure uses a mechanistic-empirical approach to identify transverse cracking in concrete slabs. The process considers both loading and thermal (warp and curl) stresses in the pavement at the bottom and the top of the slab. The critical location is considered to be the same midpoint edge location of the slab, with the critical location for bottom-up cracking at the bottom of the slab and the critical location for top-down cracking at the top of the slab as shown in Figure A-8. The location of the critical loading is different for top-down and bottom-up stresses, with the major tensile load at the bottom of the slab when the truck tires are mid-slab, and the major tensile load at the top of the slab when the truck tires are loading opposite ends of the slab. The PMED does not currently predict longitudinal cracking, but the original research effort recognized "that future additions to this design procedure should fully consider" longitudinal cracking (Yu et al., 2003).

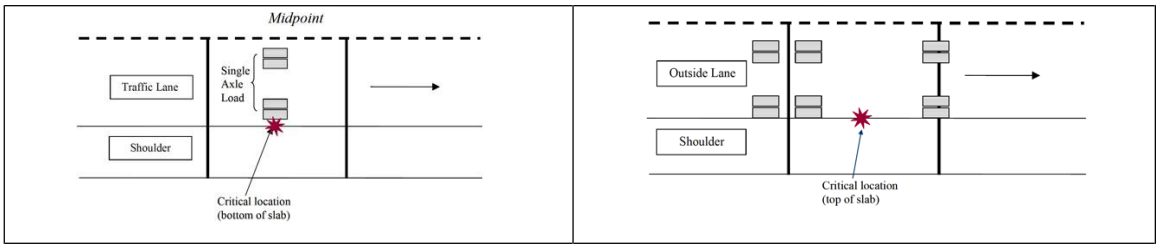

Figure A-8. Illustration. Critical location for cracking (Yu et al., 2003).

AASHTO Pavement ME damage is based on Miners Theory of accumulated damage, long exemplified by a professor twisting a paper clip back and forth in front of the class a number of time until it breaks. Miners Equation (Equation 1) shows the

relationship between the number of times the paperclip is stressed (n), and the number of cycles to failure (N). When n=N and C (damage fraction) = 1 the paperclip fails. This model is based on accumulated affects which are added together. It does not directly consider any uncertainty or variability in those affects.

The Mechanistic–Empirical approach that is the foundation of the AASHTO Pavement- ME (PMED) design software uses percent of transverse slabs cracked per mile to define pavement life for cracking. Slabs are identified to crack when the ultimate tensile stress in the slab is exceeded through accumulated incremental tensile stresses based on Miners Theory. Tensile stresses from environmental and loading effects are both computed and combined. Finite element analysis and neural networks were both used to provide the necessary stresses and related deflections in a computationally efficient manner (ARA, Inc., 2004). The maximum stress theory method utilized by PMED concentrates on strength criteria such that cracking failure is identified based on the tensile and thermal properties of the concrete, with consideration of the geometry and support of the slab and the friction on the base of the slab. Properties of the concrete are based on test methods of small samples, and strength gain over time is included. This works for pavement design since ultimate conditions (cracked slabs) and not intermediate conditions (crack propagation) are being modeled. In addition, the results are empirically calibrated to full-size slabs which should moderate size effects in the design.

Faulting in PMED is computed using an incremental approach. The incremental damage is a function of the type and erodibility of the base/subbase, rainfall, loading and slab curling. Slab curling based on environmental effects is considered as it is expected that

maximum faulting would develop when the temperature differential is such that the joints are open and the slab is curled upward (ARA Inc., 2003). But, built-in slab curl or warp is not part of the analysis for either cracking or faulting as measures to define built-in curl and warp are still being developed. Faulting is measured as the mean faulting of all joints in inches. Faulting was also calibrated with full scale testing. Faulting is used with cracking to model IRI changes over time.

