GEORGIA DOT RESEARCH PROJECT 13-19

FINAL REPORT

ENHANCING GDOT’S JOINTED PLAIN CONCRETE PAVEMENT (JPCP) REHABILITATION PROGRAM USING EMERGING 3D SENSING TECHNOLOGY AND HISTORICAL CONCRETE CONDITION SURVEY DATA

OFFICE OF PERFORMANCE-BASED
MANAGEMENT AND RESEARCH

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1.Report No.: FHWA-GA-17-1319	2. Government Accession No.:	3. Recipient's Catalog No.:	
4. Title and Subtitle: Enhancing GDOT's Jointed Plain Concrete Pavement (JPCP) Rehabilitation Program Using Emerging 3D Sensing Technology and Historical Concrete Condition Survey Data		5. Report Date: December 2016	
		6. Performing Organization Code:	
7. Author(s): Yichang (James) Tsai		8. Performing Organ. Report No.: 13-19	
9. Performing Organization Name and Address: Georgia Institute of Technology 790 Atlantic Drive Atlanta, GA 30332-0355		10. Work Unit No.:	
		11. Contract or Grant No.: PI#	
12. Sponsoring Agency Name and Address: Georgia Department of Transportation Office of Performance-Based Management and Research 15 Kennedy Drive Forest Park, GA 30297-2534		13. Type of Report and Period Covered: Final; June 2013 – December 2016	
		14. Sponsoring Agency Code:	
15. Supplementary Notes: Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration.			

16. Abstract:

The Georgia Department of Transportation (GDOT) has established a data-driven JPCP (jointed plain concrete pavement) maintenance and management program, in which the JPCSPs are evaluated annually using a standardized concrete pavement condition evaluation system (CPACES) and the data (e.g., faulting index and broken slab) is used to support maintenance, rehabilitation, and reconstruction (MR&R) decisions, including determining treatment method and prioritizing projects. Today, a majority of Georgia's JPCPs (e.g., I-16) have been in service for more than four decades with minor maintenance and no or little rehabilitation; they are now are in great need of MR&R, including actions such as broken slab replacement, grinding, re-sealing, etc., or full lane replacement. Faced with the challenges of limited funding and the increasing needs for JPCP MR&R, GDOT now relies on the data more than ever to make informed decisions for timely and cost-effective JPCP MR&R and to justify spending to the legislature. GDOT has conducted its annual pavement evaluation on JPCPs based on its CPACES since the 1970s, and the data has been used for triggering treatment, determining treatment method, prioritizing projects, etc. However, the CPACES distress protocol has not been updated for many years. In this project, a critical assessment of CPACES distress protocol was conducted by conducting field distress survey, interviewing GDOT engineers, and reviewing historical CPACES data, and issues (including negative faulting, distress categorization, etc.) were identified in the existing CPACES. The Georgia Tech (GA Tech) team had worked closely with the Office of Maintenance to 1) refine the CPACES distress protocol to address the issues identified, 2) develop an enhanced slab replacement quantity estimation method using 3D laser data to accurately estimate the needs, and 3) develop preliminary models for predicting segment-level faulting and broken slabs in support of future MR&R planning.

17. Key Words: Jointed plain concrete pavement; JPCP; slab replacement		18. Distribution Statement: No Restriction	
19. Security Classification (of this report): Unclassified	20. Security classification (of this page): Unclassified	21. Number of Pages: 102	22. Price:

Form DOT 1700.7 (8-69)

GDOT Research Project No. 13-19

Final Report

ENHANCING GDOT'S JOINTED PLAIN CONCRETE PAVEMENT (JPCP) REHABILITATION PROGRAM USING EMERGING 3D SENSING TECHNOLOGY AND HISTORICAL CONCRETE CONDITION SURVEY DATA

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In cooperation with

U.S. Department of Transportation
Federal Highway Administration

December 2016

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EXECUTIVE SUMMARY

The Jointed Plain Concrete Pavements (JPCPs) in Georgia have carried approximately 5% of Georgia's truck traffic and are critical for efficient freight logistics. A majority of Georgia's JPCPs (e.g., I-16) have been in service for more than four decades with minor maintenance and no or little rehabilitation; they are now are in great need of maintenance, rehabilitation, and reconstruction (MR&R), including actions such as broken slab replacement, grinding, re-sealing, etc., or full lane replacement. The Georgia Department of Transportation (GDOT) has established a data-driven JPCP maintenance and management program in which the pavements are evaluated annually using a standardized concrete pavement condition evaluation system (CPACES) and the data (e.g., faulting index and broken slab) is used to support MR&R decisions (e.g., determining treatment method and prioritizing projects). Faced with the challenges of limited funding and the increasing needs for JPCP MR&R, GDOT now relies on the data more than ever to make informed decisions for timely and cost-effective JPCP MR&R and to justify spending to the legislature. There is a need to critically assess the JPCP MR&R program to ensure the data collected is of sufficient quality to better support MR&R planning and programming, including determining treatment, prioritizing project, and estimating quantities.

Since the 1970s, GDOT has conducted its annual pavement evaluation on JPCPs based on its CPACES, and the data has been used for triggering treatment, determining treatment method, prioritizing projects, etc. However, the CPACES distress protocol (GDOT, 1993) has not been updated for many years. Currently, GDOT is faced with several challenges. The first is that the aging JPCPs need an

increasing number of slab replacements, and the current CPACES distress type and severity levels are insufficient to differentiate the most severely distressed slabs for replacement. Second, the current slab replacement quantity estimation practice (i.e., a windshield inspection after a project has been selected) is time-consuming, labor-intensive, and likely to interfere with traffic. More importantly, it cannot provide accurate quantity estimates, which can lead to project over-runs. Finally, to properly manage JPCPs, the Office of Maintenance (OM) needs to reliably predict future MR&R needs, such as diamond grinding, based on CPACES data to plan the MR&R. In this project, the Georgia Tech (GA Tech) research team has worked closely with OM to 1) refine the CPACES distress protocol, 2) develop an enhanced slab replacement quantity estimation method using 3D laser data to accurately estimate the needs, and 3) develop preliminary models for predicting segment-level faulting and broken slabs in support of future MR&R planning. The following are the major findings from this research project:

1) Several issues in the existing CPACES distress protocol were identified in a critical assessment of field distress survey, interviews with GDOT concrete pavement liaison Mr. Curtis Grovner, and reviews of historical CPACES data. It was found that the existing faulting index computation discounts the negative faulting readings; as a result, a lower faulting index (and higher rating) is being reported on these segments. Also, CPACES ratings were found to be inconsistent because of the issues concerning inconsistency in handling negative faulting readings, inconsistency in faulting index computation, errors in rating computation, and missing or invalid distress. These issues can potentially delay

the MR&R timing and underestimate MR&R needs and should be addressed to enhance MR&R decisions.

2) The modifications to the existing CPACES distress protocol, including refined slab definition, additional distress categorization, refined faulting index calculation, and data checking, were identified to address many of the issues identified in the current CPACES. The key changes are summarized as follows:
    - The broken slab was divided into three types of distresses to represent the distresses with different severity levels. The shattered slab was added to differentiate it from a broken slab because it requires a higher priority of treatment than a broken slab (e.g., single transverse crack). The corner break was added due to the potential for corner breaks to fault prematurely. The distress type definitions, severity levels, and measurement method, along with distress images, were detailed in this report.
    - The faulting index computation was modified as five times the average of "*absolute*" faulting readings ($\frac{5}{n} * \sum_{i=1}^{n} |Faulting\ Reading_i|$), to account for the negative faulting readings.
    - The CPACES rating computation was modified to include the additional distress categorization (including shattered slab and corner break). A "*null*" value will be assigned to the segments that miss the key distresses contributing to the deducts, including the international roughness index (IRI) and faulting index. A rating of '105' will be assigned to sections of pavement under construction to denote that they are part of the system, but unavailable for rating.

3) The historical CPACES data was processed to have a consistent faulting index and rating. The analysis of FY 2015 data shows 22% of the segments with a rating less than 70. It is also noted that 15% of the segments had a rating less than 60. The majority of the segments with a low rating are on I-20 and I-16. It appears that recent budgetary and personnel restrictions have limited the capabilities to consistently maintain the JPCPs. Districts 2 and 3 had the highest percentage (34%) of segments with a rating less than 70, 61, and 53 miles, respectively.
4) An enhanced slab replacement quantity estimation method was developed and successfully demonstrated a promising capability to effectively identify distresses and accurately estimate slab replacement quantities using 1-mile 3D laser data collected on I-285. Results show a significant improvement (approximately 26%) on the accuracy of slab replacement quantity estimation compared to the current windshield survey. This method is capable of simulating different slab replacement alternatives, e.g., replacing only the severe distresses (e.g., shattered slab) or all distressed slabs, and calculating corresponding costs. This allows OM to analyze MR&R alternatives based on different treatment criteria and estimate corresponding costs.
5) A preliminary model for reliably predicting segment-level broken slab (i.e., severities) using 3D laser data was developed in support of segment-level MR&R forecasting. A case study, using three years of 3D laser data (2013, 2014, and 2015) collected in a 1-mile section on I-16, shows transition probability matrixes can be derived using the detailed distress information derived from the 3D laser data. The proposed method is potentially promising in predicting slab replacement needs for the future.

6) A preliminary dynamic linear regression model has been developed to predict a segment-level faulting index using historical CPACES data. In conjunction with the broken slab prediction model, GDOT can better plan for future MR&R (e.g., diamond grinding and slab replacement).

Further research is recommended as follows:

1) It is recommended that the CPACES manual with the aforementioned modifications (e.g., additional distress categorization) be developed and that a computerized data collection module to implement the changes in faulting index, rating, and data checking be developed to have quality and consistent CPACES data.
2) It is recommended that statewide training is conducted on the enhanced CPACES distress protocol, especially on the additional distress categorization and slab definition, to implement the changes and to ensure consistent data being collected in the future.
3) The slab replacement quantity estimation method can be applied to a larger data set (more than 1 mile). Especially, it can be applied to an incoming JPCP slab replacement project to simulate different alternatives.
4) The preliminary broken slab prediction model needs to be expanded to include a larger data set with JPCPs in different categories by pavement deterioration stage, pavement design, and traffic.
5) It is recommended that the faulting prediction model is validated using a large data set (including the data collected in 2017) on different routes with different conditions (e.g., pavement design and traffic).

ACKNOWLEDGMENTS

The authors would like to thank the Georgia Department of Transportation (GDOT) for its support. The work conducted in this report was sponsored by the Office of Performance-base Management and Research, GDOT (Research Project 13-19). The authors would like to thank the support provided by the Office of Maintenance, and the Office of Information Technology Applications. The support and valuable inputs provided by Mr. Dale Brentley, Ms. Ernay Robinson, and Mr. Curtis Grovner of GDOT in the course of this research project are highly appreciated. The authors would like to thank the input provided by Dr. James Lai, the Emeritus Professor at Georgia Tech.

1. INTRODUCTION

1.1 Background and Research Need

The Jointed Plain Concrete Pavements (JPCPs) in Georgia have carried more than 20% of Georgia's truck traffic and are critical for efficient freight logistics. A majority of these JPCPs (e.g., I-16) have been in service for more than four decades with minor maintenance and no or little rehabilitation. These aging pavements are in great need of maintenance, rehabilitation, and reconstruction (MR&R), including actions such as broken slab replacement, grinding, re-sealing, etc., or full lane replacement. Faced with limited funding and the increasing needs for aged JPCP MR&R, the Georgia Department of Transportation (GDOT) needs to enhance its data-driven JPCP maintenance and management program to ensure program, including the concrete pavement condition evaluation system (CPACES) (GDOT, 1993), MR&R practices, and quantity estimation, to support JPCP MR&R planning and programming. These include 1) refining the JPCP distress protocol based on different levels of severity (e.g., shattered slab) to support slab replacement prioritization when funding is limited, 2) accurately estimating the MR&R quantity (e.g., slab replacement) to prevent project overruns for better budget planning, and 3) predicting the future JPCP condition and MR&R needs for better planning.

Data-driven JPCP maintenance and management program in which the pavements are evaluated annually using a standardized concrete pavement condition evaluation system (CPACES) and the data (e.g., faulting index and broken slab) is used to support MR&R decisions (e.g., determining treatment method and prioritizing projects). Faced with the challenges of limited funding and the increasing needs for JPCP MR&R, GDOT now relies on the data more than ever to make informed decisions for timely and cost-effective JPCP MR&R and to justify spending to the legislature. There is a need to critically assess the JPCP MR&R program to ensure the data collected is of sufficient quality to better support MR&R planning and programming, including determining treatment, prioritizing project, and estimating quantities.

GDOT has conducted its annual pavement evaluation on its JPCPs based on the concrete pavement condition evaluation system (CPACES) since the 1970s, and the data is used to support MR&R decisions. Originally developed in the 1970s based on the pavement conditions at the time, CPACES has not been updated since the 1990s. The current CPACES distress protocol (GDOT, 1993) focuses on identifying the distresses at an early stage to apply proper treatment to preserve the JPCPs. For example, a slab with a single working transverse crack is identified as a broken slab (Severity Level 2), which triggers a slab replacement. A slab with multiple cracks is also identified as a broken slab (Severity Level 2). With many slabs now categorized as a broken slab (Severity Level 2) with various cracking condition (e.g., single transverse crack and multiple cracks), there is a need to categorize the slabs more finely to differentiate them in support of broken slab prioritization to maintain roadway safety. Also, with the increasing needs of MR&R, the projects with a large number of broken slab replacements are typically conducted by contract. For example, slab replacement in large number is by contract. Thus, there is a need to accurately estimate the quantity to prevent project overruns for better budget planning. Finally, to balance funding needs, the Office of Maintenance (OM) needs to reliably predict future MR&R need, such as diamond grinding, based on CPACES data to support better planning.

1.2 Significance of Research

The outcome of this project, including an enhanced CPACES distress protocol, an enhanced slab replacement quantity estimation method, and a faulting prediction model, will greatly enhance current GDOT JPCP MR&R planning. The enhanced CPACES distress protocol allows GDOT to categorize the distresses more finely to differentiate them in support of broken slab prioritization to ensure roadway safety when funding is limited. The enhanced slab replacement quantity estimation method enables GDOT to effectively determine the exact extent of slab replacements and accurately estimate the broken slab replacement quantities in support of better cost estimation to prevent project over-runs. The developed faulting and broken slab prediction model enables GDOT to predict future MR&R needs. In addition, the detailed distress information extracted from the sensing data, along with the pavement performance analysis, will provide a better understanding of the actual JPCP performance and deterioration.

1.3 Research Objectives and Scopes

The objectives of this research are to 1) develop an enhanced CPACES distress protocol that can differentiate slab conditions with severe conditions (e.g., shattered slab), 2) develop an enhanced method that effectively and accurately estimates slab replacement quantities, and 3) develop distress prediction models for predicting diamond grinding and slab replacement needs. This project consisted of six work tasks as follows:

- Task 1: Review of JPCP rehabilitation strategies and performance prediction models

  In this work task, the Georgia Tech (GA Tech) research team worked closely with OM to critically assess its current practices on pavement condition evaluation based on CPACES (GDOT, 1993), the slab replacement quantity estimation, and planning for MR&R. The research team conducted field visits for CPACES survey, reviewed CPACES data, interviewed GDOT engineers in the Office of Maintenance, the Office of Construction, and Districts (Districts 3 and 7), and reviewed the documentation (e.g., technical reports and GDOT's guidelines) to document the current practices and identify the areas needing improvements to support an enhanced JPCP program. In addition, a literature review was conducted on JPCP practices and pavement performance prediction models in use by other states.

- Task 2: Select test sites and analyze the historical pavement condition evaluation data

  In this work task, the research team worked with OM selecting test sites for estimating slab replacement quantity and studying the deterioration of distresses with time. The test sites include 1) a 1-mile section on I-285 that had slab replacement in 2014 and 2) two 1-mile sections on I-16 with a significant number of distresses (e.g., broken slab). In addition, the research team processed and analyzed the historical CPACES data from 2000 to 2015 to provide an assessment of the JPCP condition and maintenance needs. In addition, the predominant distresses and the deterioration trends were studied.

- Task 3: Conduct field data collection and analysis

  The GA Tech sensing vehicle (GTSV), developed under the research project "Remote Sensing and GIS-Enabled Asset Management System (RS-GAMS)" sponsored by the US DOT, was used to collect sensing data on the test sites. The GTSV is integrated with different sensing technologies, including a 3D laser system, a global positioning system (GPS), 2D images, LiDAR, an inertial measurement unit (IMU), and a high-resolution distance measurement instrument (DMI). Data were collected on I-285 before and after the slab replacement.

- Task 4: Refine JPCP rehabilitation strategies

  In this work task, an enhanced slab replacement quantity estimation method was developed to effectively and accurately estimate quantities and determine the exact extent for slab replacement using 3D laser data.

- Task 5: Develop JPCP distress prediction models

  In this work task, a faulting prediction model and a transition matrix were developed to predict the faulting and the broken slabs that require treatment. Changes in the crack severity were developed into transitional probability matrices (TPMs) using Markov Chain principles to provide an assessment of the JPCP condition and maintenance needs.

- Task 6: Summarize research findings

  This task documented, organized, and summarized all research findings obtained in the previous work tasks.

1.4 Organization of This Report

This report is organized as follows:

1) Chapter 1 introduces the background, significance, objective, and work tasks.
2) Chapter 2 presents the development of an enhanced CPACES distress protocol. The existing CPACES was critically assessed through field observation, interview with GDOT's engineers, and review of CPACES data to identify the avenues for

improvements. The modifications to the existing CPACES distress protocol, including a finer distress categorization, a refined faulting index, the definitions for slab and joint, and data check rules, were identified.

3) Chapter 3 analyzes the historical CPACES data to provide an understanding of the JPCP condition in Georgia, including the condition in 2015, the predominant distresses, etc.
4) Chapter 4 presents the development of an enhanced slab replacement quantity estimation method. The current practice was reviewed by interviewing GDOT's engineers, and a method was developed to effectively and accurately determine the exact extent for full and partial slab replacements and to reliably estimate the slab replacement quantity using the 3D sensing data.
5) Chapter 5 presents the review of faulting prediction models and the development of a faulting prediction model using historical CPACES data.
6) Chapter 6 presents the review of transverse cracking prediction models for JPCPs and the proposed methodology for modeling the changes in the broken slab severity levels, which is critical for forecasting the future needs for slab replacement. The preliminary results based on two 1-mile sections on I-16 are presented.
7) Chapter 7 summarizes the findings of this project and makes recommendations.

2. ENHANCED CPACES DISTRESS PROTOCOL

GDOT has conducted annual condition evaluation on its JPCPs since the 1970s to track the performance of different design features (e.g., joint spacing, use of dowel, etc.) and to support its MR&R decisions (e.g., determining treatment and prioritizing projects). A concrete pavement condition evaluation system (CPACES) has been developed to standardize nomenclature for distresses and define their respective severity levels and measurement method. However, CPACES distress protocol has not been critically reviewed and updated since 1996 to address today's need – prioritizing MR&R when funding is limited. Developed in the 1970s when there were fewer and less severe distresses on JPCPs, CPACES focuses on identifying the distresses at an early stage and applying proper treatment to preserve the pavements. For example, a single working transverse crack is counted as a broken slab severity level 2, which triggers slab replacement. As JPCPs are aging and deteriorating, many of them now exhibit more severe distresses (e.g., shattered slab with multiple cracks) and may need to be treated with urgency for maintaining roadway safety. However, the existing CPACES distress protocol (GDOT, 1993) was not designed to differentiate the JPCP conditions with serious distresses that lead to safety concerns. Thus, there is a need to revisit the CPACES distress protocol to ensure it can provide adequate and quality data in response to today's pavement condition and MR&R practices. This chapter presents 1) a critical assessment of CPACES distress protocol by conducting field observation on CPACES survey, interviewing GDOT's engineers, and reviewing historical CPACES data and 2) the modifications to the existing CPACES distress protocol that allows GDOT to collect

JPCP with additional distress categories (or severities) to differentiate the urgency for treatment.