APPENDIX B ANALYSIS OF LTPP DATA

The LTPP General Pavement Sections 3 (GPS3) are composed of jointed plain concrete pavements, both doweled and undoweled, that were constructed between 1960 and 1989. The pavements vary in thickness, joint spacing, and base type. In this study, the LTPP GPS 3 sections were in the Wet-No-Freeze (WNF) region, as Georgia is located in the WNF regions. There are 41 sections from 13 different States and Puerto Rico in the GPS 3 WNF climatic region. For the purposes of reviewing the cracking behavior at a slab level, only the 33 GPS 3 WNF sections located in or near the southeast were considered. The sections number of LTPP were from the 10 states involved are as follows: Alabama (1), Arkansas (1), Florida (7), Georgia (8), Kentucky(1), Mississippi(2) Oklahoma(4), North Carolina (5), South Carolina (1) and Texas (3). Two of the seven Florida sites were omitted due to early cracking (at 4 or 5 years) indicating that a construction issue was involved. Another Florida site had a WIM site installed shortly after the construction, which affected the cracking, therefore it was not considered. The majority of the sections were on the order of 8 to 12 inches thick with joint spacing around 20 feet. Two Florida sites had slabs less than 7.5 inches thick, so they were not considered. One Texas section consisted of a 12.5 inch slab, therefore it was omitted also, but it also had no cracking,. Similarly, two North Carolina sites were omitted due to 30 ft. joint spacing, one which had no cracking. The remaining 25 LTPP sites were reviewed for trends in cracking behavior. Table B-1 summarizes the 25 sections.

Table B-1. Range and average values for the GPS 3 WNF sections reviewed.

GPS 3 WNF sections	# slabs in the sections	# cracked slabs *	% cracked slabs *	JPC Thickness (inches)	Construction Date Range
Minimum	20	0	0	7.9	1960
Maximum	33	25	100	11.8	1986
Average	26.7	6.5	26	9.6	1978

*maximum number of slabs with any type of cracking identified at any one inspection

Data collected through the LTPP inspection, typically performed every 2 years, was used to study the cracking behavior. The inspections were performed manually on site typically with traffic control for close inspection (termed MDS for manual distress survey) or using equipment that collected images and information automatically (noted ADS for automatic distress survey). The inspections included noting the locations and length of cracking on sheets that depicted every slab in the test section. Spalling, other type of cracking (map, D-cracking), patching, and other distress types noted in the LTPP Distress Identification Manual (REF) were collected and documented by trained inspectors. The length of cracking for each section and other distress values and indicators are included in the LTPP database for each section. Fields include the length of longitudinal cracking at different distress levels (i.e. LONG_CRACK_L_L for length of longitudinal cracking severity level 1), the number and length of transverse cracks (i.e. TRANS_CRACK_NO_L for the number of transverse cracks and TRANS_CRACK_L_L for length of transverse cracking Severity Level 1).

The information in the database is summarized by LTPP section and is not separated for each slab. To gather information at the slab level, the individual distress maps were reviewed individually. Reviewing the individual cracking maps also provided

evidence of data inconsistencies in the LTPP data, which will be further discussed later in this appendix. For each LTPP section, the progression of cracking in each slab was identified and compiled on to one form using colors to depict changes in the cracking measured in different years. An example of one side of one of these composite crack maps is shown in Figure B-1. Each full slab is shown and numbered (note after the first row only the first slab was numbered on the form). The dates of inspections were recorded on the form until the first crack appeared. Dates after cracking were noted in color and also color coded on the slab that was cracked. Cracks that extended in subsequent years show up as different colors to show the progression of cracking in the slab and to identify when a previously cracked slab went from a partial crack to a crack connecting the joints, as shown in Slab 8 in Figure B-1. Slab 8 first experienced longitudinal cracking in 1999 (orange), and one of the cracks extended in 2002 (blue), while the other crack extended all the way across the slab in 2012 (brown). Patching was noted in 2002 (blue), as shown on Slabs 14 and 15 in Figure B-1.