2.1 Review of CPACES

GDOT first conducted statewide faulting measurement of its interstate highways in 1971 as part of the data collection effort for a research project to study concrete pavement faulting (GDOT, 1972). Since then, GDOT has developed a standardized CPACES for consistent annual pavement condition evaluation on JPCPs. CPACES had been modified over the years to address the changes in pavement condition and to support MR&R decisions. A brief history of the CPACES distress protocol is described in Appendix A. The current CPACES, last updated in 1993, consists of measuring joint faulting and counting pavement defect occurrences for each segment (approximately 1-mile long) in outside lanes for each mile of JPCP in Georgia (GDOT, 1993). According to the CPACES manual, the faulting of every 8th joint is measured to obtain representative samples of each mile of JPCP using a Georgia Faultmeter (GDOT, 1993). The rest of the CPACES survey is a visual tally of distressed slab and joints, including broken slabs, slabs with longitudinal cracks, replaced slabs, spalled joints, patched joints, failed spall patches, and shoulder distress. Table 2.1 lists the distresses included in the CPACES manual. The pavement roughness values, i.e., the International Roughness Index (IRI), are included in the CPACES, although these values are collected by a different unit. A performance rating (CPACES rating) scale of 0 to 100 is then computed for each segment based on the types of distresses and their extent. While CPACES defines distress types, severity levels, and measurement method, there is ambiguity and subjectivity in how the

CPACES is measured in the field. For example, replaced slabs can be difficult to discern after a number of years, so it is unclear if replaced slabs include all prior replaced slabs or just recent replaced slabs. Therefore, a field visit was conducted to closely observe the CPACES survey and to discuss questions with regard to the distress classification with the survey crew. In addition, historical CPACES data was carefully reviewed to identify issues related to data quality for improving CPACES.

Table 2.1 Types of distresses in CPACES

Distress Type	**Sample Location**	**Severity**	**Report Unit**
Faulting[1]	Every 8th joint	-	Faulting Index
Broken slab	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 Georgia Faultmeter.
2. Roughness is collected by Laser Profiler.

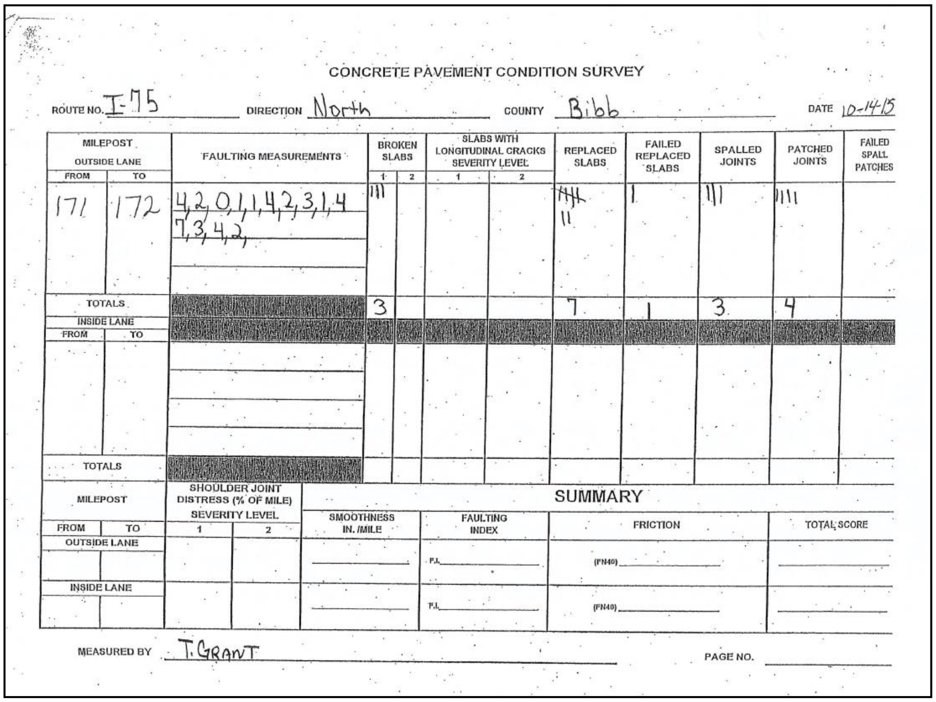
2.1.1 Review of CPACES Field Survey

The GA Tech team conducted a field visit with GDOT District 3's survey crew on a CPACES survey on I-16 westbound on October 13, 2015. The CPACES survey was conducted by the bridge unit with a crew consisting of a survey team (in a van) and a traffic control team (a buffer truck). The survey team rides slowly in the van on the shoulder followed by a buffer truck to provide moving traffic control for safety (see Figure 2.1(a) and (b)). The survey team consists of a driver, a surveyor who visually tallies the distresses on the slabs and records them on the survey form, a faultmeter operator who operates the Georgia faultmeter, and, often, a fourth-person for backup. The van traveled on the shoulder at a slow speed (approximately 20 mph). The surveyor, sitting behind the driver, as shown in Figure 2.1 (c), was responsible for keeping track of the distresses, adding tally marks for distresses, such as broken slab, replaced slab, spalled joint, etc. and noting down the faulting readings signaled by the faultmeter operator. An example of the survey form is shown in Figure 2.2. The faultmeter operator was on foot (or exiting/entering the van at each joint to be measured). He found gaps in the traffic to place the faultmeter at the joint and used hand signals to denote if negative (by drawing hand across the neck) and the total number (using fingers, turning hand back and forth to denote >5, >10), as shown in Figure 2.1 (d). The driver would help keep track of the faulting reading as well. A typical CPACES takes approximately 20-25 minutes per lane-mile for a survey team of 3-4 persons plus a buffer truck. The faulting measurement was clearly the bottleneck in the CPACES survey. It took on average about 5 to 6 seconds to make a faulting measurement and could take longer when the traffic is heavy. The presence of bridges and ramps reduced the time taken as faulting readings were not taken on ramps and bridges.

(a) Survey vehicle (b) Buffer truck

(c) Visual survey and record distresses (d) Hand signals a faulting reading

Figure 2.1 CPACES survey



CONCRETE PAVEMENT CONDITION SURVEY

ROUTE NO. I-75 DIRECTION North COUNTY Bibb DATE 10-14-15

MILEPOST OUTSIDE LANE		FAULTING MEASUREMENTS	BROKEN SLABS		SLABS WITH LONGITUDINAL CRACKS SEVERITY LEVEL		REPLACED SLABS	FAILED REPLACED SLABS	SPALLED JOINTS	PATCHED JOINTS	FAILED SPALL PATCHES
FROM	TO		1	2	1	2					
171	172	4,2,0,1,1,4,2,3,1,4 7,3,4,2,	|||				𝍸 ||	|	|||	||||	
TOTALS			3				7	1	3	4	
INSIDE LANE											
FROM	TO										
TOTALS											

MILEPOST		SHOULDER JOINT DISTRESS (% OF MILE) SEVERITY LEVEL		SUMMARY			
FROM	TO	1	2	SMOOTHNESS IN. /MILE	FAULTING INDEX	FRICTION	TOTAL SCORE
OUTSIDE LANE					F.I.	(FN40)	
INSIDE LANE					F.I.	(FN40)	

MEASURED BY T. GRANT PAGE NO.

Figure 2.2 Concrete pavement condition survey form

The survey team conducted two runs of the survey on two 1-mile segments on I-16 westbound (MP 17-16 and MP 51-14) with different survey formats. In the first run, the survey team conducted the survey based on their typical practices using the condition survey form. In the second run, the survey team conducted a modified survey, in which they rated the distresses in the outside lane based on the original slab (i.e., use the inside slabs as the slab number), and by slab number. The purpose of this design is to track and compare distresses on the original slab. The results of the two runs of survey are listed in Table 2.2, and the issues are discussed in the following.

Table 2.2 CPACES survey results

		Time (mins)	BS1	BS2	LC1	LC2	RS	Spall	Patch Joint	Failed RS
MP 17-16	Run 1	26	24	14	10	2	5	2	1	1
	Run 2	34	33	6	19	2	8	3		10
MP 15-14	Run 1	25	4		5		1			
	Run 2	33	6		4	4	1			

BS1 (broken slab severity level 1); BS2 (broken slab severity level 2);
LC1 (slab with transverse cracking severity level 1);
LC2 (slab with transverse cracking severity level 2);
RS (repaired slab); Failed RS (failed repaired slab)

- Slab Definition

  One significant source of inconsistency involved how to count the number of slabs. In general, the number of distressed slabs in Run 1 (based on current survey practices) was lower than the ones recorded in Run 2 (based on the original slab). This is because the small replaced slabs can be grouped and counted as only one slab in run 1. It is noted that the GDOT crew defined a slab as the group of current slabs that lied between two “original” transverse joints. Original transverse joints were defined as those which spanned across both the inner and outer lanes (Figure 2.3 (a)). Due to slab replacement carried out on the outermost lane, the slabs on that lane were much smaller. In the case of multiple distresses in the group of slabs, the most severe distress was recorded. This leads to two issues: 1) a broken slab can be long in length (sometimes more than 100 ft.) and 2) the number of broken slabs may decrease as more slabs are being repaired (this is an issue when studying the trend of broken slabs).

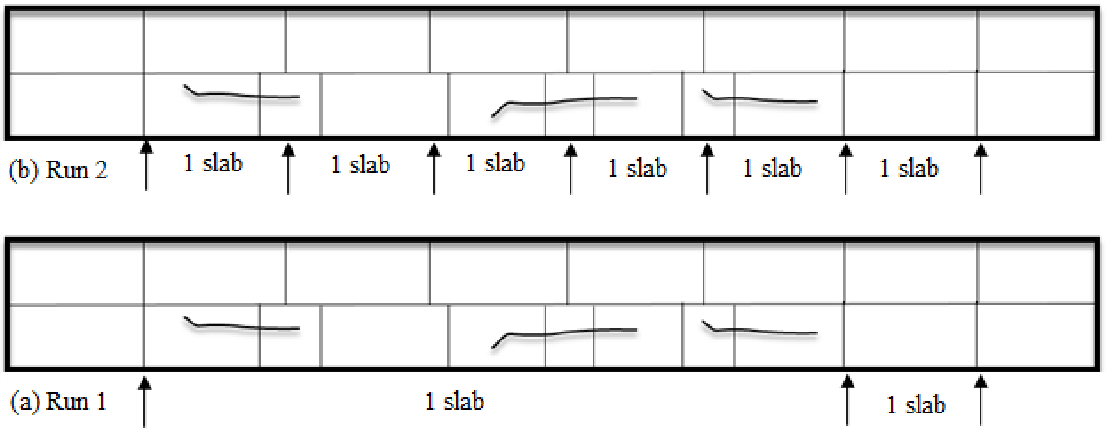


Figure 2.3 Definitions of slabs

For the modified survey (Run 2), the surveyor found it difficult to keep track of the slabs and record simultaneously, as shown in Figure 2.3 (b). If the surveyor loses track of the slab number once, then the shift will propagate through all subsequent slabs. Hence, it is very difficult to perform this type of survey accurately. A refined slab definition that can describe the increase in broken slabs and is easy to count in the field is needed.

- Faulting Measurement

  Through the field observation and discussion, it was identified that the survey crew counts only the original joints when taking faulting measurements at every 8th joint. If a prior repair went over a joint, then that joint would not be counted. Maintenance work (e.g., slab replacement and joint patch) can cause faulting. This design is to track faulting at the original joint without considering the faulting introduced by repair (e.g., slab replacement and joint patch). The use of original joints for faulting measurements should be clarified in the CPACES manual to ensure it is followed in the CPACES survey.

- Distress Classification

  There were issued observed in classifying the distresses. First, some level of subjectivity and ambiguity was observed in distress classification even within the same survey team. A slab with multiple severe longitudinal cracks was identified as a broken slab (Severity Level 2) by one surveyor's interpretation of the distress description in CPACES and a longitudinal cracked slab (Severity Level 2) by another. It is noted that the longitudinal crack is not used in the current treatment criteria. There were also different interpretations for a slab with a diagonal crack. Second, a wide range of distresses can be classified as a broken slab severity level 2, ranging from a single traverse crack to a shattered slab with multiple cracks, as illustrated in Figure 2.4. During the discussion, the crew mentioned District 3 has a crew (5 persons) working on slab replacement in 32 counties. With the limited capacity, there is a need to prioritize the slab replacements. A severe severity level 2 broken slab should be separated out (e.g., shattered slab). A slab with multiple cracks can lead to a variety of worsening distresses such as spalling, differential settlement or pop out and typically would need to be addressed sooner to maintain roadway safety. Thus, there is a need for refining distress classification to differentiate slabs with severer levels of distresses (e.g., a slab with multiple types of cracks).

Figure 2.4 Various broken slab severity level 2

- Repaired Slab

  During the discussion, the survey crew mentioned there are different definitions for the replaced slab even within the team. It can be the slabs that had been replaced regardless when they were replaced or the slabs that had been recently replaced. It is difficult to identify all the replaced slabs, especially those replaced for many years. This may explain the inconsistency in the number of replaced slabs in the CPACES data and difficulty to analyze the trend.

2.1.2 Review of Historical CPACES Data

Quality CPACES data is essential for supporting the JPCP program, including reporting JPCP condition, determining treatment, prioritizing projects, and studying the trends in distress deterioration. Therefore, the historical CPACES data was carefully reviewed to identify 1) questionable data and 2) the criteria for checking or removing such data for improving the data quality. Questionable data, including very high number of negative faulting readings, negative faulting index, extremely low or high IRI, inconsistent ratings, and missing data, were identified in the CPACES data collected between 2000 and 2015. As a result of the review, changes to the faulting index calculation were recommended. This section discusses the questionable data observed in the CPACES data and recommended methods to improve data quality.

- Negative Faulting readings

  A positive faulting reading is expected when the leaving side of the joint is lower than the approaching side and a negative faulting indicates the leaving side of the joint is higher, as illustrated in Figure 2.5. More than 10% of the surveyed segments had at least one negative faulting reading; 2% of them have negative faulting readings in the entire segment. While negative individual faulting readings can be valid, it was identified that in the early development of CPACEs a negative faulting value was rare and sometimes the result of a reading taken with the Faultmeter facing the wrong direction. This is typically the case when continuous negative faulting readings were reported within a segment. For example, all negative or zero faulting readings were reported on MP 59-60 on I-16 eastbound in 2003; however, all positive or zero faulting were reported in the previous year. In other cases, negative faulting readings can be reported when the faulting was taken at improperly sealed joints, partial-depth spall repairs, and full-depth repair patches. Instead of discarding the negative faulting readings, which occurs in approximately 10% of the segments, it is recommended to take these negative faulting readings into consideration as discussed in the next section.

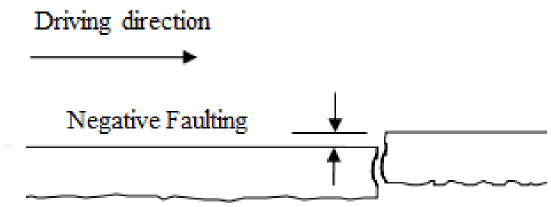


Figure 2.5 Example of negative faulting

- Faulting Index

According to the CPACES manual, a faulting index is computed as five times the average fault meter readings (i.e., the average fault meter reading equals the sum of all readings divided by the number of readings). Negative faulting readings are turned into 0s, essentially discounting the negative values. Thus, a faulting index is expected to be 0 or positive values. However, a review of the CPACES data shows approximately 6% (1,171 entries) of the data included negative a faulting index, which potentially means negative faulting readings were not turned into 0s. 4% of the data had a faulting index of 0; it is unclear how the zero faulting readings were calculated since most of the entries also recorded positive faulting values greater than 0. This indicates inconsistency in the faulting index calculation; therefore, a faulting index needed to be recalculated for further analyses. The use of 0 for negative faulting readings results in a lower faulting index that does not properly represent the actual faulting condition. Therefore, a revised faulting index computation is needed to take the negative faulting readings into account by the use of absolute faulting values.

In addition to the negative faulting readings, the total number of faulting readings is inconsistent in the CPACES data. Currently, the number of faulting readings in each segment is not recorded explicitly. Instead, the database includes 35 fields for storing faulting readings. It was assumed that the last faulting value was never a 0, and that all 0s after the last non zero number were not readings. There is an inherent bias with this assumption, but the impact was considered insignificant. A 0 faulting is expected relatively rare. It is recommended to record the number of faulting readings taken in the database no matter it is positive a potential extra quality control check in the future.

- Questionable IRI Values

  Approximately 9% of the entries have an invalid IRI value (e.g., missing, 0, or negative). It is noted that another 11% of the data reported an IRI less than 800 mm/km on old JPCPs, which is a relatively low number, not necessarily impossible, but somewhat questionable. Therefore, 20% of the IRI values were considered questionable. Because IRI is a major component in the CPACES rating, these records were excluded from the rating analysis.

- Questionable Ratings

  The CPACES rating is computed by deducting points for each distress, such as faulting index, IRI, cracked slabs, etc.; no deduct (or 0) is considered for any missing distresses. As a result, the segments with missing distresses will be rated higher than if the correct faulting index or IRI was used. Faulting index and IRI are the predominant distresses of the largest deducts, therefore. It is recommended that a rating should not be calculated when any of these distresses is missing. A “null” value will be assigned in the rating for the segment with missing distresses.

  In addition, a review of the CPACES rating shows inconsistencies and errors where the individual distresses did not match the rating data. As an example, one entry (I-16, MP 54 to 53, 2005) with a faulting index of 26 had a CPACES rating of 94. The faulting index value alone would provide for a maximum faulting index deduct of 25; thus, a rating of 94 was an obvious error. It is recommended the refined faulting index and CPACES rating computation are used to recalculate every segment and every year to have consistent faulting index and rating. Compared to the values currently reported in the database, a higher faulting index is expected because the negative faulting readings are included. CPACES ratings are expected to be lower because of the new faulting index and the exclusion of missing distresses.

- Other Distresses

  Other distresses, such as replaced slabs and spalls, were also reviewed to identify issues or errors in the data. A one mile section that consists of 30 ft. joints would have about 176 slabs (5280/30 = 176), but 25 entries had over 350 replaced slabs identified. These entries represented I-75 in the area of MP 34 to 39 in FY 2010 and MP 143 to 153 in FY 2004, which were both respectively under construction during those timeframes. It is assumed that the number of replaced slabs was entered to show that they were all being replaced. Some records noted as having a CPACES rating of 0 also had a comment that the section had been overlaid with asphalt. It appears the 0 ratings are errors or identifiers of construction activities and are not actual ratings. There were other locations where the comment field noted “under construction” but data was included or/and a CPACES rating was provided. It is recommended that a CPACES rating value such as 105 is used to denote ‘under construction’ in the future, as a 105 used in COPACES for asphalt pavements, this could reduce these types of errors. It can also provide a clear timeframe for when maintenance or reconstruction work was performed on a section.

- Location Data

  In addition to the distress data and rating, the location data was reviewed to ensure represented similar roadway lengths. It was anticipated that each record would be approximately 1 mile, but 269 records were greater than 1 mile, with three over 1000 miles. This would result in an overstated surveyed miles. The milepost data was reviewed closer and some obvious errors were identified and rectified (i.e. in FY2004 MP 136 to MP 1637 was changed to MP 136 to 137 and MP 1804 to MP 18 was changed to MP 18.4 to MP 18). It was noted that in some cases a higher mileage single entry was noted as a section under construction (i.e. In FY2014 MP 37.1 to 69 on I-16). It is recommended that a segment be limited to less than 2 miles unless the surveyor notes the reason for a long segment.

2.1.3 Summary of CPACES Review

The following summarizes the key issues identified through the field observation and review of CPACES data.

- There is a lack of clear definition for a slab after it was repaired and divided into 2-3 small slabs. Current practices count a slab as the group of current slabs that lie between two “original” transverse joints. This means the number of broken slabs can decrease as the slabs are being repaired (and grouped). The number of broken slabs can be misleading when studying the trend of broken slabs. It is also difficult to estimate the slab replacement quantity since a broken slab can be comprised of several small slabs which may have varied lengths.

- There is ambiguity in current distress classification. Currently broken slab severity level 2 covers a wide range of cracked slabs, ranging from a single working transverse crack to severely cracked slab (i.e., multiple cracks). There is a need for additional distress categories to differentiate the distresses in severities.
- There is a need to clarify that faulting measurement should be taken at every 8th original joint to ensure consistent readings.
- A revised faulting index equation is recommended for handling negative faulting readings. Negative faulting readings are discounted in the current faulting index, which results in a lower faulting index that is not representative of the actual condition. There is a need to take the negative faulting readings into account in the faulting index. In addition, negative faulting readings can be checked while they are input, and faulting index calculations can then be more reliable.
- Segment lengths can be standardized and checked for accuracy while being input by electronic means.

2.2 Proposed CPACES Distress Protocol

An enhanced CPACES distress protocol, including 1) slab definition, 2) finer distress categorization, 3) revised faulting index, and 4) CPACES rating, were developed to address many of the issues discussed in the previous section. In addition, data checking rules were recommended to ensure data quality. This section describes the key changes (or modifications) in the CPACES distress protocol.

2.2.1 Slab Definition

It is difficult to keep track of the same slab after partial slab replacement (as observed in the CPACES survey); a slab can be divided into 2-3 sub-slabs, and the joints no longer align at the original location. After consulting with OM, a slab is defined as the area between two consecutive joints regardless if they are original or replaced joints. This design is to make sure the surveyor has a clear and consistent definition during CPACES survey. It is noted that with this slab definition the number of slabs in a mile can increase because of partial slab replacement.

2.2.2 Distress Categorization

In new distress categorization, “broken slab” is divided into three types of distresses to represent the distresses with different severity levels. “Shattered slab” is added to differentiate it with the broken slab because of its severe conditions that require higher priority of treatment compared to the broken slab (e.g., single transverse crack). The three new distress types are described in the following:

- Shattered slab

  A slab with multiple intersecting cracks such that the slab is separated into three or more pieces is categorized as a Shattered Slab. In this category, the concrete block(s) may pop out and pose safety concerns to the road user. There was no shattered slab in CPACES previously. The number of shattered slabs will be counted and recorded; there is no severity level for Figure 2.6 shows examples of shattered slab.

Figure 2.6 Examples of shattered slab

- Corner break

  A crack that occurs at a corner of the slab, running from a transverse joint to the shoulder joint or from a transverse joint to the center longitudinal joint. Corner break is separated from longitudinal and transverse crack because it may deteriorate faster than the other two. This type of distress might lead to pop out. There is no severity level for a corner break. Figure 2.7 shows examples of corner break.

Figure 2.7 Examples of corner break

- Slab with transverse cracking

  A slab with transverse cracking only was considered as a broken slab previously, but it will be termed as transverse cracking now in the new CPACES distress protocol. There are two severity levels: Severity level 1 is categorized as hairline and tight working crack; Severity level 2 is categorized as moving crack, generally wider and may be spalled. Figure 2.8 (a) and (b) shows transverse crack severity levels 1 and 2, respectively.

Figure 2.8 Examples of transverse cracking Severity Levels 1 and 2

2.2.3 Faulting Readings and Faulting Index

Faulting reading should be taken at every 8th original joint using the Georgia Faultmeter. The original joint refer to a joint that is still intact, typically aligns with the joint in the inside lane, as illustrated in Figure 2.9. If a prior repair (slab replacement) goes beyond a joint, then that joint would not be counted for faulting measurement. It is important to make sure the faultmeter is facing in the right direction, especially if it reads many negative values. The minus sign should be included in the readings (e.g., -1, -2, etc.). If the outside lane was replaced, all joints on the outside lane are considered as the original joint. There is no need to align the joint in the outside lane to the joint on the inside lane.

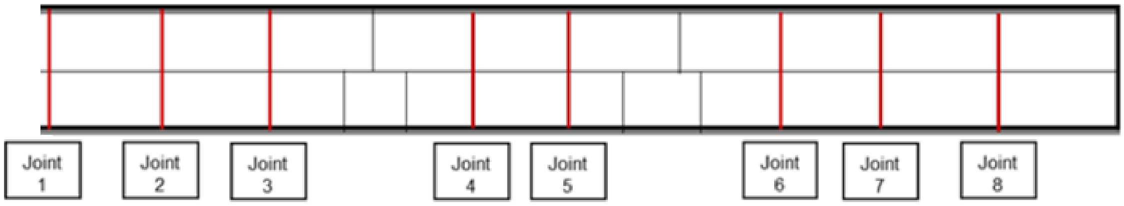


Figure 2.9 Faulting reading taken at 8th original joint

2.2.4 Faulting Index

The negative faulting readings appear to be more common as JPCPs are aging. Thus, a modification was made to the faulting index. It will be computed as five times of the average of "*absolute*" faulting readings, as shown in Equation 2.1, to account for the negative faulting readings.

$$Faulting\ Index = \frac{5}{n} * \sum_{i=1}^{n} |S_i| \qquad \text{Equation 2.1}$$

It is noted that the final faulting index is always rounded to the nearest integer (e.g., 5.09=5 and 5.74=6). The following shows an example of the faulting index calculation. There was a total of 22 faulting readings and the sum of those reading is 36 (1+1+2+2+4+2 +3+5+3+2+1+1+1+3+2+2 +1= 36). Therefore, the faulting index is 8 (36×5/22=8.19 and rounded to 8).

S_i	1	1	0	2	-2	0	4	2	3	5	3	0	0	2	-1	1	1	3	2	2	-1	0

2.2.5 CPACES Rating

A performance rating (CPACES rating) scale of 0 to 100 is computed for each mile based on all the distresses collected, including smoothness. The CPACES rating was modified to include the changes in the distress categorization, as shown in Equation 2.1. It is noted that shattered slab, corner break, and transverse crack severity level 2 are considered the same in terms of deducts. Each of these distresses has a deduct value of 1, which is the same as broken slab severity level 2. Table 3.1 summarizes the maximum deduct value for each distress and Appendix B lists the deduct values for faulting index and smoothness. A "null" values should be assigned to the segments with missing faulting index and/or IRI. This is because 0 deduct will be assigned for missing faulting index and. Thus, a null value will be assigned. This will result in a higher rating that does not represent the actual pavement condition.

Rating = 100 - D_{FI} - D_{SM} – D_{CS} - D_{LC} - D_{SD} - D_{SP}

- D_{FI}: Deduct value for Faulting Index (see Appendix B for the deduct value)
- D_{SM}: Deduct value for Smoothness (see Appendix B for the deduct value)
- D_{CS}: Deduct value for Cracked Slabs

  $D_{CS} = \frac{\#Transverse\ Crack\ Level\ 1}{2}$ + #Transverse Crack Level 2 + #Shattered Slab + #Corner Break

  If $\frac{\#Transverse\ Crack\ Level\ 1}{2} > 15$ Then $\frac{\#Transverse\ Crack\ Level\ 1}{2} = 15$

  If $D_{CS} > 30$ Then $D_{CS} = 30$

- D_{LC}: Deduct value for Longitudinal Cracks

  D_{LC} = 0.25 * #Longitudinal Cracks Slabs Level1 + 0.5 * #Longitudinal Cracks Slabs Level 2

  If $D_{LC} > 20$ Then $D_{LC} = 20$

- D_{SD}: Deduct value for Shoulder Distress

  D_{SD} = 0.1 * Percentage of Shoulder Distress Level1 (%) + 0.2 * Percentage of Shoulder Distress Level2 (%)

If $D_{SD} > 10$ Then $D_{SD} = 10$

- D_{SP}: Deduct value for Spalls

  D_{SP}=0.25 * #Spalled Joints

  Note: Failed Spalled Joints are counted along with Spalls.

Table 2.3 shows the current maximum deducts along with the distress conditions to reach the maximum deducts.

Table 2.3 CPACES maximum deduct values and distresses

	Max Deduct	Distress values and deduct points
D_{FI}	25	FI<5 (Average faulting of 1/32”) has no deduct points. Maximum average considered is 5/32” (FI=25).
D_{SM}	40	IRI<900 mm/km has no deduct points. The smoothness deduct value goes to 30 (Rating = 70) between 1900 and 2000 mm/km.
D_{CS}	30	At 17% cracking (30/176 slabs) the deduct value maxes out at 30. Therefore the rating can only go to 70 with just Cracked Slabs.
D_{LC}	20	At 23% cracking (40/176) the deduct value maxes out at 20, therefore the rating can only go to 80 with just Longitudinal Cracks.
D_{SD}	10	Shoulder distress is only considered to go up to 50% of the length.
D_{SP}	10	At 46% spalled joints (160/352) the deduct value maxes out at 10, therefore the rating can only go to 90 with just Spalled Joints.

Table 2.4 shows an example of a CPACES rating calculation. A segment with a faulting index of 14, smoothness of 1300 mm/km, 3 cracked slabs, 8 longitudinal cracked slabs, spalls, and shoulder distress has a rating of 71. It is noted that the deducts were developed in the 1990s based on the pavement condition at that time. The deducts need to be further validated based on current pavement condition and MR&R practices.

Table 2.4 An example of rating calculation

		Value	Deduct
Faulting Index (1/32 in.)		14	11
Smoothness (mm/km)		1300	4
Cracked Slabs	Level 1	2	1
	Level 2 Trans and SS and CB	1	1
Long Cracks	Level 1	5	1
	Level 2	3	2
Shoulder Distress	Level 1	10	1
	Level 2	28	6
Spalls		6	2
Rating		100-11-4-1-1-1-2-1-6-2=71	

2.2.6 Data Checking

Based on the historical CPACES data, it is suggested to include the following data checking procedures during data entry to ensure data quality.

- The milepost from and to should be checked for the length since a segment should be approximately 1-mile long.
- The faulting reading should not be greater than 19 or less than -19, which is the largest value that can be read by the Georgia faultmeter. A reminder should be provided for a value of 16 or more (or less than -16), since that would be equivalent to a discernable (½ inch) difference in elevation.
- A reminder (i.e., a pop-up message) should be given to negative faulting readings. Although negative faulting readings are possible, it is often caused by placing the Georgia faultmeter in the opposite direction.

- A reminder (i.e., a pop-up message) should be given to an IRI less than 800 mm/km or greater than 2400 mm/km because such values are improbable.

2.3 Summary

The current CPACES survey practices were critically reviewed through field observation, discussion with the survey crew, and review of historical CPACES data. Issues such as slab definition, distress classification, negative faulting readings, faulting index, inconsistent rating, etc. were identified. An enhanced CPACES distress protocol, including refined slab definition, additional distress categorization, refined faulting index calculation, and data checking, was developed to address many of the identified issues. The following changes are recommended for the future implementation of the enhanced CPACES distress protocol.

- Update the CPACES manual to include the additional distress categorization, the change in slab definition, and other modifications;
- Develop a data collection module to implement the changes in faulting index, rating, and data checking and to ensure quality data. Apply to larger data set (more than 1 mile), especially apply to the incoming JPCP slab replacement plan and projects; and
- Conduct training on the data collection module and modified CPACES manual.

3. ANALYSIS OF HISTORICAL CPACES DATA

This chapter presents the analyses of historical CPACES data, including rating, faulting index, broken slab, etc., to get insight into JPCP condition in Georgia, especially the condition and MR&R needs based on FY 2015 data and the predominant distresses. Historical CPACES data was carefully reviewed and processed to obtain consistent and quality data for the analyses. Data with missing or invalid data was removed. The faulting indexes were recalculated, including counting the number of faulting readings and recalculating the index based on the modified faulting index definition that takes the negative faulting into account. Finally, the ratings were recalculated to ensure the consistency. The processed data were analyzed and presented in this chapter.

3.1 JPCP Condition in FY 2015

The analysis of most recent CPACES data is presented in this section to provide an assessment of the JPCP condition at network level. Although there were data collected in FY 2016, the total surveyed-miles (422) were much less than ones reported in other years. Thus, the data collected in FY 2015 was analyzed. There were errors found in data, including the duplicated records (data recorded more than once at the exact same location), errors in milepost (e.g., MP 240 to MP 25), errors in identifying if a roadway section was an Interstate or non-Interstate. There errors were noted and rectified; after remedying these entry errors, the 2015 data included 820 records for a total of 792 surveyed-miles. A total of 792 miles of JPCPs were surveyed in FY 2015, including 178 miles of non-interstate and 614 miles of interstate, with a composite rating of 79. It is noted that there was no data in Districts 6 since FY 2014. Figure 3.1 shows the rating distribution by percent mileage. The majority (78%) of the surveyed JPCPs had a rating of greater than 70; approximately 22% (176 surveyed-miles) of JPCPs had a rating less than 70. Based on GDOT's rating criteria, these pavements were due or past due for maintenance. It is noted that 15% (119 surveyed-miles) of the JPCPs actually had a rating less than 60. This implies more extensive work, such as major rehabilitation, may be needed for the segments with low ratings.

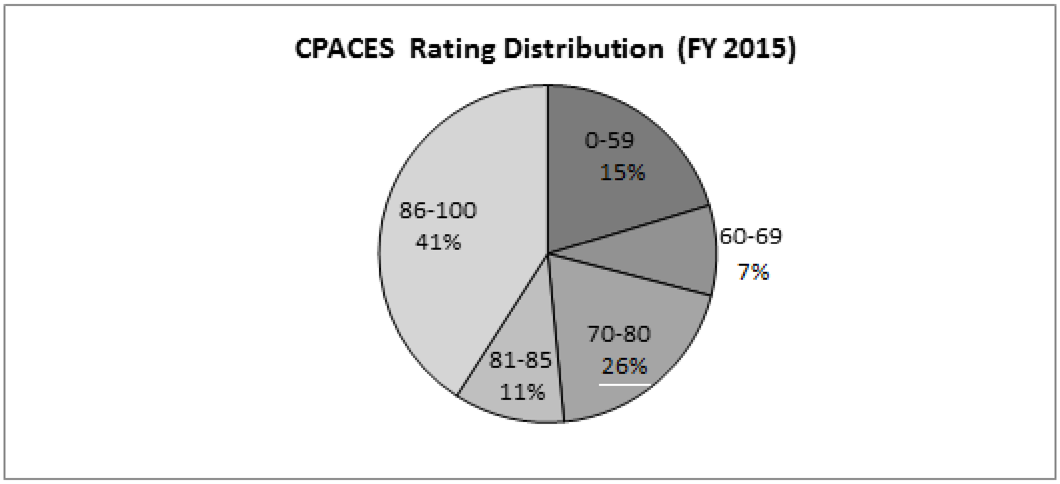


Figure 3.1 CPACES rating distribution (FY 2015)

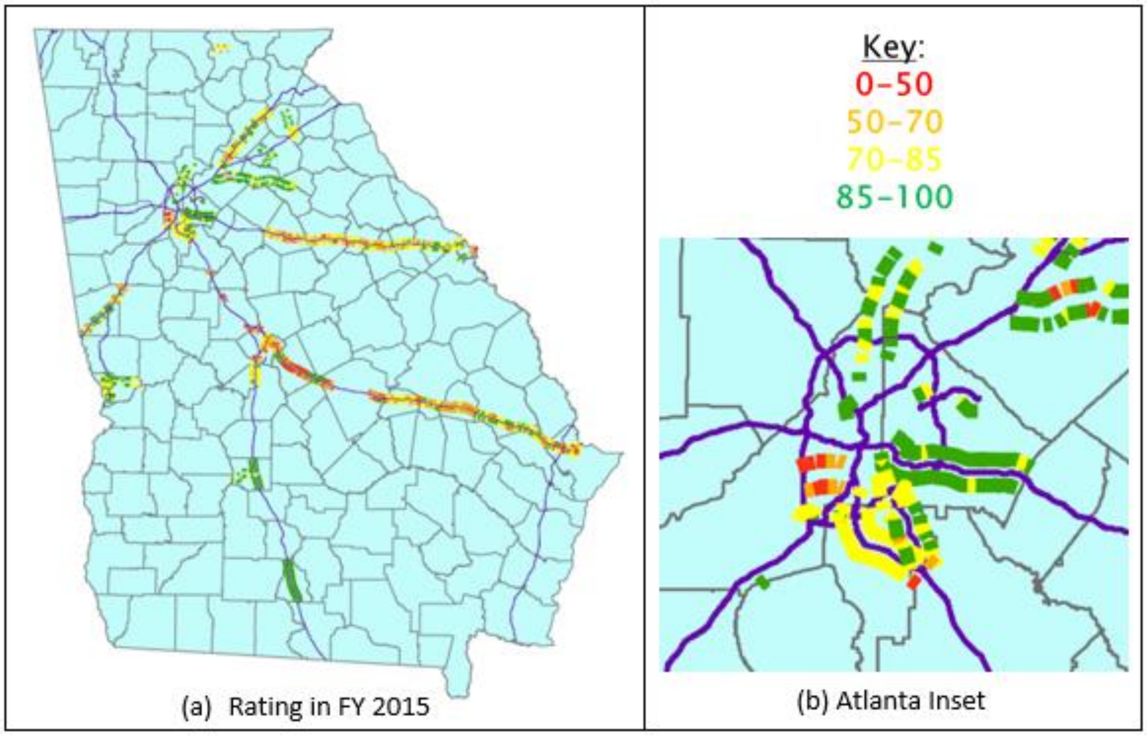
Table 3.1summarizes the JPCP condition by district. Different criteria, including a rating less than 70, the number of broken slabs severity level 2 greater than 10, a faulting index greater than 15, were applied to the data to provide an estimate of the maintenance need. As shown in Table 3.1 , District 2 and 3 have the highest percentage (34%) of miles under a 70 rating and the highest percentage (42% and 31%) of miles with faulting index greater than 15, while District 5 has the highest percentage (16%) of broken slab severity level 2 greater than 10. This follows expected trends since I-16 (which is an original interstate over 40 years old, and is predominately an undoweled pavement) is in District 2, 3 and 5, which was noted earlier as accounting for about half the segments below 70.

Other data was not as clear; looking closer at District 7 data provided some concerns. Of the 60 miles in District 7, not one has any broken slabs (level 1 or 2) and only 4 have very minor longitudinal cracking (severity level 1). In addition, negative faulting readings were observed in the data; 99% of the faulting readings were negative. The high traffic volume in the District 7 area is not very conducive to low speed, traffic disturbing rating using manual methods, which may account for the anomaly. The number of level 2 broken slab and longitudinal crack are also summarized to provide an estimate of the MR&R need. District 5 had the highest number of broken slabs (425); most of them are on I-16. District 2 had the extremely high number of longitudinal cracked slabs (787) compared to the other districts; many of them were reported on I-20. Note that the number of broken slab and longitudinal cracked slabs can be greatly affected by the definition of a slab. It is important to ensure a consistent definition is used by all districts for a comparison among the districts. Figures 3.2, and 3.3 show the spatial distribution of the rating and IRI based on the data collected in FY 2015. This map confirms that the majority of the network is in relatively good condition (considering >5% cracking or >8 slabs BS2 [5% of 176, for 30ft slabs] cracked as the limit for good). CPACES data collected in FY 2015 was also reviewed closer for individual distresses. Spalling was identified as the most common distress in FY 2015 at the same percentage (50%) of segments identifying at least one spalled joint in 2015. Similarly, broken slab severity level 1 (49%) was also the most common cracking type in FY 2015 and followed by longitudinal crack severity level 1 (44%).

Table 3.1 CPACES distresses by district

District	1	2	3	4	5	6[a]	7	Total
Total Surveyed-Mile	210	182	157	26	157		60	792
Composite Rating	85	73	74	91	80		83	79
Rating < 70 (%/surveyed-miles)	11% (22)	34% (61)	34% (53)	0	18% (29)		18% (11)	22% (176)
FI > 15 (%/surveyed-miles)	4% (9)	42% (76)	31% (48)	0	24% (38)		2% (8)	23% (179)
BS2 > 10 (%/surveyed-miles)	4.5% (9.5)	0	5% (8)	0	10% (16)		0	4% (33.5)
# of BS2	359	226	288		425		0	
# of LC 2	180	787	219	1	240		0	

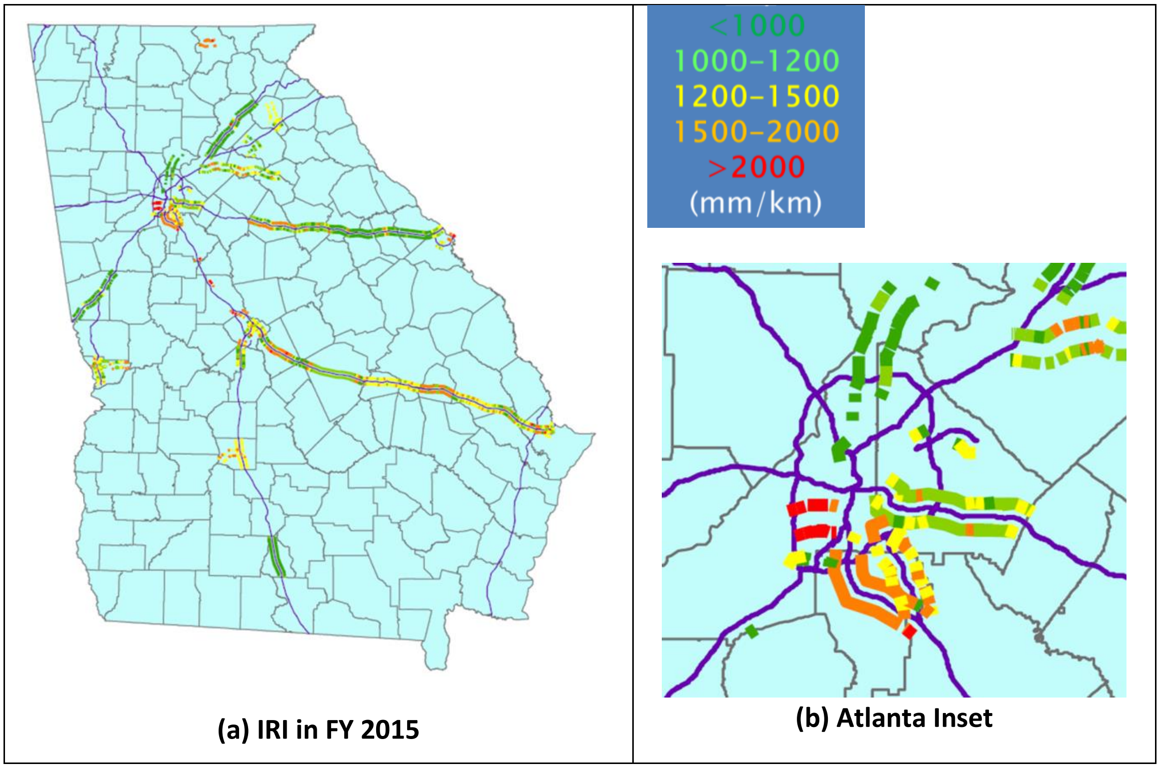
a: There was no data in District 6.