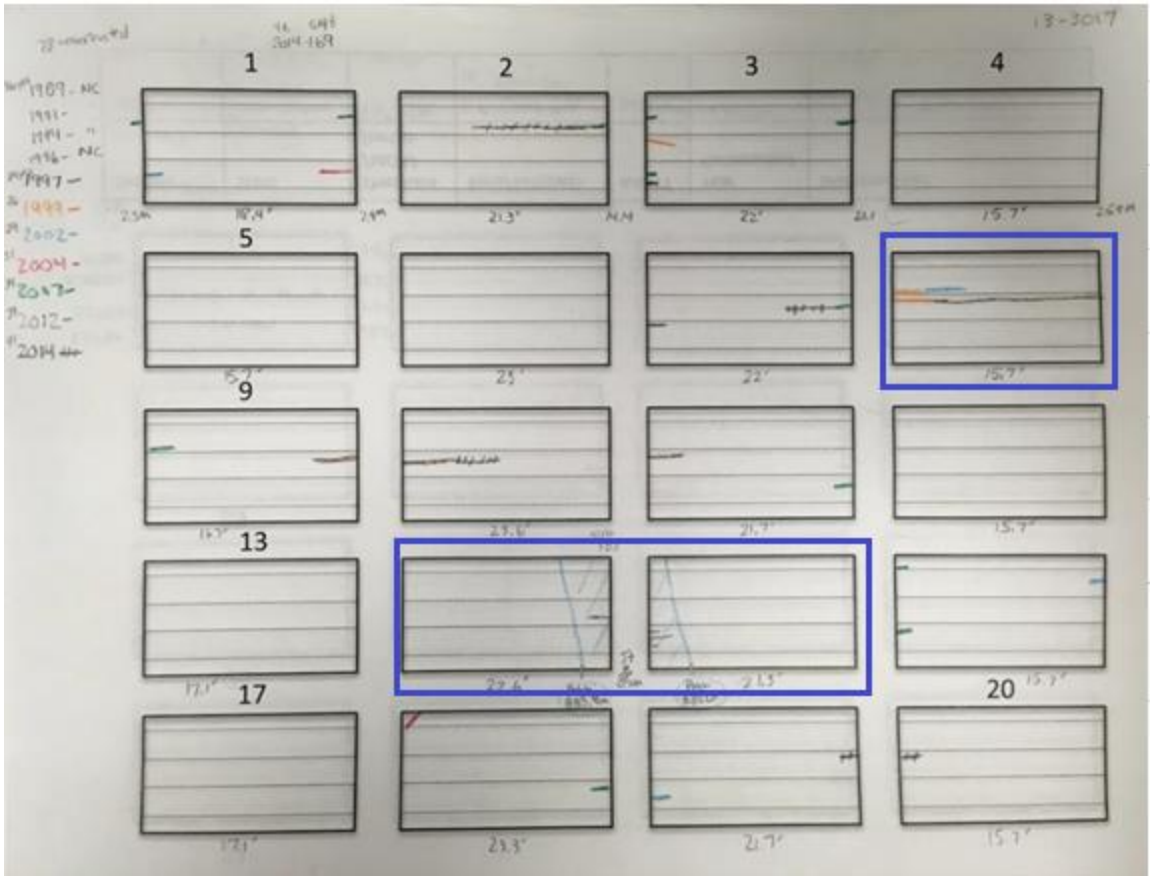

Figure B-1. Illustration. An example of cracking on Slab 8.

The LTPP data, including the distresses in each section and on each slab (based on the crack map), were analyzed to study the cracking behavior at different levels. This section summarizes general cracking behavior at the section level and at slab level.

<u>General Cracking behavior of the LTPP Sections</u>

The section summarizes the general cracking information observed on the LTPP sections.

- Six of the 25 sections (053011 in Arkansas; 133007 and 133011 in Georgia; 283018 in Mississippi; 404157 and 404160 in Oklahoma), which is 24% of the sections, have no cracking whatsoever after 30, 33, 41, 26, 29, and 28 years of inspection reports, respectively.

- Another seven sections (124000, 133017, 403018, 404162, 483003, 483589) do not have any transverse cracking after 41, 41, 28, and 12 years, respectively. This means 13 (6+7) out of the 25 sections (48%) are showing no transverse cracking, which is the main cracking distress modeled by the AASHTO Pavement PMED. For the 12 sections with any transverse cracking, the percentage of transverse cracking (computed as the number of transverse cracks divided by the total number of slabs) measured at different ages is shown in Figure B-2. The first transverse crack was recorded between 16 and 36 years. Most of the sections have limited transverse cracking (only one). Only two sections (list sections) had more than 10%.

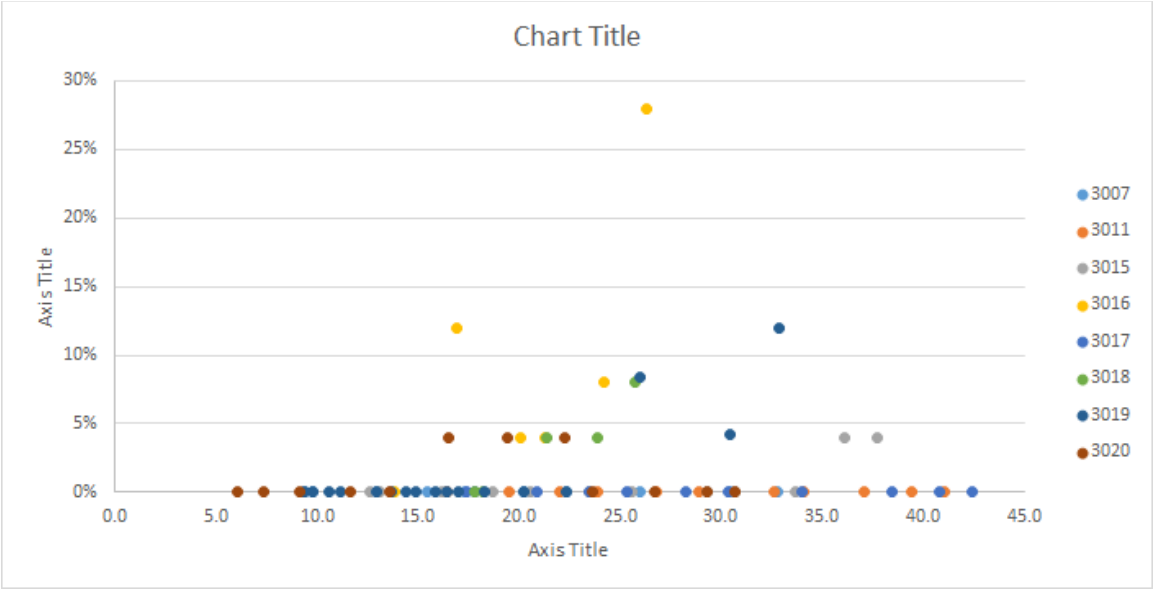

Figure B-2. Graph. Cracking on LTPP sections.

- Fifteen of the 25 sections showed some longitudinal cracking, which was more than the sections with transverse cracking. This is also the case in the when comparison of the length and number of longitudinal cracking to the transverse cracking.

The distress maps were reviewed to identify the patterns of cracking; the observations are summarized as follows.

- Out of 667 slabs, 178 were identified as cracked, but just 16 of these slabs had both longitudinal and transverse cracking. Half of these slabs contained longitudinal and transverse cracks that did not go from joint to joint, while half had at least one crack touch both sides of the joint (either the transverse or longitudinal joints). The projects that had slabs that experienced both transverse and longitudinal cracking and the complete cracking (123811, 133018, 213016, 283019, 373008, 453012); the projects that had slabs that experienced transverse and longitudinal cracking that did not (133016, 133019) were from different projects.
- Of the 54 slabs with some type of transverse cracking, 61% (33) cracked completely joint to joint. Of the 33 slabs that cracked completely transversely, 76% (25) completely cracked in one review cycle (typically 2 years). Transverse cracks that did not crack completely in one inspection cycle typically started cracking at the shoulder joint. In contrast, longitudinal cracking was more common than transverse cracking.
- Over 100 slabs had longitudinal cracking. Longitudinal cracking was typically found in the wheel paths or in the center of the pavement. As noted earlier, longitudinal cracking that went from joint to joint more often showed up after a number of inspections, while transverse cracking from joint to joint showed up more often in one inspection. An example of this is shown in Figure B-3 below.

Slab 17 from Section 13-3018 shows longitudinal cracking starting on the left side after 18 years (orange) and then cracking on the right side after 19 years (blue); then. the cracks both extended by year 26 (brown). In year 24 another small crack started below the original crack (green).

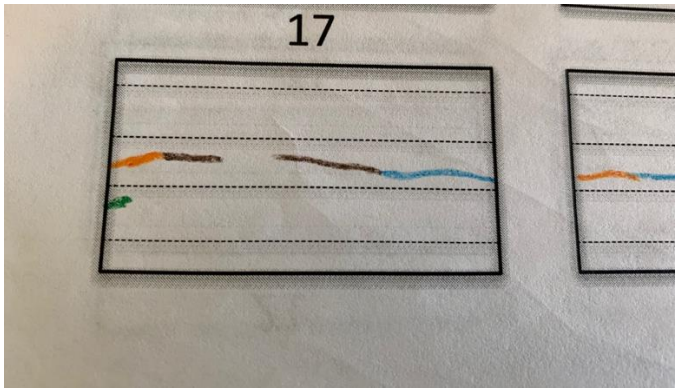

Figure B-3. Illustration. Slab 17 cracking.

- Longitudinal cracking was more often found in consecutive slabs, while transverse cracking was more often not found in consecutive slabs. Even for the section that had 21 of 24 slabs transversely cracked (123811), the slabs cracked in alternate years as shown in the Figure B-4 below. Slab 9 cracked before the first inspection at Year 13, Slab 10 cracked by Year 23 (green), and Slab 11 (brown) cracked at Year 26.