(a) Rating in FY 2015

(b) Atlanta Inset

Figure 3.2 CPACES rating in FY 2015



(a) IRI in FY 2015

(b) Atlanta Inset

Figure 3.3 IRI in FY 2015

3.2 JPCP Condition Trends

3.2.1 Predominant Distresses

The historical CPACES data collected from 2000 to 2015 was reviewed to address the type of distresses that were most commonly identified. Over 50% of the entries identified at least one spalled joint, by far the most common distress. The next most common distresses identified were Broken Slab, Severity Level 1 (BS1) at 42% of all entries and Longitudinal Crack, Severity Level 1 (LC1) at 37%. BS2 and LC2 were identified in 22% and 16% of the sections respectively. These values were for all entries in the database. As a comparison, the total number of distresses per mile and percent of distresses per mile by year, separated by Interstate and Non-Interstate, are shown in Figure 3.4and Figure 3.5. BS1 and BS2 are more common on the Interstate than on the non-Interstate routes, while LC1 is a large portion of the identified distresses on both the non-interstate and interstate roadways. It is also clear that the number of distresses per mile is higher for the Interstates as a whole, varying from a total of 8 to 16 per mile as compared to less than 8 for non-Interstates. Pavement age is most likely the cause of this difference, while design may also pose a factor, especially between longitudinal (LC) and transverse cracking (BS). A number of truck lane replacements were completed in recent times, but much of the concrete pavements, especially on the interstate, are nearing 50 years old and were originally placed without the benefit of dowels.

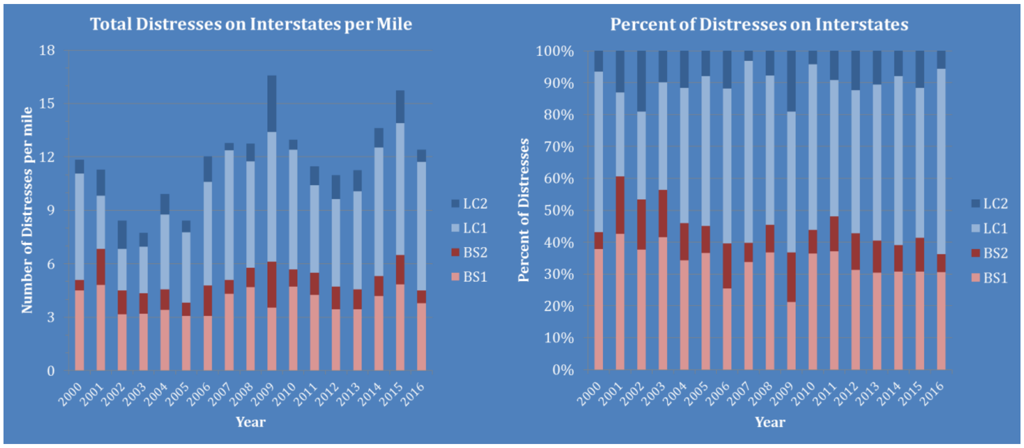


Figure 3.4 Interstate distresses 2000-2015

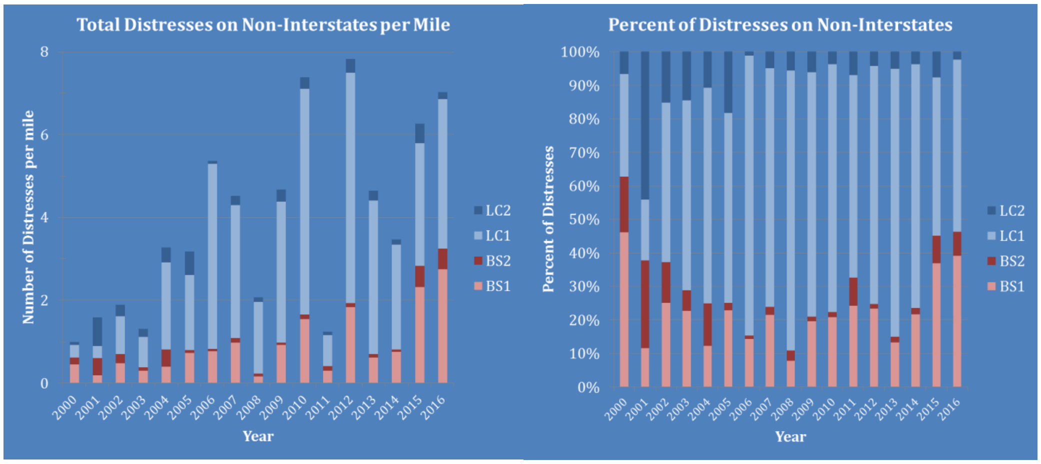
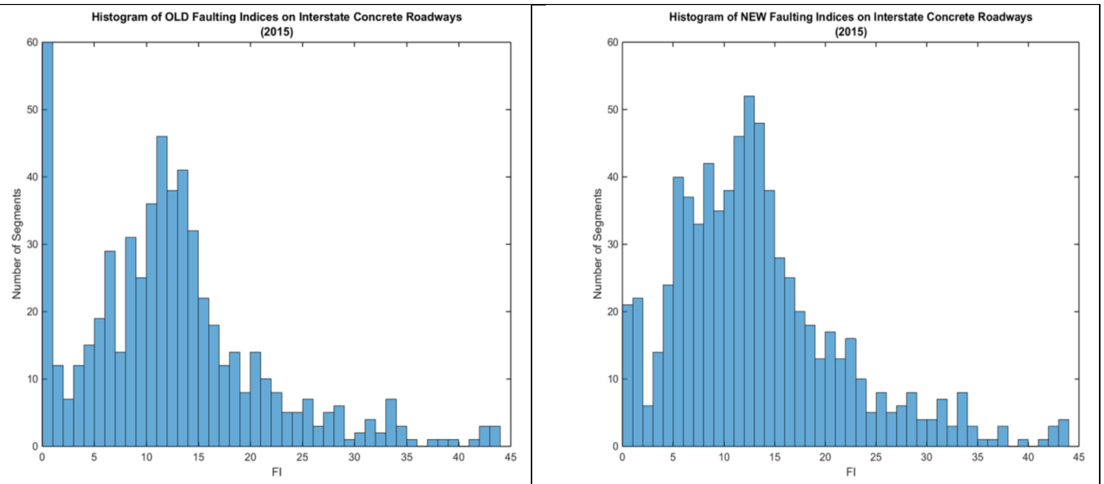


Figure 3.5 Non-interstate distresses 2000-2015

3.2.2 Faulting

This section presents the analyses on faulting index at both network and segment level. As noted previously, negative Faulting Index entries were encountered in the historical CPACES. Figure 3.10 shows the distributions of the original and revised faulting index that was recalculated based on the “absolute” faulting readings using Equation 2.1. The revised faulting index clearly reduces the number of faulting index values of 0. It also increases the mode (most common) value about 2 faulting index values, but also maintaining a similar overall distribution and maximum value.



(a) Original faulting index

(b) Revised faulting index

Figure 3.6 Faulting index distribution (original vs. revised)

A summary of the average faulting index by year is presented in Table 3.2. It shows a steady average faulting index about 9 from 2000 to 2005; this can be attributed to the MR&R conducted in the late 1990s. The faulting index increased from 2006 to 2008 and decreased from 2008 to 2016. It is noted that the average faulting index values presented in Table 3.2 are affected by the MR&R, such as full lane replacement and diamond grinding. The segments on I-16 (MP 24 – 58) contributed the most in the faulting index increase from 2006 to 2008. These segments were under construction; thus, there was a downward trend observed from 2008 to 2016. In addition to the full lane replacement, slab replacement and diamond grinding were applied on many locations on I-16. Figure 3.7 shows the faulting index and rating by year. The faulting index, shown on the right axis, only varied from 8.2 to 12.3 from 2000 to 2016, while the CPACES overall rating varied from 88 to 78. The figure shows the inverse relationship between faulting index and CPACES rating. The average CPACES rating was a low of 78 in 2007, while the faulting peaked above 12 in 2007. Rehabilitation/replacement of older concrete pavements is evident in the time period from 2010 to 2016 as the CPACES rating increased and the faulting index dropped. During this same time period, individual faulting of the segments varied with faulting index values from the minimum of 0 up to 50, or an average of 5/16 inch of faulting per mile. Figure 3.8 also provides another view of the faulting index. At this scale the average appears very stable but the maximum shows drastic changes and peaks and plateaus, and the 66 percentile shows the difference in the variation of the faulting index.

Table 3.2 Faulting index by year

Year	Average CPACES rating	Average Faulting Index
2000	84	9.8
2001	88	8.4
2002	87	8.9
2003	88	8.2
2004	85	9.0
2005	84	8.8
2006	83	10.0
2007	78	12.1
2008	79	12.3
2009	80	12.2
2010	79	11.1
2011	79	11.5
2012	79	10.7
2013	81	10.5
2014	83	9.4
2015	79	11.8
2016	85	8.7

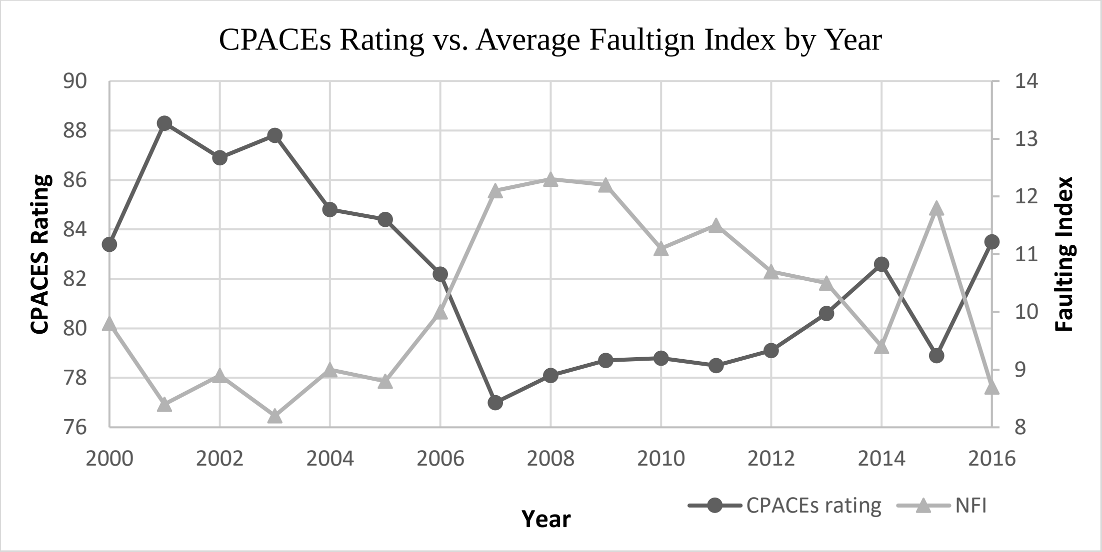


Figure 3.7 Average faulting index and CPACES rating by year

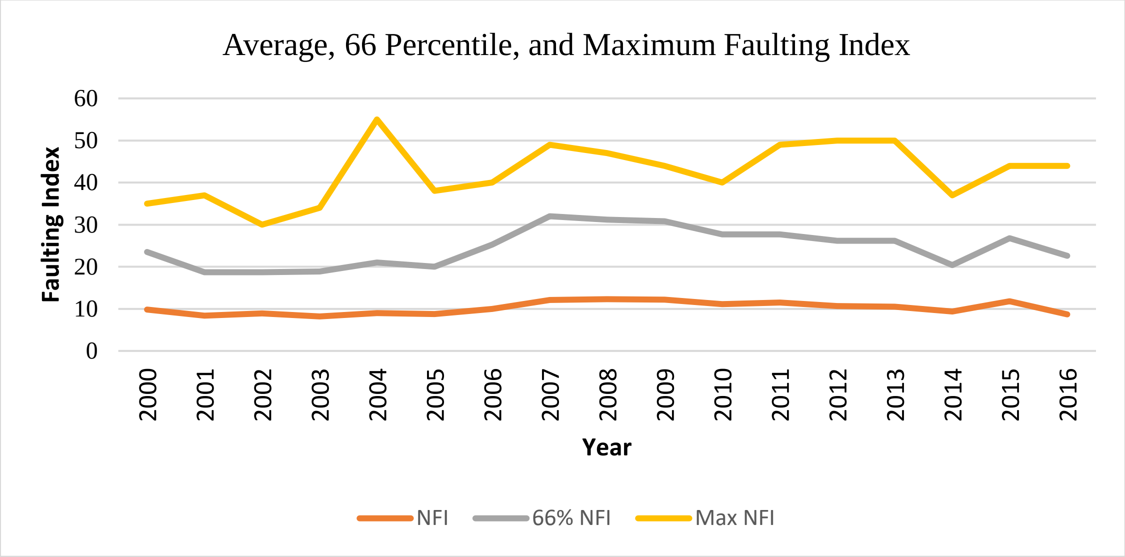


Figure 3.8 Average, 66 percentile, and maximum faulting index

Because the network-level faulting index trend does not represent the natural faulting deterioration without the interference of MR&R, the faulting index was studied on selected segments without MR&R (e.g., lane replacement and diamond grinding that remove fault) to provide insight into the faulting deterioration. Three segments on I-16 (MP 13 to MP 15) were studied. The time series faulting index, as shown in Figure 3.9, shows the faulting indexes increased or remained stable with age. However, there were questionable time series trend of faulting index, i.e., decreasing with time (e.g., MP 13 2007 to 2008 and MP 14 2012 to 2013), was observed. The decrease can be attributed to the change in faulting sample locations within the segment, minor maintenance such as joint patch, different temperatures when the faulting was measured, etc.

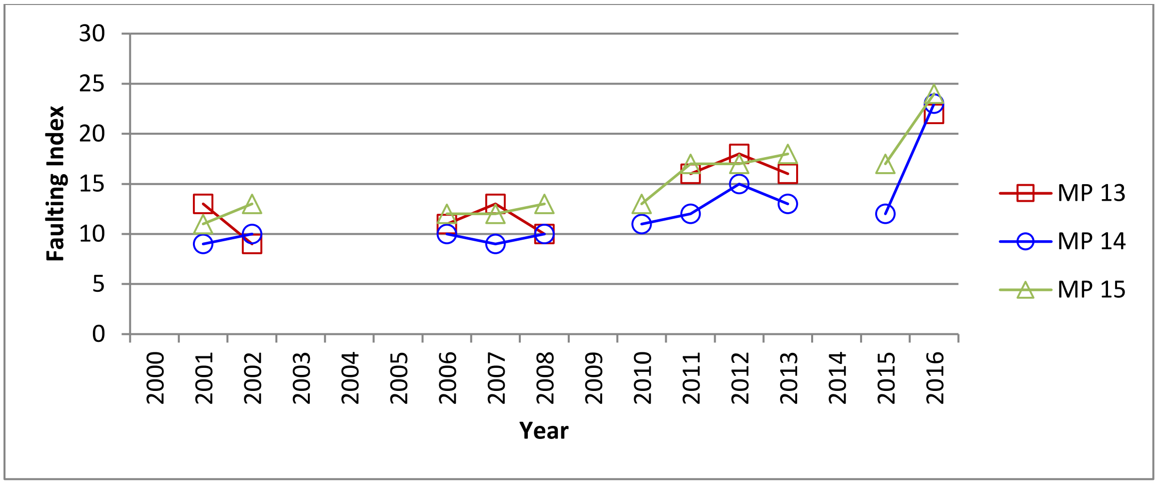


Figure 3.9 Faulting index on I-16 (MP 13, MP 14, MP 15)

Georgia has evolved their pavement designs for concrete pavements over time. Previous DOT research projects have identified four different categories of pavement designs that have been historically used:

- ND, 1960-1970: non-doweled 9-10 inches (23-25 cm) of JPCP on top of an 8-inch (20 cm) soil with the top 3 inches (7.6 cm) stabilized with a cutback or emulsion asphalt, or a soil cement base, and a 30-ft (9.1 m) joint spacing.
- ND-IB 1970's: non-doweled JPCP with a cement stabilized Graded Aggregate Base (GAB) or soil cement, a variation of joint spacing (e.g., random) and joint orientation (e.g., skewed).
- D-IB late 1970's-1980s: doweled JPCP on GAB, with a joint spacing of 20-ft (6.1 m) or 30-ft (9.1 m).
- D, Current deign of doweled 11 or 12 inch JPCP on a 3 inch HMA interlayer over 12 inches of GAB, with 15 ft. joint spacing is used on all Interstates. Concrete pavements on state routes can vary from 10 inches to 12 inches JPCP on 10 inches to 12 inches GAB.

The effect of design feature (e.g., dowel bar) on the faulting index values was also investigated. Previous studies have indicated a major influence of dowel bar use on the reduction of joint faulting (Gulden and Thornton, 1985; Foxworthy and Darter, 1985; ARA, 2016). Data on the pavement type and construction year of the pavement was developed from a historical evaluation of the Interstate pavements, in conjunction with typical sections identified in old plans. This information was added to the CPACES data to differentiate the different designs. Doweled pavements are expected to last longer, have less faulting and perform better overall than non-doweled pavements. From the database it was identified that all pavements identified as being constructed after around 1973 were doweled, and all 1973 or before were non-doweled. The average CPACES rating for all doweled pavements in 2015 was 84.3 and the average faulting index was 9.7. The average CPACES rating for non-doweled pavements was 75.3 with an average faulting index of 13.8. Doweled pavements that had the lowest ratings included portions of State Route 316, which has been identified as having alkali-silica reaction (ASR), a materials related distress.

3.2.3 Broken Slab

The data was also analyzed to identify the average number of BS2 that were identified per mile of collected pavement, per year. The BS2 average varied from 0.82 BS2/mile up to 1.02 BS2/ mile with large variations (ranging from 3 to 9). As shown in Figure 3.10, the trend was not totally consistent, with the lowest values occurring in 2004 and 2007. There does appear to be a slight increase in the average BS2 per mile when comparing between the 2000 to 2008 timeframe and the 2008 to 2016 timeframe overall. For other distresses, at least one replaced slab was identified in over 30% of the data collected. A failed replaced slab was only identified in 6% of the segments.

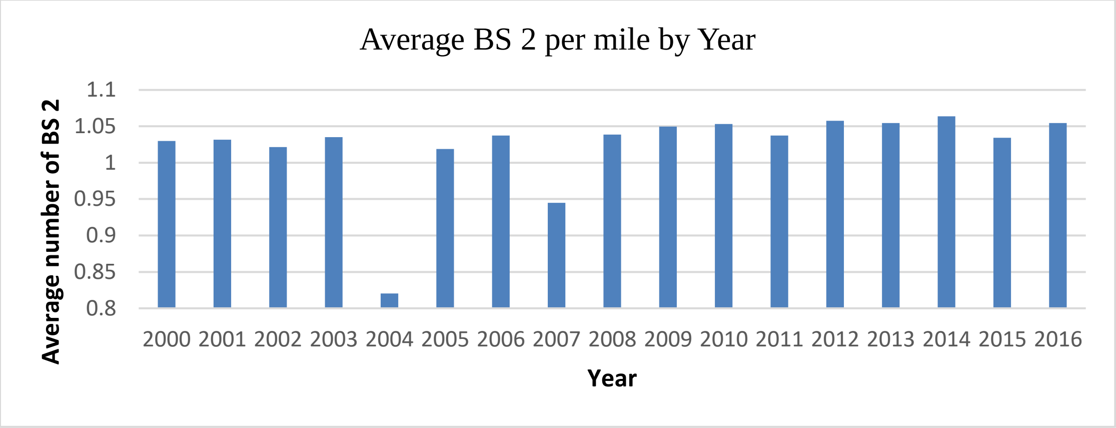


Figure 3.10 Average broken slab severity level 2 per mile

As noted earlier, BS1 is the most frequent cracking distress in the database, followed by LC1. The most highly distressed sections for any time period are sections of I-20 and I-16 for broken slabs and predominately I-20 for longitudinal cracking. These are also understandably some of the oldest concrete pavements. Partly due to the effect of GDOT's proactive history of replacing slabs, the number of broken slabs or longitudinal cracked slabs identified in a section of pavement does not always show a consistent trend. As an example, data on two segments on I-20 (MP 15 to MP 16) for BS and LC is shown in Table 3.3. No clear trend of increased distress can be identified. It also appears that slabs that were identified previously as broken slabs were identified as longitudinal cracked slabs in 2003, 2005 and 2012. Even with considering the replaced slabs the values over time do not form a logical progression. If location of the distressed slabs were also captured, it could assist in identifying if slabs were misidentified or repaired. As shown in Table 3.3 by the Total Cracked Slabs column, even adding up all the cracked slabs still does not provide a clear trend over time. Besides the effect of repaired slabs, the manner in which slabs are counted can lead to discrepancies. The windshield survey that was the source of the data is fraught with issues such as: difficulty in assessing and recording the data at a traveling speed, other vehicles interfering with the ability to see distresses, lighting and shadows obscuring views, and the natural subjectivity of a manual windshield survey. Therefore, it is difficult to study the broken slab deterioration using the CPACES data. 3D laser data that is capable of providing detailed distress information on each slab is recommended for studying the crack deterioration on JPCPs.