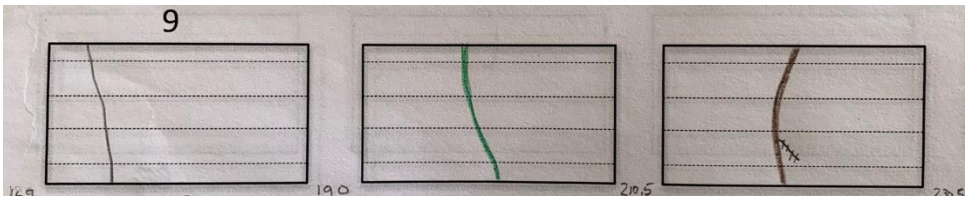

Figure B-4. Illustration. Slabs 9, 10, and 11 cracking.

- In this same section, Slab 21 cracked by Year 15 (orange) and Slab 22 did not till Year 18 (blue), and Slab 23 cracked at Year 21 (red), as shown in Figure B-5 below.

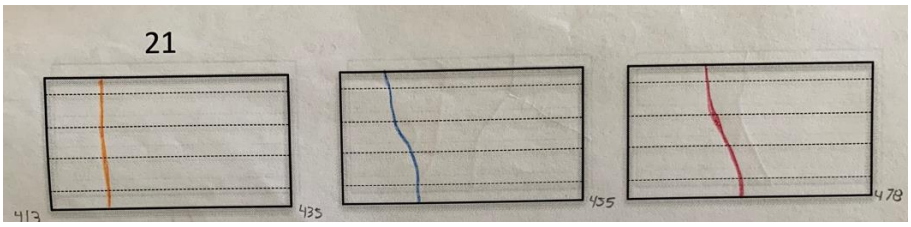

Figure B-5. Illustration. Slabs 21, 22, 23 cracking.

- In general, longitudinal cracking was predominately found in the center of the slab or close to the centerline. Longitudinal cracking was observed to both extend out from transverse joint to both adjacent slabs at the same location and to be isolated. Transverse cracks typically start at the shoulder. Slabs with transverse cracks were more often found in isolated slabs. In contrast, longitudinal cracking was more often found adjacent to other slabs with longitudinal cracking.

Through the review, some discrepancies were identified. Of the 6 sections that have no cracking at the last inspection reviewed, 5 have inconsistent cracking identified in the Infopave database. Transverse crack was identified using ADS measurements, but it was not shown in any later MDS measurements.

As evidenced by these five sections, some errors were identified in the Infopave database. Based on a review of the data and the individual maps three different scenarios containing discrepancies between the database and the LTPP maps were identified by a close review of the individual LTPP maps.

- Scenario 1 – Automated data detection error

  The database includes cracking that was identified using early versions of automated detection, which appears to have had issues with false positives. At least five sections that were identified as having experienced cracking in the database do not appear to have ever been cracked based on subsequent manual inspections. Visual observation of the results of some of the ADS results show these misidentified cracks are predominately small cracks that are often found in the center of the slab, not at a joint. This could be due to shading, material related to distress issues, map cracking or aggregate popouts. It is possible that other sections are included in the database in a similar situation.

- Scenario 2 – Misidentification of cracking type

  Based on review of the individual distress maps, crack lengths in the database are in question. It was found in a number of sections (namely sites 133016, 133019, 132020, 213046, 373008, 373807, and 483589) that cracking, especially longitudinal cracking, was later identified as map cracking and not longitudinal cracking. This was predominately cracking that did not extend to a joint or the cracking was made of short lengths of longitudinal cracking. Typically, short distances of longitudinal cracking in the center of a slab was later identified later as map cracking. Cracks at joints appear to stay where cracks are noted more often; those not going to a joint later were more often noted to be map cracking. One problem identified with longitudinal cracking near a joint was that in one year, it would be noted as longitudinal cracking and labeled as spalling the next year. Longitudinal cracking also disappeared without explanation much more

often than transverse cracking. This could be misidentification as map cracking, or maintenance of the section (diamond grinding).

- Scenario 3 – Cracks moving for unknown reasons

  An example of a moving crack was noticed in Section 133020 where a crack noted in 2007 in Slab #13 either shrinks or moves closer to the centerline in 2009 for unknown reasons.

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