Table 3.3 Cracking history for I-20 MP 15-16 EB

	Broken Slabs Level 1	Broken Slabs Level 2	Long. Cracks Level 1	Long. Cracks Level 2	Replaced Slabs	Total Cracked Slabs
2000	24	0	0	0	7	24
2001	26	20	0	0	9	46
2003	9	0	33	0	5	42
2004	61	9	5	0	9	75
2005	2	0	28	0	0	30
2010	12	59	0	0	0	71
2012	5	0	7	23	2	35
2014	20	1	2	0	14	23

4. ENHANCED SLAB REPLACEMENT QUANTITY ESTIMATION USING 3D LASER DATA

There is an increasing need for jointed plain concrete pavement (JPCP) slab replacement because of the aging JPCP in Georgia. This situation and limited highway budgets have highlighted the need for an accurate and effective slab replacement estimate method, which is crucial for reliable budget planning and to prevent from project overruns (Crossett and Schneweis, 2011; Anderson et al., 2007) and, also, for slab replacement programming during construction. Unlike resurfacing on asphalt pavement, which treats the entire segment or project, slab replacement is applied on a slab-by-slab basis to remove and replace individual distressed slabs. Currently, GDOT, like many of its counterparts, uses a windshield inspection to manually identify distressed slabs and estimate the JPCP slab replacement quantity (i.e., area of slabs to be replaced). However, a windshield inspection is time-consuming, labor-intensive, and sometimes dangerous because of high volumes of traffic; more importantly, the windshield inspection cannot provide accurate quantity estimates, especially when there are many distressed slabs and existing replaced slabs. With emerging sensing technologies, including 3D laser technology, and GPS/GIS technologies, and with automatic extraction of distresses, many pavement distresses, including cracking and faulting, can now be extracted using 3D laser data (Ritchie et al., 1991; Oliveira and Correia, 2013; Tsai et al., 2014; Tsai et al., 2013; Lettsome et al., 2012; Tsai et al., 2012). Consequently, GDOT has taken the initiative to explore new method(s) to enhance its practices for achieving reliable planning and budgeting by leveraging emerging 3D sensing technology in its pavement condition evaluation of JPCP and slab replacement quantity estimating. This chapter presents an enhanced method that can safely, effectively, and accurately determine the exact extent of slab replacement and calculate the slab quantity based on detailed, slab-level distress information extracted from 3D laser data. This information can also be used for guiding the slab replacement during construction because the exact locations of distressed slabs are available.

4.1 Review of Slab Replacement Quantity Estimation Practices

Slab replacement (or full depth repair) is one of the most common treatments for repairing distressed (or cracked) slabs. Its purpose is to replace cracked slabs when much of the remaining pavement is still in good condition. Unlike resurfacing on asphalt pavement, which treats the entire segment or project continuously, slab replacement is applied on a slab-by-slab basis to remove and replace only distressed areas on individual slabs. Slab replacement typically covers a full lane-width at full depth, but the extent (in terms of length) can vary (FHWA, 2005). Full slab replacement refers to an entire slab that is replaced, while partial slab replacement replaces only a portion (in length) of the slab being distressed (FHWA, 2005; Zollinger et al., 2001). Figure 4.1 illustrates how a 6-ft partial slab replacement can be used to replace a distressed area on a 30-ft slab. Thus, the quantity estimation for slab replacement is more complicated than a resurfacing project. It requires 1) identifying the distressed slabs (i.e., broken slab severity level 2) for slab replacement, 2) determining the extent (in length) to be replaced, and 3) estimating the quantity.

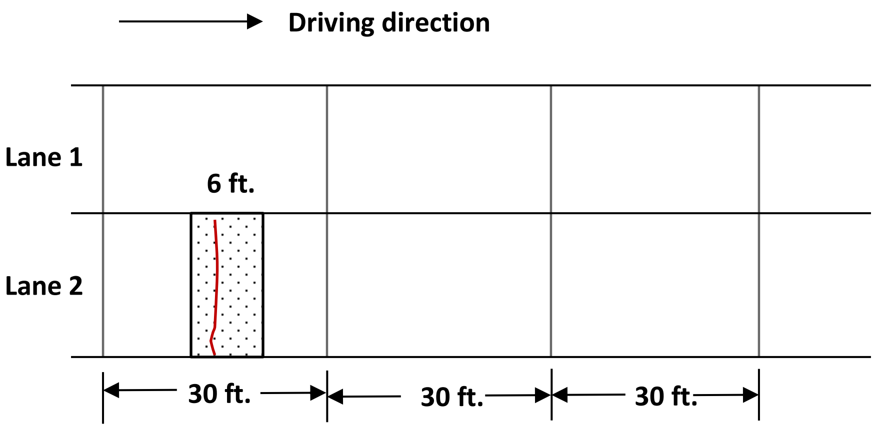


Figure 4.1 An example of partial slab replacement

Currently, GDOT uses a windshield inspection to identify distressed slabs and to estimate the JPCP slab replacement quantity (GDOT, 1993; Attoh-Okine and Adarkwa, 2013). Based on the interviews with District 7, a crew consisting of 2-3 engineers drives at slow speeds (e.g., 20-25 mph) in a lane to estimate the slab replacement quantity using a visual inspection. A buffer truck follows the van to provide safety. During the windshield inspection, an engineer needs to make several decisions, including identifying the distresses on the slab, determining if the distresses warrant a slab replacement, determining if a full or partial slab replacement is required, and counting the number of full and partial slab replacements in each mile of roadway. It is unlikely that the engineers can determine the exact extent (e.g., length) for each slab replacement; thus, the quantity is estimated using an average length for full and partial slab replacement. For example, if the original joint spacing is 30 ft., then 30 ft. and 15 ft. are used for full and partial slab replacement, respectively. The engineer counts the full and partial slab replacement in each 0.25-mile for each lane and estimates the quantity for slab replacement. It took a 5-person crew one week to conduct a slab replacement estimate on a 144-lane-mile project on I-285 in Atlanta, Georgia. Such a windshield inspection is time-consuming, labor-intensive, and sometimes dangerous. It is likely to interfere with traffic due to low-speed (e.g., 20-25 mph) of survey vehicles on interstate highways. More importantly, the windshield inspection cannot provide accurate quantity estimates, especially when there are many distressed slabs and existing replaced slabs. Because the exact extent of slab replacements is not available, during construction, the project engineer typically conducts a walk through to identify the exact extent/need; from this assessment, the full and partial slab replacement are constructed and the quantity is measured. Consequently, there is usually a difference between the estimated and actual slab replacement quantity. There is a need for an enhanced method that can effectively and accurately estimate the quantity for slab replacement.

4.2 Proposed Method

This section presents the proposed method for determining the exact extent of slab replacement and calculating the quantity based on the detailed slab-level distress information extracted from 3D laser data. The proposed method consists of the following: 1) acquiring 3D laser data; 2) extracting and classifying slab-level distress information based on GDOT’s Concrete Pavement Condition Evaluation System (CPACES) (GDOT, 1993); and 3) determining the exact extent of full and partial slab replacement and calculating the quantity based on an agency’s criteria and construction practices.

4.2.1 Acquiring 3D Laster Data

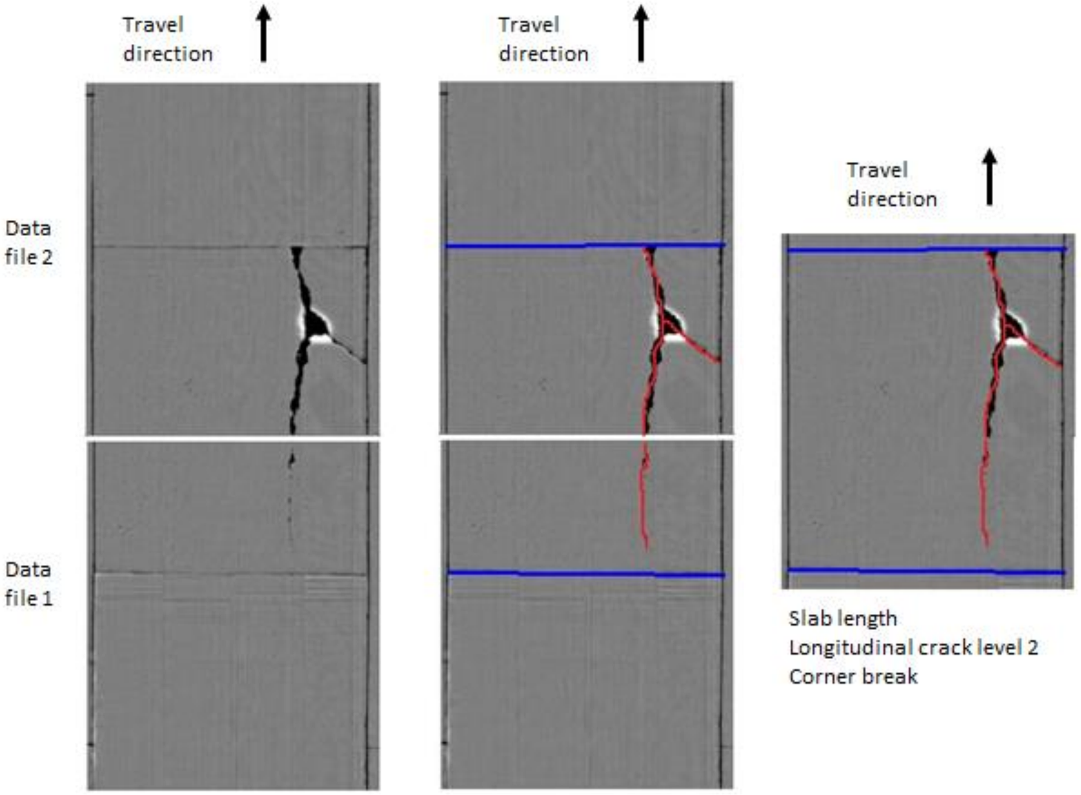
The first step is to collect high-resolution 3D laser data of the JPCP to provide data that has a high level of granularity; this will support the extraction of essential pavement distress information for JPCP, such as cracking, faulting, etc. In the research project entitled "Remote Sensing and GIS-Enabled Asset Management System (RS-GAMS)," sponsored by the US DOT, an intelligent GA Tech sensing vehicle (GTSV) has been developed by integrating a 3D laser system, a global positioning system (GPS), 2D image cameras, two LiDAR systems, an inertial measurement unit (IMU), and a high-resolution distance measurement instrument (DMI). The GTSV, as shown in Figure 4.2(a), was used to collect JPCP data at highway speed without interfering with the traffic flow. With a line scan rate of 5,600 profiles per second, the system can provide a resolution of 1-mm (~0.04 in) in the transverse direction and 5-mm (~0.2-inch) in the longitudinal (or travel) direction at a speed up to 100 km/hr (62.5 mph) (Tsai et al., 2012). On a 30ft slab on I-285, approximately 7.3 million 3D points can be collected; detailed distress information can be extracted from this set of data. Figure 4.2 (b) illustrates the 3D data collected near a joint. The 3D laser data can achieve 0.5-mm accuracy in the z-direction.

(a) GA Tech sensing vehicle (b) Example of 3D laser data

Figure 4.2 Acquiring 3D laser data

4.2.2 Extracting and Classifying Distress Information at Slab-level

The second step is to automatically extract crack and joint data from the high-resolution 3D laser data and classify the slab condition based on GDOT's CPACES (GDOT, 1993) to support slab replacement decisions. 3D laser data has been used for detecting cracks in asphalt pavement (Ritchie et al., 1991; Oliveira and Correia, 2013; Tsai et al., 2014; Tsai et al., 2013; Lettsome et al., 2012). In this study, cracks and joints were extracted from the 3D laser data collected every 5 m based on the detection methods developed in previous studies (Tsai et al., 2014; Tsai et al., 2013; Lettsome et al., 2012; Tsai et al., 2012). Figure 4.3(a) and (b) show examples of the 3D laser data and the extracted joints and cracks, respectively. As shown in Figure 4.3 (b), joints were distinguished from cracks based on their unique characteristics, including their length (covering a full lane width), orientation, and straightness (a straight line compared to a crack). Thus, prior information on the joint spacing is not needed for detecting the joints. The data from the cracks and joints extracted from the 3D laser data were then integrated using their topological information to determine joint locations, define slabs, and identify distresses (e.g., cracks, faulting, etc.) on individual slabs. Figure 4.3 (c) shows the slab (between two consecutive joints) and the distresses on the slab after the integration. This process is vital for obtaining slab-level distress information, which supports slab classification and decisions on slab replacement. Fundamental crack properties, such as length, width, location, orientation, and type, were recorded for the cracks on individual slabs. Figure 4.4 shows the complete crack elements defined in the crack fundamental element model (Tsai et al., 2014). Finally, each slab is classified into a distress type and severity according to GDOT's CPACES (GDOT, 1993) to mimic its pavement condition evaluation. Based on GDOT's concrete distress manual and inputs from engineering representatives, crack orientation is used to classify the distress type. The width and length are further used to classify the distress severity levels. Table 4.1 summarizes the key characteristics used for classifying the slab.



(a) 3D laser data (b) Detected cracks and joints (c) Slab-level distresses

Figure 4.3 Extracting and classifying distresses at slab level

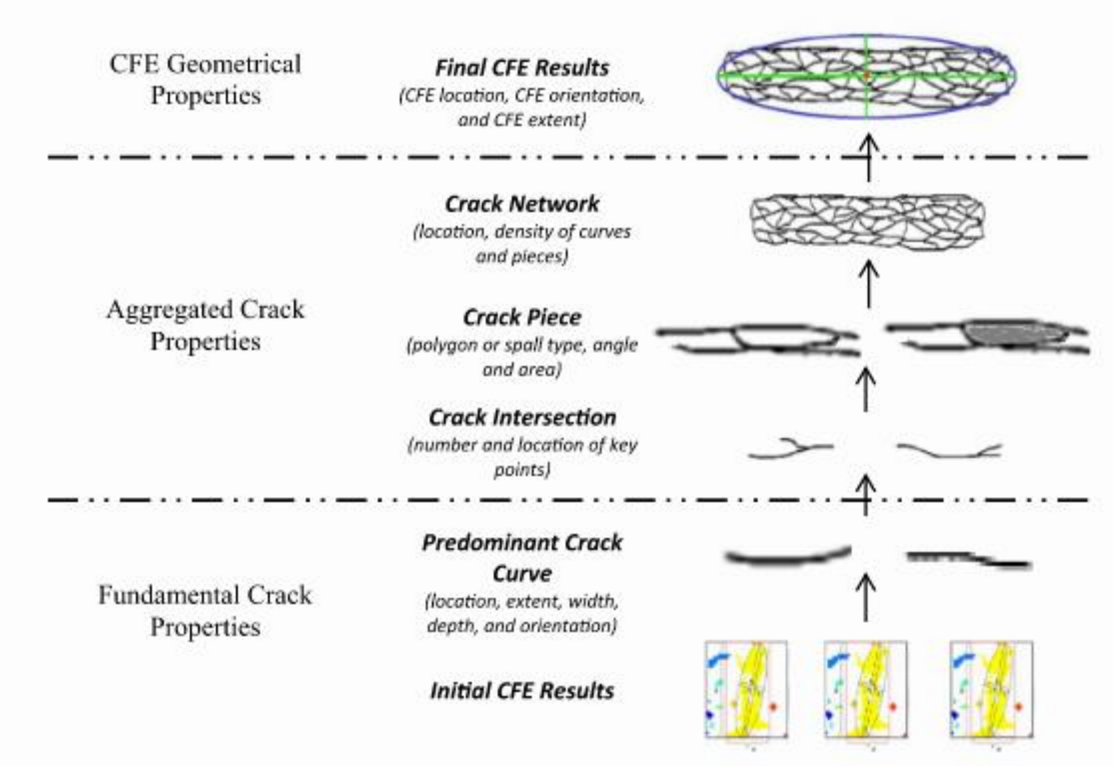


Figure 4.4 Multiscale crack characteristics inside each crack fundamental element (CFE) (Tsai et al., 2014)

Table 4.1 Key Characteristics of slab classification

Distress Type	Key Characteristics		
		Level 1	Level 2
Longitudinal Crack	L length/T length>3	Width < ¼”	L length > 10 ft. Width > ¼”
Broken Slab	Transverse Crack L length/T length< 1/3	Width < ¼”	T length > 75% of SLength Width > ¼”
	Corner Break 1/3<L length/T length< 3	Crack faulting < ¼”	Crack faulting >= ¼”

T length: crack extent in transverse direction
L length: crack extent in longitudinal direction
S length: slab length

4.2.3 Determining Extent of Slab Replacement and Calculating Quantity

This step is to determine the exact extent of slab replacement for individual slabs based on the slab-level distress information; it is also to calculate the slab replacement quantity. This involves 1) identifying slabs to be replaced based on GDOT's criteria (e.g., broken slab Level 2), 2) determining the exact extent to be replaced based on slab-level distress information and GDOT's Construction Standards and Details (GDOT, 2016), and 3) calculating the quantity based on the extents. First, slabs that require replacement are determined based on an agency's criteria. For example, GDOT, based on its standard practices, requires slab replacement for broken slab Level 2, and for slabs with longitudinal cracking at Level 2. Since the slabs were classified based on GDOT's CPACES criteria (GDOT, 1993) in the previous step, the slabs requiring slab replacement are determined by selecting the slabs meeting the criteria. Second, the exact extent of slab replacement is determined for individual slabs based on the distress information and GDOT's guidelines in Construction Standards and Details (GDOT, 2016), which are summarized as follows:

- The engineer shall determine which slabs to remove and replace and whether or not to use full or partial slab replacements.
- For partial slab replacement, the engineer needs to determine the smallest limits of removal necessary to repair the failed area using the guidelines.
- The minimum length of a replacement slab is 6 ft.
- Existing slabs retained must have a minimum length of 10 ft.
- An intermediate transverse joint shall be established at the mid-length for full length slab replacement at 20 ft. or more in length.

- Existing dowel bars need to be removed if they are within a slab replacement area.

Figure 4.5 illustrates the guidelines for determining the extent for slab replacement. Case A shows a 6-ft slab replacement is needed because of the minimum slab replacement length (6 ft.), although the distressed area is approximately 3 ft. Case B shows a 6-ft slab replacement is applied to fix the distressed area on a 30-ft slab, and transverse joints will be used on both sides of the slab replacement. The retained slabs are 10 ft. and 14 ft., which meet the required length of 10 ft. Case C shows a 10-ft slab replacement is applied to fix the distressed area of a 30-ft slab. Although the distressed area can be limited to a 6-ft slab replacement, the retained slab on the left is less than 10 ft.; thus, the slab replacement is extended to the existing joint. This results in a 10-ft slab replacement. Case D shows the need for a 30-ft full slab replacement. A transverse joint is placed in the middle, since the replacement is more than 20 ft. In addition, the existing dowel bars need to be removed, and any existing cracks at the new joint locations need to be removed to avoid a failure at the joint.

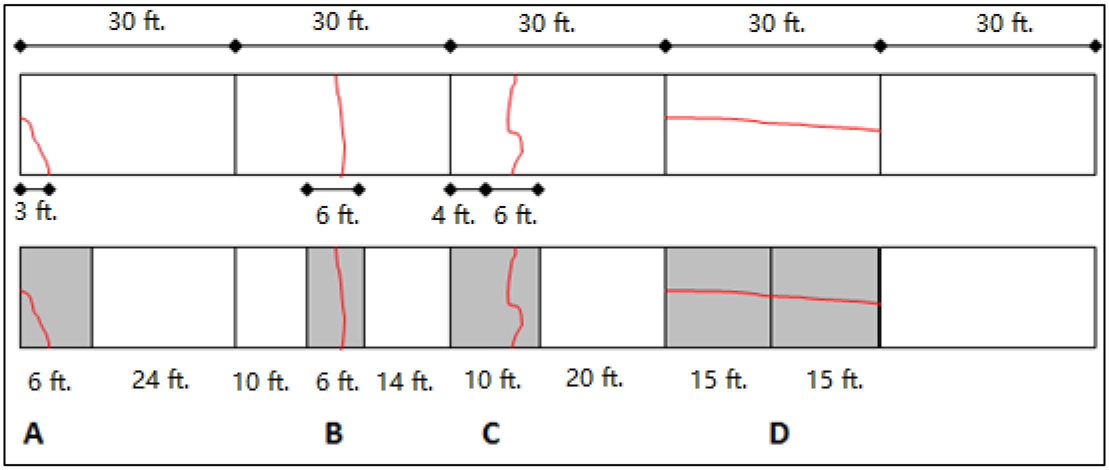


Figure 4.5 Illustration of guidelines for slab replacement

An in-house program was developed to identify the slabs requiring slab replacement, to determine the exact extent for individual slab replacement, and to calculate the quantity. In the program, the slabs are identified based on GDOT's criteria (e.g., broken slab Level 2 and longitudinal slab Level 2). Then, an initial slab replacement extent is generated for each distress on the selected slab with a 1-ft buffer around the distress to make sure the distresses are fully taken care of. The extent is then checked against the minimum slab replacement length (6 ft.), and the retained slab length is calculated and checked against the retained slab length (10 ft.). These initial slab replacement extents are then extended and/or combined if necessary. An iterative processing is taken to check if all the slab replacements can fulfill the guidelines discussed above. Figure 4.6 shows an example of the initial slab replacement extents and the processed slab replacement extents. The areas (A, B, and C in Figure 4.6) highlighted in green are the initial areas to be replaced based on the distress extents. It is noted that the retained slabs (C and D in Figure 4.6) are shorter than 10 ft.; thus, the replaced areas are combined and the entire slab needs to be replaced. The replacement is extended 1-ft to the left (F in Figure 4.6) to remove the dowel bars at the existing joint. In addition, the replacement needs to cover the crack on Slab 34 (G in Figure 4.6) to prevent its further deterioration due to the construction. Thus, instead of a 15-ft slab replacement, a total of 20 ft. must be replaced. Joints (as highlighted in red) will be placed on both side of the replaced slab because it is within 20 ft. After the process, a list of the exact extent of the slab replacement, along with joint location(s), is generated for all slabs requiring slab replacement, and the quantity is calculated based on the extents (sum of extents multiplied by the lane width and slab depth).

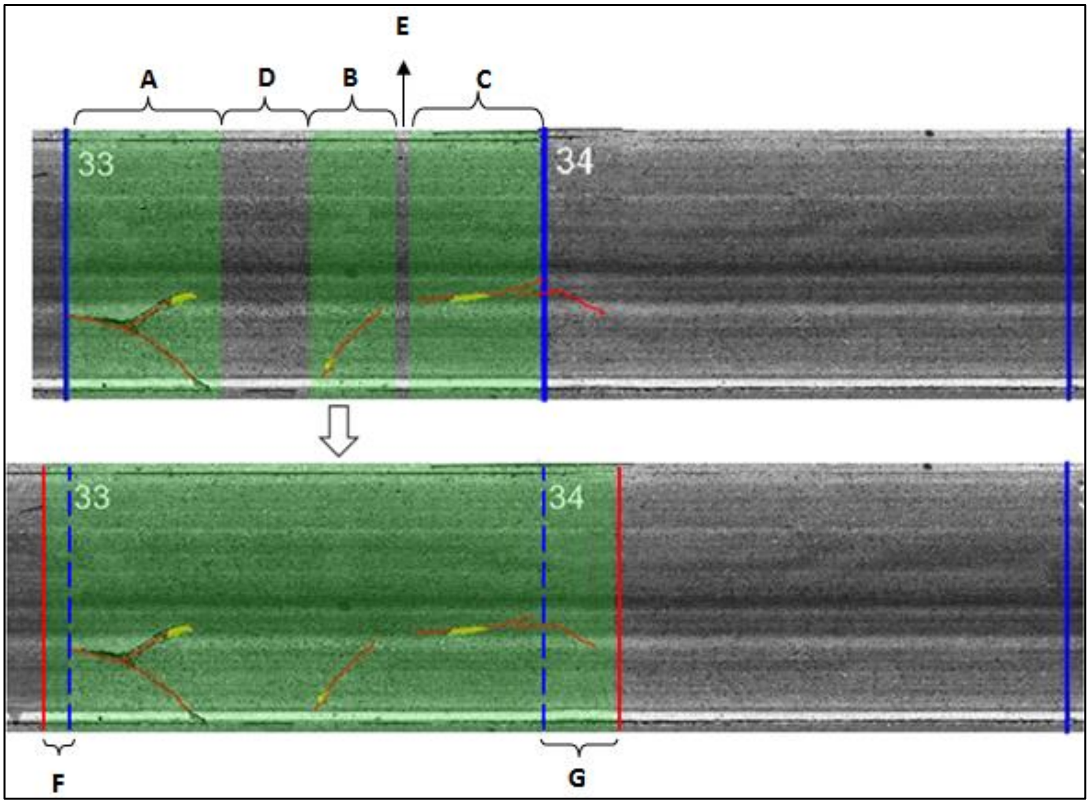


Figure 4.6 An Example of processing slab replacement

4.3 Case Study

A case study was conducted using 3D laser data collected on a 1-mile section of I-285 to demonstrate the feasibility of the proposed method, which will effectively and accurately determine the exact extent for slab replacement and calculate the quantities. This 1-mile section was constructed in 1967 and opened to traffic in 1968. It was constructed un-doweled, and with a 30-ft joint spacing and 10-in of PCC (Portland cement concrete). The pavement design layers consisted of a 10-in thick PCC layer, a 6-in cement stabilized graded aggregate base, and an 8-in thick sub-base, followed by subgrade and bedrock, as shown in Figure 4.7. This section of roadway is busy with heavy traffic and high truck volume. According to Georgia's State Traffic and Report Statistics (STARS), the average

AADT between 1990 and 2010 was approximately 100,000 with a truck percentage of 12%. After more than 40 years of service, there were many replaced slabs and many more distressed slabs requiring replacement.

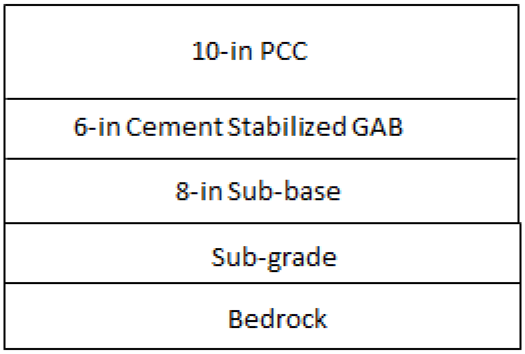


Figure 4.7 Pavement layer design on I-285

GTSV was used to collect the 3D laser data on a one-mile section in Lane 4 from MP 13 to MP 12 at highway speed. Figure 4.8 shows an example of the pavement condition on the I-285 project. The data was processed by an in-house program that extracted and classified slab-level distress information based on GDOT's CPACES, as shown in Table 4.2. Slab replacement had been conducted in the past; many slabs no longer maintained a 30-ft spacing. Thus, there are a total of 289 slabs, including replaced slabs with small spacing, in this 1-mile section. There are 34 Level 2 broken slabs and 19 Level 2 slabs with longitudinal cracks that need to be replaced based on GDOT's criteria. Figure 4.9 shows the distribution of these distressed slabs within this mile. It is noted that distressed slabs were concentrated in two areas (MP 12.0 – MP 12.4 and MP 12.6 - MP 12.8) as shown in Figure 4.9.

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Figure 4.8 An example of pavement condition on I-285

Table 4.2 Distress summary

Number of Slabs	289
Number of Slabs with Longitudinal Crack Level 1	49
Number of Slabs with Longitudinal Crack Level 2	19
Number of Broken Slab Level 1	0
Number of Broken Slab Level 2	34

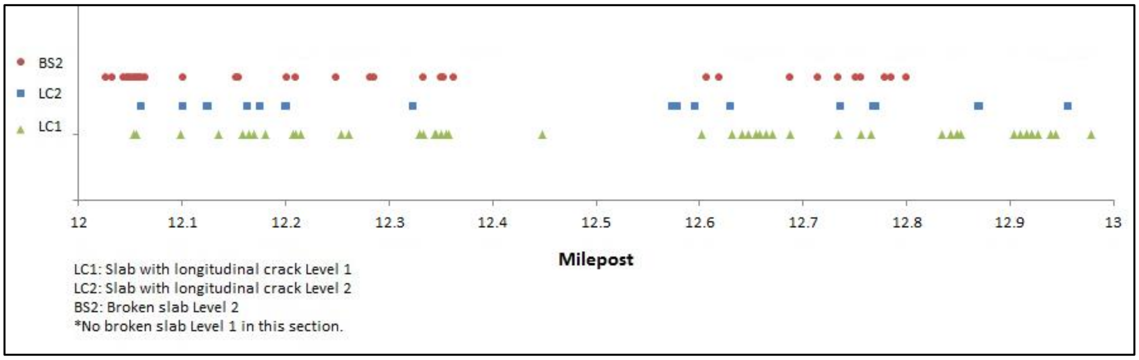


Figure 4.9 Spatial distribution and pattern of broken slabs

Based on the slab-level distress information and GDOT's Construction Standards and Details (GDOT, 2016), the in-house program was used to automatically determine the exact extent for slab replacement, including full and partial slab replacement, by taking into account the following factors: 1) a minimum slab replacement length of 6-ft; 2) a minimum retained slab length of 10-ft; 3) a maximum slab replacement length of 20 ft. (divided using transverse joint data), and 4) the removal of existing dowel bars (1 ft.) if within the slab replacement. Figure 4.10 shows examples of the outcomes; this information is available for the entire 1-mile section. The top section of Figure 4.10 shows the existing slabs with respect to length and condition. The slabs requiring slab replacement (e.g., broken slab Level 2 and longitudinal crack Level 2) are heighted in red; Level 1 broken slabs and slabs with no distresses are in yellow and gray. The bottom section of Figure 4.10 shows the exact extent for the slab replacements. The joint locations for slab replacements are also shown as black lines. It is noted that some full slab replacements longer than the maximum slab length of 20 ft. were split into two slabs (Case A). Case B shows partial slab replacement with the exact extent to treat the distressed area of a broken slab. Case C shows a small portion of a slab (6-ft) with no distress that was replaced because the removal of dowel bars made the retained slab length less than the requirement. In addition, the detailed slab replacement information, including total length and quantity, can be generated, as shown in Figure 4.11. This demonstrates a detailed slab replacement plan that considers GDOT's construction practices can be derived accurately and effectively using the proposed method. Besides using this information for slab replacement planning, this information can then be used by the project engineer to guide the slab replacement during the construction of slab replacement.

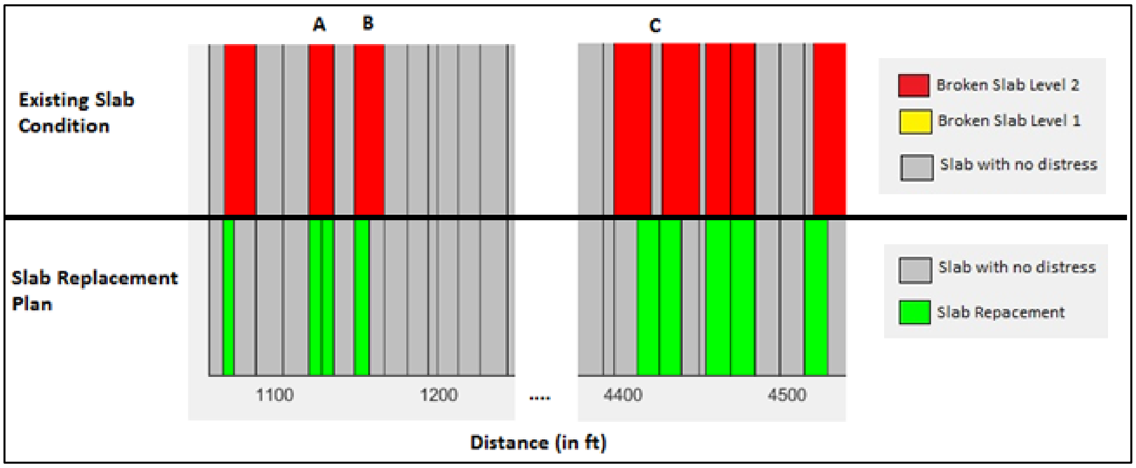
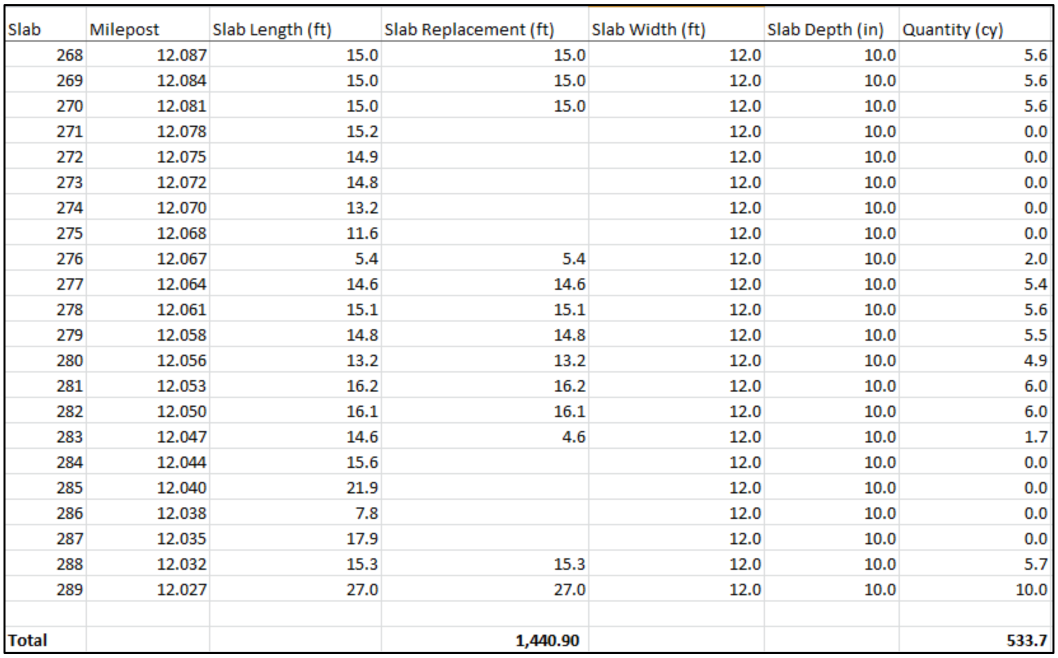


Figure 4.10 Examples of slab replacement outcomes



Slab	Milepost	Slab Length (ft)	Slab Replacement (ft)	Slab Width (ft)	Slab Depth (in)	Quantity (cy)
268	12.087	15.0	15.0	12.0	10.0	5.6
269	12.084	15.0	15.0	12.0	10.0	5.6
270	12.081	15.0	15.0	12.0	10.0	5.6
271	12.078	15.2		12.0	10.0	0.0
272	12.075	14.9		12.0	10.0	0.0
273	12.072	14.8		12.0	10.0	0.0
274	12.070	13.2		12.0	10.0	0.0
275	12.068	11.6		12.0	10.0	0.0
276	12.067	5.4	5.4	12.0	10.0	2.0
277	12.064	14.6	14.6	12.0	10.0	5.4
278	12.061	15.1	15.1	12.0	10.0	5.6
279	12.058	14.8	14.8	12.0	10.0	5.5
280	12.056	13.2	13.2	12.0	10.0	4.9
281	12.053	16.2	16.2	12.0	10.0	6.0
282	12.050	16.1	16.1	12.0	10.0	6.0
283	12.047	14.6	4.6	12.0	10.0	1.7
284	12.044	15.6		12.0	10.0	0.0
285	12.040	21.9		12.0	10.0	0.0
286	12.038	7.8		12.0	10.0	0.0
287	12.035	17.9		12.0	10.0	0.0
288	12.032	15.3	15.3	12.0	10.0	5.7
289	12.027	27.0	27.0	12.0	10.0	10.0
Total			**1,440.90**			**533.7**

Figure 4.11 Examples of slab replacement plan

Table 4.3 lists the slab replacement quantity estimated by GDOT's windshield inspection, and the proposed method along with the actual construction quantity provided by GDOT. It is noted that the windshield inspection was conducted in 2013, and the proposed method uses the 3D data collected in May, 2013. The construction work on this section was completed in 2014. The windshield survey method (including a 20% tolerance) underestimated the quantity (approximately 69% of the actual quantity). The proposed method provided an estimate that is approximately 95% of the actual quantity. It shows a significant improvement (approximately 26%) in the accuracy of slab replacement quantity estimation when compared to the windshield survey. According to the results, besides being dangerous to the surveyors and interfering with traffic due to slow speed (e.g., 20-25 mph) the windshield survey is likely to underestimate the slab replacement quantity and potentially lead to a budget overrun on the project. In addition, the program can simulate slab replacement scenarios based on different criteria (e.g., slab replacement for broken slab Levels 1 and 2) to assist agencies in making informed decision on slab replacement based on budget availability. Engineers can determine the total cost needed to replace the slabs with only Severity Level 2 broken slab or to replace both Severity Levels 1 and 2. The slab replacement plan and the drawing/map of replaced slabs can be displayed along with surrounding distresses. Therefore, engineers can also decide whether to replace other adjacent low-severity level distresses if it is economically feasible. In addition, it can be used to consider the economic feasibility of replacing the entire 1-mile section or only the most distressed slabs.

Table 4.3 Estimated quantities vs. actual quantity

Quantity Estimation Method	Total Quantity (cubic yard)	% of Actual Construction Quantity
Quantity Estimated by Windshield Inspection	386.63	69.0%
Quantity Estimated by Proposed Method	533.70	95.2%
Actual Construction Quantity	560.18	

4.4 Summary

State DOTs need to accurately and effectively determine slab replacement quantities for reliable budget planning. This is especially important as the need for slab replacement increases due to aging infrastructure and limited budgets. The current windshield survey for estimating the broken slab replacement is time-consuming, labor-intensive, dangerous, and likely to interfere with traffic, since it uses a low-speed (e.g., 20-25 mph) survey vehicle on interstate highways. More importantly, a windshield survey cannot accurately estimate quantities, especially when there are many distressed slabs compounded with existing replaced slabs. This chapter proposes a new method that can effectively and accurately estimate slab replacement quantity using high-resolution 3D laser data. The method consists of three steps: (1) acquiring 3D laser data, (2) extracting and classifying slab-level distress information, and (3) determining the exact extent of slab replacements and calculating the quantity based on an agency's criteria and construction practices. A case study was conducted on a 1-mile section of I-285 in Georgia to demonstrate the feasibility of the proposed method. The results show the proposed method provides a systematic approach for accurately and effectively estimating slab replacement with the exact extents, and in consideration of an agency's criteria and construction practices. Results show a significant improvement (approximately 26%) over the windshield survey in the accuracy of slab replacement quantity estimation. In this case study, the proposed method has more than 95% accuracy - the estimated quantity is approximately 95% of the actual construction quantity. In addition to the total quantity, the proposed method can provide a detailed slab replacement plan with the exact locations for full and partial slab replacements. Besides using the information for slab replacement planning, such information can also be used by the project engineer to guide the slab replacement during the construction. Also, the proposed method can simulate slab replacement plans based on different criteria, which can help agencies make informed, data-driven decisions.

A method has been developed and has successfully demonstrated its promising capability of identifying distresses and determining slab replacement using 1-mile 3D laser data collected on I-285. The proposed method is capable of simulating different treatment alternatives, such as replacing only the severe distresses or all distressed slabs, and corresponding costs. With the detailed level of slab replacement plan and drawing, engineers can determine whether or not to fix adjacent slabs, even if they are not in as a severe condition, for continuity of construction purposes.

The following considerations are recommended for the future implementation of the proposed method:

- Apply the method to a larger data set (more than 1 mile) and especially apply it to the incoming JPCP slab replacement plan and projects;
- Incorporate other distresses, such as spalling, into distress identification and slab classification; and

- Incorporate additional information, such as the distress deterioration rate, the age of pavement, and the condition of adjacent slabs, into the slab replacement prioritization and cost optimization.

5. DEVELOPMENT OF A BROKEN SLAB PREDICTION MODEL

Slab replacement is the most common maintenance/rehabilitation treatment for repairing distressed JPCPs. It is essential to have a slab replacement forecasting method to support JPCP MR&R planning. Especially, a majority of JPCPs in Georgia have been in service for more than 40 years; now these aging JPCPs are in need of MR&R, including slab replacement. There is typically about a two-year gap between MR&R planning and actual construction. Thus, it is important to develop a method to reliably forecast slab replacement in support of reliable MR&R planning to most effectively manage pavement assets. The future of pavement management lies in having comprehensive information on pavements assets in a timely manner. However, there is currently no segment-based slab replacement forecasting model that considers using slab-level distress classification and deterioration. With emerging 3D technology and automatic detection of pavement distresses, it has become feasible to develop a reliable deterioration model in support of network level MR&R forecasting. This chapter proposes an enhanced slab replacement forecasting method to support segment level JPCP MR&R planning; the method uses 3D technology, slab-level distress classification, and deterioration with Markov Chain modeling. As noted later in this Chapter, this is the first use of Markov Chain modeling for JPCP on the slab level, and, as such, the model is still in development and will need to be validated prior to full-scale implementation. The proposed method includes 1) 3D data acquisition, 2) slab-level distress detection and classification, 3) slab-level deterioration analysis using Markov Chain modeling, and 4) a slab replacement forecasting method based on categorized Markov Chain models. A case study using 3 years of 3D laser data (2013, 2014, and 2015) collected from a one-mile JPCP located on I-16 in Georgia, was conducted to demonstrate the development and use of the proposed slab replacement forecasting method. The case study shows the proposed method is potentially promising in predicting slab replacement needs for the future.

5.1 Review of GDOT's Broken Slab Replacement Practices

Typical JPCP maintenance involves repair and replacement of individual distressed slabs or portions of slabs. GDOT has one crew per District to perform concrete pavement full depth and partial depth (spall) replacement repairs. The crew considers all broken slab severity level 2 (BS2) for full-depth repairs, but decides on longitudinal crack severity level 2 (LC2) slabs on a case-by-case basis when estimating quantities per mile. Also, GDOT currently looks at the overall CPACES rating in combination with individual distresses of faulting, IRI, and cracked slabs to identify the priority of the concrete pavement segments to be treated. An IRI of greater than 1,100 mm/km and at least 10 slabs identified as BS2 in a mile, combined with a certain level of faulting, will result in a recommendation for slab replacement, grinding and resealing the joints. Since 2000, GDOT has also done a number of complete outside (truck lane) replacements when the number of cracked slabs needing repair exceeded 1/3 of the mile (1.6 km). This involves full lane replacement of the outside lane, including stabilizing the subgrade where necessary.

GDOT lets the MR&R work out to contract when 1) the needs of a section of roadway exceed the capability of the District crew to repair it in one season, 2) if grinding will be necessary, or 3) if complete outside lane replacement is warranted. Therefore, being able to predict the increase in slabs that need replacement would be beneficial to GDOT. However, because of limited budgets and personnel, only the most highly distressed slabs are being repaired with in-house personnel, and, therefore a simple count of distressed slabs by mile can be inconsistent due to repairs that have been performed. Also, individual slabs that are distressed can be repaired and end up divided into two slabs. Figure 6.1shows an example in which the same section of pavement is shown in 2013 and 2014, but after repairs there is an additional slab in 2014. These factors make it difficult to predict future slab replacement from current conditions on a mile basis. Therefore, continuous coverage and slab-by-slab comparisons would be beneficial for describing the complete history of the pavement's condition over time.

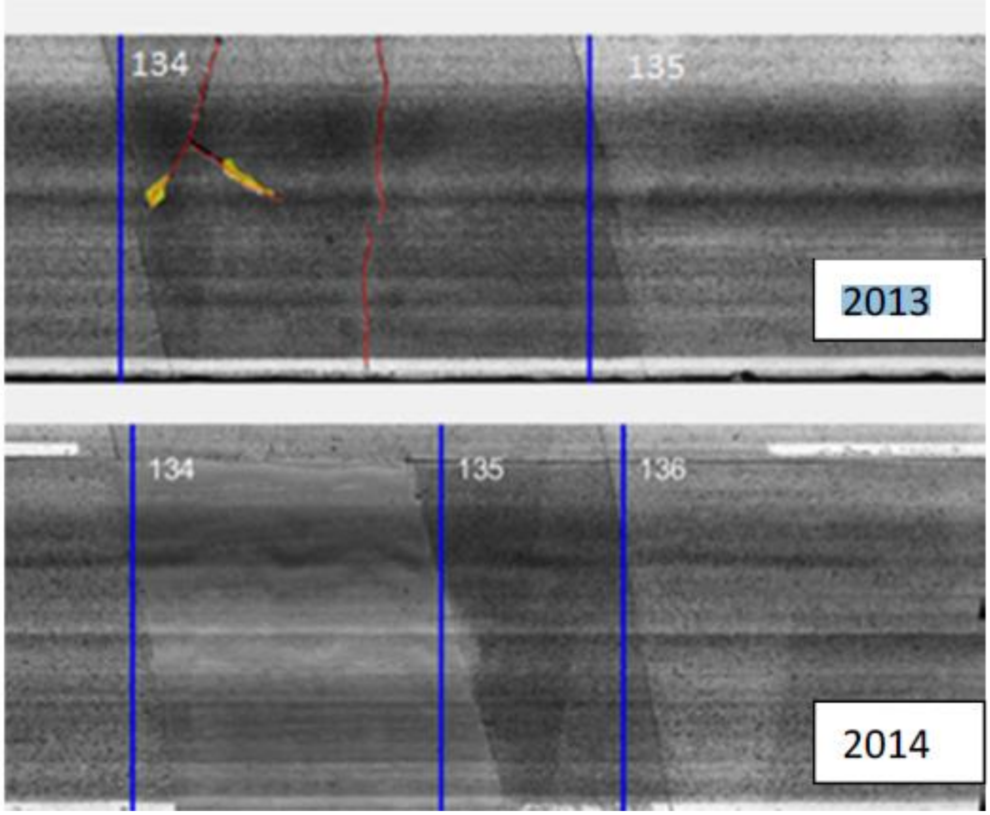


Figure 6.1 Effect of repaired slab on a number of slabs and distress records

5.2 Proposed Slab Replacement Forecasting Method

The only JPCP slab level cracking performance model in wide use is included in the AASHTO PavementME program (AASHTO 2001). It predicts the percentage of slabs that will crack based on material, loading and climatic conditions. It is a fatigue-based model based on Miners' theory and, as such, provides for incremental damage to the pavement until the point at which the weakest slabs develop transverse cracking. Miners' theory is simply a relationship between the accumulated and allowable loading on the slab and, therefore, cracking is predicated on linear damage accumulation in relation to the loading. The percent of cracked slabs provided by PavementME does not provide an indication of the severity of the cracking in the slabs. In reality, slabs do not typically crack in linear or predictable ways due to a myriad of factors (i.e. isolated poor subgrade conditions, construction anomalies, dynamic impact, etc.) and the severity of cracking is needed to prioritize maintenance activities.

The benefit of the Markov Chain model specifically for JPCP is that the slabs can be modeled and predicted in different states (severity levels), the existing condition of the pavement (current cracking severity) is used to predict future cracking and future condition. The original AASHTO Pavement Management Guide (PMG) identified 3 types of pavement performance prediction models: deterministic, probabilistic and Bayesian (AASHTO 2001). Markov chains are a form of probabilistic modeling that is specifically mentioned in the PMG. The Markov Chain method has been used with performance indexes (i.e. composite pavement ratings from 0 to 100) to model the probabilistic nature of changes in the state of a pavement section at the network level (from Excellent to Good, Good to Fair, and Fair to Poor) and can be used with only 2 years of data (Hassan et al., 2015). Markov chains have also been used recently for pavements based on surface conditions (IRI) (Porras-Alvarado et al,. 2012), and for modeling bridge deterioration (Li et al., 2016). GDOT, also, has historical experience and a certain comfort level with using performance prediction from Markov chains, as they were used to develop pavement deterioration models for GDOT's asphalt pavements based on the asphalt PACES rating (Wang et al., 2009). While Markov chains have been used for rating systems such as Georgia's asphalt rating system, IRI of pavement sections, and even for cracking in asphalt pavements (Mills et al., 2012; Kobayashi et al., 2014), using Markov chains for cracking on concrete pavements on a slab by slab basis appears to be unique to this project. Probabilistic Markov Chain (MC) models are now used extensively in bridge deterioration modeling, replacing earlier deterministic, regression-based modeling methods. Several studies have shown that probabilistic models (i.e. MC based) are better at predicting individual bridge deterioration conditions than deterministic models. MC models for bridges are in use to predict the change in condition state of major components of bridge (deck, superstructure, substructure), and, as additional bridge data is being collected, they are also used to model the deterioration of individual bridge components (or elements), such as beams and columns (Cavalline et al, 2015).

This section presents a proposed slab replacement forecasting method that uses 3D laser data, slab-level distress classification, and deterioration with a Markov Chain. The proposed method includes 1) 3D laser data acquisition, 2) slab-level distress detection and classification, 3) slab-level deterioration analysis using the Markov Chain, and 4) a slab replacement forecasting method based on categorized Markov Chain models.

5.2.1 Acquiring 3D Laster Data

The first step is to collect high-resolution 3D laser data on JPCP, which is necessary for measuring crack length, crack type and severity. The GA Tech Sensing Vehicle (GTSV), described previously in Chapter 4, was used to collect the data. 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) and detailed distress information can be extracted from this set of data.

5.2.2 Slab-level Distress Detection and Classification

This step consists of 1) distress detection and 2) classification. The distress detection is based on the same algorithms described in Chapter 4; this section focuses on the distress classification. 3D laser data has been used to detect cracks in asphalt pavements (Tsai et al., 2012; Jiang and Tsai 2015). AASHTO even has a provisional standard, PP67 (AASHTO, 2014), related to automatic measurement of cracking in asphalt pavements that has been used by others to evaluate and rate pavements (Qiu et al., 2014), but there is no current similar standard related to cracking in concrete pavements. Therefore, in the absence of a concrete pavement cracking standard, the results of the automated distress detection were designed to be compared to GDOT’s current pavement evaluation procedure. The detected distresses have been combined in each slab and then further classified based on an enhanced CPACES distress protocol. To align the distresses to the

CPACES distress protocol, the flow chart shown in Figure 6.2was used for classifying distresses. Shattered slabs were considered as slabs with both transverse (Severity Level 2) and longitudinal (Severity Level 2) cracking. With this information it is expected that comparisons of changes in specific slabs over time can be made. GDOT does not currently have a shattered slab definition but it is included in the enhanced CPACES distress protocol; it is assumed that the raters would have called most shattered slabs BS2, since this is the worst distress identified in the CPACES.

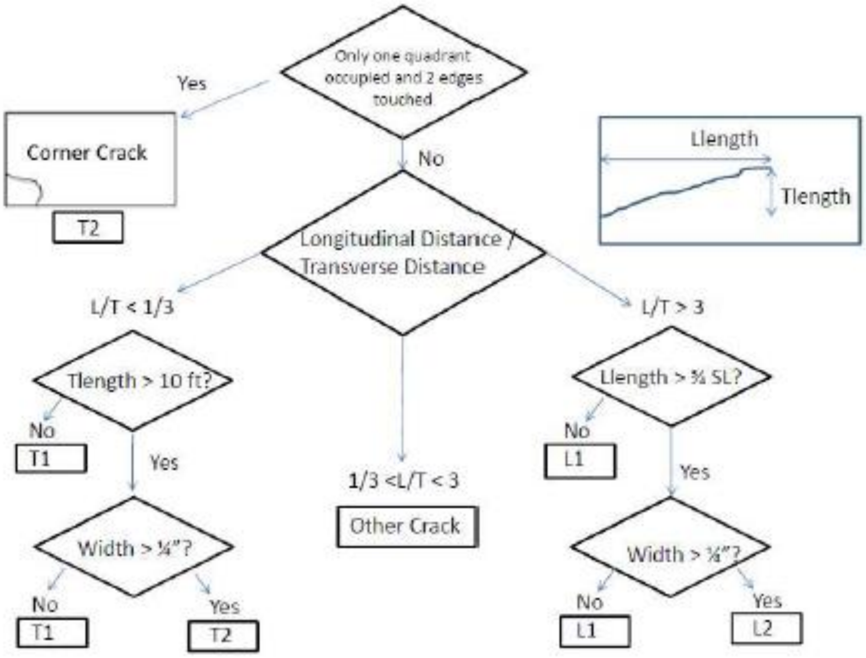


Figure 6.2 Distress classification flow chart

5.2.3 Slab-level Deterioration Analysis Using Markov Chain

The Transition Probability Matrix (TPM) is used to identify the change in the state of a pavement in the Markov Chain model. TPMs are developed by categorizing changes in state over time, and a definition of the "states" is the basis for the TPM development. While previously mentioned Markov Chains used bands or ranges of values (i.e. Good =

0 to 70.87 in/mile; Fair = 70.87-106.30 in/mile; etc., in the case of IRI (Porras-Alvarado et al., 2014) or percent of transverse cracking in the case of asphalt pavements (Mills et al., 2012) , to define “states,” this new method uses definitions of states of longitudinal cracking and transverse cracking as shown previously in Figure 6.2: L1 to L2 and T1 to T2, with the addition of a shattered slab (SS) state. SS (slabs with both horizontal and longitudinal cracking) were separated into SS states that started as longitudinal cracks (SS_L) and SS that started as transverse cracks (SS_T). So, the different states for slabs with transverse cracking are Not Cracked (NCT), T1, T2, and SS_T, in that order. Similarly, different states for slabs with longitudinal cracking are Not Cracked (NCL), L1, L2, and SS_L, in that order. A case study, using 3 years of 3D pavement data collected in a one mile JPCP located on I-16 in Georgia, will be used to demonstrate the development and use of this unique Markov Chain TPM model. As this project is the first identified use of MC with slab-level data for JPCP pavements, additional data and testing will be needed to identify the best definition of MC condition states and categories that will develop the most efficient models for future use.

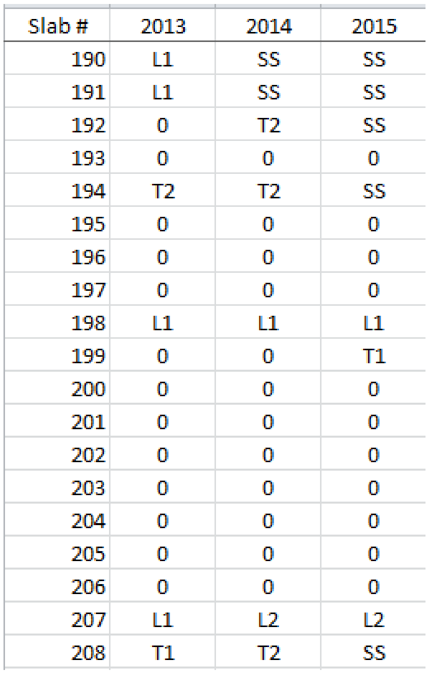
3D laser data was collected in 2013, 2014, and 2015 on I- 16 westbound MP 17 to MP 16 to study the slab-level deterioration of the JPCP. This section of interstate is 44 years old and was constructed with undoweled JPCP, 9 inches (23 cm) thick over a 6 inch (15 cm) soil cement base. The joints were placed on a ~10º skew with repeated spacing of 17 ft., 23 ft., 22 ft., and 16 ft. (5.2 m, 7 m, 6.7 m, and 4.9 m). Table 6.1 summaries the slab-level condition for the 267 slabs (including replaced slabs) in this 1-mile test section. As noted, slab cracking was classified into longitudinal cracks (LC), transverse cracks (TC), and shattered slab (SS). LC and TC were also separated into two severity levels based on crack length and crack width as noted in the previous section (Figure 6.2). Any corner cracks were lumped with transverse level 2 (TC 2) to align with GDOT's broken slab definition. Slabs that exhibited multiple cracks (e.g., both LC 2 and TC 2) were noted as shattered slabs (SS).

Table 6.1 Slab-level condition for the 1-mile test section on I-16 (MP17-16)

	Load Cracking Level 1	Load Cracking Level 2	Transverse Cracking Level 1	Transverse Cracking Level 2	Shattered Slab	Total
2013	24	6	21	17	20	88
2014	14	11	8	36	32	101
2015	11	13	3	31	53	111

A replaced slab was identified between 2013 and 2014 for the MP17 section. The 2014 data actually included 269 slabs. The original slab from 2013 and the replaced slabs in 2014 and 2015 were omitted from this analysis to eliminate any maintenance and rehabilitation effects; therefore, a total of 267 slabs were used. Crack sealing was also neglected due to lack of access to maintenance records to identify timing.

Each of the 267 slabs in the mile was identified as not cracked (0), longitudinally 1 cracked (LC 1 or LC 2), transversely cracked (TC 1 or TC 2) or Shattered Slab (SS) for each of the three years; an excerpt of this is provided in Figure 6.3. The SS slabs were further defined as SS_L or SS_T. As shown in Figure 6.3, Slab 190 and 191 were both LC 1 in 2013 and then went to SS in 2014. The SS in 2014 would then be considered SS_L, as they both started out as a longitudinal crack; therefore, both slabs would be included in the number of slabs that went from LC 1 to SS_L in 2013/2014. Slab 208 went from TC 1 to TC 2 in 2013/2014 and then from TC 2 to SS in 2014/2015, so it would be considered SS_T in 2015. Slab 199 was not cracked in 2013 or 2014 but developed a crack in 2015, so it was included in the number of NCT to TC 1 in the 2014 to 2015 timeframe. In this way, the changes in the slabs were identified and included in the TPM by turning the number of changes into percentages. It should be noted that slabs that were already SS in 2013 could not be identified as either starting as longitudinal or transversely cracked (SS_L or SS_T), so they were not included in the TPM. Only the identified cracks starting as longitudinal or transversely cracked are used in the final TPM. This does point out a potential limitation of this method with already heavily distressed pavements.



Slab #	2013	2014	2015
190	L1	SS	SS
191	L1	SS	SS
192	0	T2	SS
193	0	0	0
194	T2	T2	SS
195	0	0	0
196	0	0	0
197	0	0	0
198	L1	L1	L1
199	0	0	T1
200	0	0	0
201	0	0	0
202	0	0	0
203	0	0	0
204	0	0	0
205	0	0	0
206	0	0	0
207	L1	L2	L2
208	T1	T2	SS

Figure 6.3 Examples of change in slab distresses between 2013, 2014, and 2015

As noted earlier, TPMs were developed separately for longitudinal cracking and transverse cracking. Since the slabs came from the same mile, the original state (Not Cracked) was considered to be not cracked longitudinally (NCL= total number of slabs – LC1 – LC 2 - new LC) for the longitudinal state and not cracked transversely (NCT=

total number of slabs – TC 1-TC 2-new TC) for the transverse state. The transitions from different states of longitudinal or transverse cracking were developed from the slab-level condition data of each year by comparing the results of the detailed condition data by slab as described earlier. As an example of how this transitioned into the TPM, half of the slabs that were identified with LC 1 cracking in 2014 were still identified as LC 1 cracked in 2015; therefore, the LC 1 to LC 1 value is 50 (or 50%) in Table 6.2(b). The results shown in Table 6.2 (a) and (b) are then combined (averaged) to develop a t2-year TPM, shown in Table 6.2 (c).

The transverse cracking is showing higher variability per year (Table 6.3(a) and (b)) than the longitudinal cracking Table 6.2(a) and (b), for this 3-year time frame. Trends in the changes of the TPM per year can be an indicator of the increasing rate of distresses. Based on the two year analysis, it appears that a slab that experiences Level 1 transverse cracking (TC 1) has a higher 1 probability to move to level TC 2 in two years (78% vs 25%) than a longitudinal crack. This is logical, since the longitudinal crack would typically have to traverse farther than a transverse crack. Using the 2015 data of 226 (NCT), 3 (TC 1) and 31 (TC 2), the 2016 expected stages would be as follows: 220 (NCT), 3 (TC 1), 29 (TC 2), and 9 new SS_T. Similarly, using the 2015 data of 233 (NCL), 11 (LC 1) and 13 (LC 2), the 2016 expected stages would be as follows: 221 (NCL), 9 (LC 1), 14 (LC 2), and 6 new SS_L. Based on GDOT’s replacement criteria (where TC 2 is equivalent to BS2, and assuming all SS_L and SS_T are considered BS2), they could expect 15 new BS2 (SS) along with the 29 BS2 (TC 2) slabs and so they would be looking at replacing 45 slabs along with the 53 existing SS in Table 6.1, for a total of 98. Based on this, they would be looking to let a contract to perform this amount of work, and it would be a full outside lane replacement.

Table 6.2 Transition probability matrix for longitudinal crack

		NCL	LC 1	LC 2	SS_L
(a) 2013-2014	NCL	98	1.5	.5	0
	LC 1	0	46	21	33
	LC 2	0	0	83	17
	SS_L	0	0	0	100
		NCL	LC 1	LC 2	SS_L
(a) 2014-2015	NCL	98	2	0	0
	LC 1	0	50	29	21
	LC 2	0	0	73	27
	SS_L	0	0	0	100
		NCL	LC 1	LC 2	SS_L
(b) 2-year TPM	NCL	98	1.75	.25	0
	LC 1	0	48	25	27
	LC 2	0	0	78	22
	SS_L	0	0	0	100

Table 6.3 Transition probability matrix for transverse crack

(a) 2013-2014		NCL	TC 1	TC 2	SS_T
	NCL	96	1.8	2.2	0
	TC 1	0	19	81	33
	TC 2	0	0	82	18
	SS_T	0	0	0	100
(b) 2014-2015		NCL	TC 1	TC 2	SS_T
	NCL	97.7	1.4	0.9	0
	TC 1	0	0	75	25
	TC 2	0	0	64	36
	SS_T	0	0	0	100
(c) 2-year TPM		NCL	TC 1	TC 2	SS_T
	NCL	98.6	1.6	1.6	0
	TC 1	0	9.5	78	12.5
	TC 2	0	0	73	27
	SS_T	0	0	0	100

An example is provided here to demonstrate the use of TPM for predicting slab conditions at segment level and slab replacement need. Assuming there is a segment with the existing condition described in Table 6.4. There are a total of 240 slabs; 40 of them are shattered slabs (20 SS_L slabs and 20 SS_T slabs) and 50 are with transverse or longitudinal cracking (20 LC1 slabs, 10 LC2 slabs, 10 TC1 slabs, and 10 TC2). Based on this data, which can be obtained through a pavement condition evaluation, separate initial state vectors can be generated for longitudinal and transverse crack. The initial state vectors can be expressed as [150, 20, 10 , 20] for longitudinal crack and [150, 10, 10, 20] for transverse crack. The initial state vectors were then multiplied by respective TPM in Table 6.2 (c) and Table 6.3 (c) to predict the number of slabs in each state in the next time period, as shown in Table 6.5 (a) and (b). The total number of cracked slabs (LC1, LC2, TC1, TC2, SS_L, and SS_T) can be obtained by summarizing the number of slabs in each state; the summarized values were rounded into an integer to represent the number of slabs in each state. Note that a majority of Level 1 cracked slabs deteriorated and moved to Level 2; there are only 15 Level 1 cracked slabs compared to 30 in previous year. There is also an increase in the shattered slabs (from 40 to 52). Note that the NC slabs were used in both longitudinal and transverse crack; thus, the sum of NCL and NCT would double-count the NC slabs. Thus, the number of NC slabs is computed by subtracting the cracked slab from the total slabs (240-98=142). Table 6.5 shows the predicted number of slabs in each state. With this information, MR&R decision can be made with regard to whether or not the segment needs to be treated and estimate the quantity based on different criteria. For example, the agency can explore two MR&R alternatives: 1) treating all shattered slabs and 2) treating all Level 2 cracked slabs and shattered slabs. For Alternative 1 (treat all shattered slabs), a total of 52 slabs need to be treated. For Alternative 2 (treat Level 2 cracked slabs and shattered slabs), a total of 83 slabs need to be treated, which is one third of the total slabs. With so many slab replacements, the full lane replacement may be considered as another alternative. This example demonstrates the proposed method is potentially promising in predicting slab replacement needs for the future.

Table 6.4 Assumed initial state conditions

NC	LC1	LC2	TC1	TC2	SS_L	SS_T
150	20	10	10	10	20	20

Table 6.5 Predicted cracked slabs based on TPM

(a) Longitudinal Crack

	NCL	LC 1	LC 2	SS_L
NCL	147	2.625	0.375	0
LC1	0	9.6	5	5.4
LC2	0	0	7.8	2.2
SS_L	0	0	0	20
Total	145	12	13	28

(b) Transverse Crack

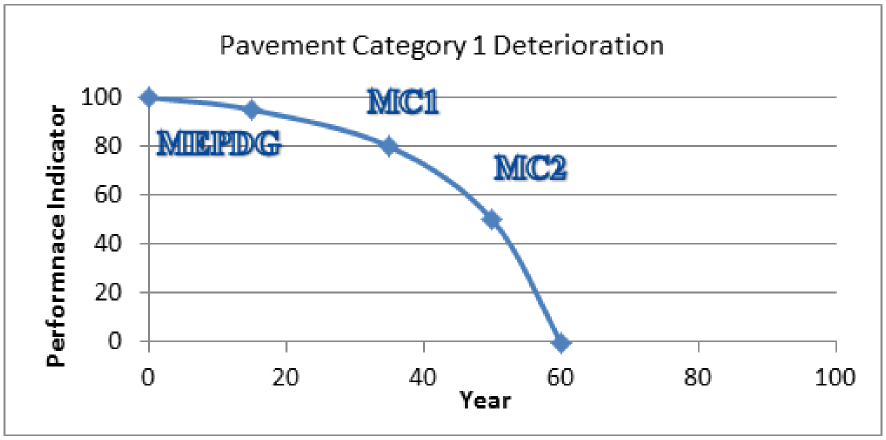
	NCT	TC 1	TC 2	SS_T
NCL	145.2	2.4	2.4	0
TC1	0	0.95	7.8	1.25
TC2	0	0	7.3	2.7
SS_T	0	0	0	20
Total	145	3	18	24

Table 6.6 Predicted conditions for each state

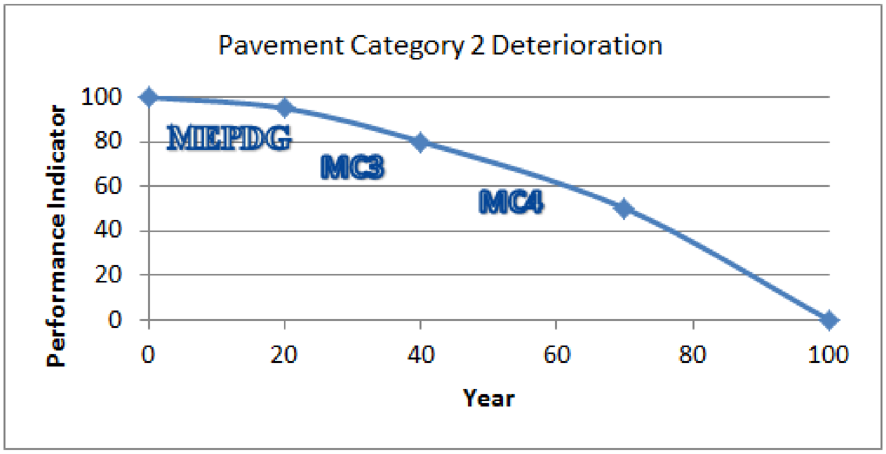
NC	LC1	LC2	TC1	TC2	SS_L	SS_T
142	3	18	3	18	24	24

5.2.4 Development of the slab replacement forecasting method based on categorized Markov Chain models

The current Transition Probability Matrix (TPM) of the Markov chain model, which considers the deterioration and the transition from one state (i.e. T1) to another state (T2), is specific for this segment at this time. To implement the proposed MC method, it is recommended to establish TPMs based on pavement category considering pavement deterioration stage, pavement design, and traffic. In this way, pavements are categorized based on similar conditions. A categorized TPM will better consider the actual pavement deterioration behavior as compared to an uncategorized TPM. The pavement deterioration is anticipated to be non-linear and the rate of deterioration can be different through the pavement life. Pavements will exhibit minimum to no distress for a certain period of time (unless material related distress issues), then due to fatigue factors they will deteriorate at a constant rate for a period of time, at which point the deterioration will increase to a higher level, at which point the deterioration will increase to such a level that they should be replaced. Figure 6.4 (a) shows a depiction of the different analysis methods that will be used for different pavement ‘ages’ or periods. The rate of deterioration is expected to be the lowest in the first period and can be modeling 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 for the early life of the pavement will be less than 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 life. At a point (shown as year 50 in Figure 6.4 (a)) the pavement becomes distressed to the point that further deterioration is exponential to end of pavement life, shown as age 60 in Figure 6.4 (a). Different pavement categories will exhibit different distress rates (MC3 and MC4) and even potentially different distresses as shown in hypothetical pavement category 2 in Figure 6.4 (b).



(a) Pavement Category 1



(b) Pavement Category 2

Figure 6.4 Illustration of deterioration based on pavement category

With the rich 3D data and slab level distress data that will become readily available, appropriate ranges for the categories can be developed that will provide the best actual deterioration behavior to categorize different TPMs. Similarly, different JPCP designs and traffic volumes will impact the pavement deterioration. For example, the design features of JPCP in Georgia have evolved through the years, and various designs of JPCP have been constructed in Georgia (Tsai et al., 2012). JPCP in Georgia can be categorized based on design features and construction time, as described below:

- ND, 1960-1970: non-doweled 9-10 inches (23-25 cm) of JPCP on top of an 8-inch (20 cm) soil with the top 3 inches (7.6 cm) stabilized with a cutback or emulsion asphalt, or a soil cement base, and a 30-ft (9.1 m) joint spacing.
- ND-IB 1970's: non-doweled JPCP with a cement stabilized Graded Aggregate Base (GAB) or soil cement, a variation of joint spacing (e.g., random), and joint orientation (e.g., skewed). I-16 MP 17-16 is in this category.
- D-IB late 1970's-1980s: doweled JPCP on GAB, with a joint spacing of 20-ft (6.1 m) or 30-ft (9.1 m).

Today, GDOT's JPCP design for interstate highways and heavy truck routes consists of doweled JPCP with a 15-ft (4.6 m) squared joint spacing and a 13-ft(4 m) wide slab on top of a GAB base with a 3-inch (7.6 cm) HMA interlayer between the concrete slab and the GAB base. The "13-ft (4 m) wide slab" is a 12-ft (3.7 m) outside lane (as marked by the edge traffic stripe) plus 1-ft (0.3 m) of the same slab as part of the shoulder to provide better edge support. Therefore, at least four TPMs could be categorized based on these four major different design features. Certainly, the TPM can be further refined/categorized with additional data, and the actual deterioration behavior can be better used to differentiate their behavior.

To use the TPMs in different category, a rating will be computed based on the distress conditions each year. Based on the rating, a pavement deterioration stage can be determined. This combined with pavement design and traffic will be used to determine the pavement category, and corresponding TPM is used to predict the distress conditions in the next period of time. The process for determining the pavement category is repeated in each time period to determine the TPM to be used for predicting future distress. Thus, a single TPM is not used through the entire pavement life.

5.3 Summary

This chapter explored a unique use of Markovian principles in the evaluation of pavement deterioration models for JPCPs. Cracking in JPCPs was analyzed on a slab-by-slab basis and, also, separated into longitudinal and transverse cracking. Changes in the crack severity were developed into transitional probability matrices (TPMs) using Markov Chain principles. Of course, validation of the model is a necessary next step, and the 2016 3D pavement data that is currently being gathered will be used for this purpose, along with analyzing other JPCP roadways.

In addition, some unique issues were presented regarding performance prediction of JPCPs, where changes in slab configurations and repairs on individual slabs need to be considered in the future performance of the pavement. Concrete pavement surfaces also typically last longer, so they typically deteriorate slower, where a slab by slab identification of 3D measured cracking could be beneficial, as changes could be categorized at different levels of granularity, to pick up changes in cracking behavior. The combination of these factors could lead to less uncertainty in future pavement performance predictions. A cracking standard that identifies consistent terminology for classification purposes for concrete pavement would also benefit future development of JPCP cracking prediction models.

Other potential uses for this method may be to identify pavements that are increasingly skipping states (i.e. going from a Level 1 crack to shattered slab), which would indicate a faster level of cracking progression. It also may be used to check the data integrity of a manual method, to determine if the data is following an expected trend, or it could be used in conjunction with other factors, such as IRI and faulting, to provide a more holistic approach to performance prediction.

6. DEVELOPMENT OF A FAULTING PREDICTION MODEL

Faulting, the elevation difference between two slab edges across a transverse joint, is an important performance indicator for JPCP and, also, the criteria for triggering MR&R (e.g., diamond grinding). As a majority of JPCPs in Georgia are more than 40 years old, faulting has been developed on these pavements and timely MR&R is needed to prolong the service life and to maintain ride quality and safety. Therefore, it is important to develop a method to reliably predict faulting in support of MR&R planning and programming, such as plan for diamond grinding. This chapter presents a review of the faulting prediction models and a segment-level dynamic linear regression model for predicting faulting index based on the CPACES data collected by GDOT.

6.1 Review of Faulting Prediction Models

Faulting is the elevation difference between two slab edges across a transverse joint caused by inadequate load transfer, differential deflection at the joint, inadequate base support, and sub-base erosion (Jung et al., 2008). The difference in elevation affects the ride quality, accelerates vehicle damage, and leads to distresses, such as corner breaks and blowups and needs to be treated (e.g., diamond grinding) to maintain ride quality and safety. Various models have been developed to predict faulting prediction in previous studies. These models can be categorized into empirical models, mechanistic (or structure) models, mechanistic-empirical models and ANN (Artificial Neural Network) models. Empirical models rely on field measured data. For example, GDOT developed a faulting prediction model (Gulden 1974) based on the limited faulting data collected in Georgia. However, the drawback of this type of model is they are limited to the data (range of values) that used in developing such models. The model is considered valid only when the data is within the limited range of values or conditions (e.g., traffic loads, temperature, etc.). Mechanistic models are based on the mechanics of the materials and physics behind the problem. With mechanistic models, stress, strain, or resulting deflections are determined to explain the elevation difference and calibrated based on lab experimental tests. KENSLABS (Huang 1993) and ILLI-SLAB (Foxworthy and Darter 1989) use finite element to model the stress and strain. However, it is recognized that there are gaps between lab and field performance. The M-E models use mechanistic method to account for the material characterization (e.g. strength development of the concrete) and use this to compute the pavement response. The response is then calibrated with the field observation to predict distresses, such as faulting. Simpson et al. (1994) developed faulting prediction models for JPCP with and without dowels under a SHRP (SHRP P-020) study. . Both models predict faulting as a function of traffic, age, design features, and site conditions. As expected, both models were positively correlated with cumulative ESALs. The outputs of the models show a trend that non-doweled JPCP develop more faulting than doweled pavements. For doweled JPCPs, faulting decreases as dowel diameter increases. Yu et al. (1997) also developed separate models for doweled and non-doweled pavements under the FHWA Rigid Pavement Performance and Rehabilitation (RPPR). Several design features such as wide-lanes were identified as significantly affect faulting. The results of these models were found to generally agree with the results from the SHRP models. The presence of a wide-lane was found to be negatively correlated with faulting in both models. The faulting decreases as wide-lane is used. Wu et al. (1994) also developed separate mechanistic-empirical faulting models for doweled and non-doweled pavement for ACPA. Erodibility was identified and included as one of the key factors influencing faulting. The percent of erosion damage at the slab corner was computed using the Miner's linear damage concept. Owusu-Antwi et al. (1997) developed mechanistic-empirical faulting model under the FHWA Nationwide Pavement Cost Model (NAPCOM) study. The model illustrated the presence of dowels significantly reduces faulting. It also shows a stabilized base, stiff subgrade and improved drainage are negatively correlated with faulting. Titus-Glover et al. (1999) recalibrated the NAPCOM model using the LTPP data. The model expresses traffic in terms of ESALs. In addition, the effects of climate are characterized with different variables, such as number of wet days. A review of these models shows relationship between faulting and traffic, age, design features, and site conditions. All models show that faulting increases rapidly and slowly leveling over time. The use of dowels can reduce the faulting significantly.

While faulting prediction models have been developed in previous studies, it is difficult to adopt these models for predicting the faulting on the aging JPCPs in Georgia. First, the mechanistic and M-E models are developed to predict faulting for new and rehabilitated (e.g., AC overlay) pavement designs, but they do not include the impact of maintenance (e.g., slab replacement and diamond grinding) on faulting performance. Most JPCPs in Georgia have been in service for more than 40 years and several maintenance treatments (e.g., slab replacement, diamond grinding, resealing, etc.) have been applied at different times. Second, the developed models were not calibrated using 40-year field observations. The models are somehow limited to the data that calibrated the distress transfer function (in terms of traffic load, weather, age, etc.). Third, these models do not make use of the existing faulting measured in the field, which is valuable for predicting faulting. The future faulting is largely dependent on the existing faulting. Finally, the current CPACES database does not provide many of the parameters such as traffic loads, drainage, etc. used in the models. It requires significant amount of efforts to acquire these inputs to use the models. Therefore, a segment-based dynamic linear regression model is proposed to predict faulting at segment level using CPACES data.

6.2 Proposed Segment-level Faulting Prediction Model

A dynamic linear regression model was proposed to predict segment-level faulting. The proposed method utilizes the historical faulting index of a segment in the CPACES database to develop a linear regression equation and uses that to forecast the next year's faulting index for the segment. Before the decision was made to use the linear regression model, the faulting predicted using the PavementME that was reviewed to provide an understanding of the faulting deterioration behavior. Figure 5.1 shows the faulting (in inches) predicted on dowel and non-dowel JPCPs by the PavementME using Georgia calibration coefficients developed under the project "Verification and Local Calibration/Validation of the MEPEG Performance Models for Use in Georgia" (ARA 2016). It shows the use of dowels and dowel diameter has significant impact on the predicted faulting. The non-dowel JPCP could reach a faulting index of 0.2 in (which is the performance criteria) in three years, while the JPCP with dowel greater than 1 in. will not reach a faulting of 0.2 in. at the end of 30 years. A close look of the deterioration rates shows the faulting increases steadily at approximately the same rate before reaching 0.2 in. After that, the faulting increases at a slower rate.

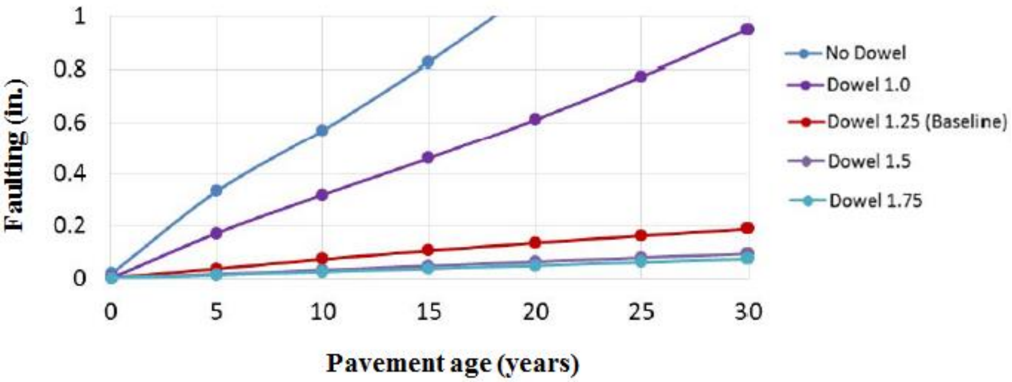


Figure 5.1 Faulting predicted using PavementME (ARA, 2016)

A review of time-series faulting index on selected segments shows the faulting index increased at a linear rate with some fluctuations. Figure 5.2 shows the time-series faulting index for non-doweled JPCPs on I-16 westbound MP 15 to MP 21. Note that they have been in service for more than 40 years and the faulting index is approximately 20 in 2016. A faulting index of 20 is equivalent to an average faulting of 3.125 mm (20/32/5*25.4~.125 mm); these segments have outperformed the predicted faulting for the non-doweled JPCPs. As discussed in Chapter 2, the faulting index can be affected by various factors, including the sample joints faulting readings were taken, the temperate, the joint repair, etc.; thus, certain fluctuations are considered reasonable. It was observed that the faulting index increased at a faster rate after reaching a faulting index of 15, which is GDOT's target for maintaining the faulting index on JPCP. Figure 5.3 depicts the detailed steps for the segment-level dynamic regression model. Each step is discussed in the following.

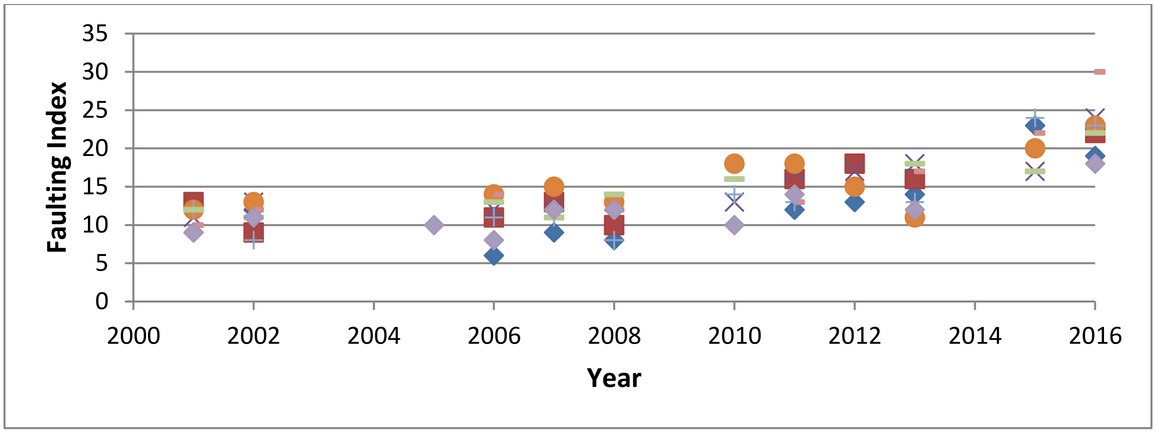


Figure 5.2 Time-series faulting index at segment level (I-16 EB)

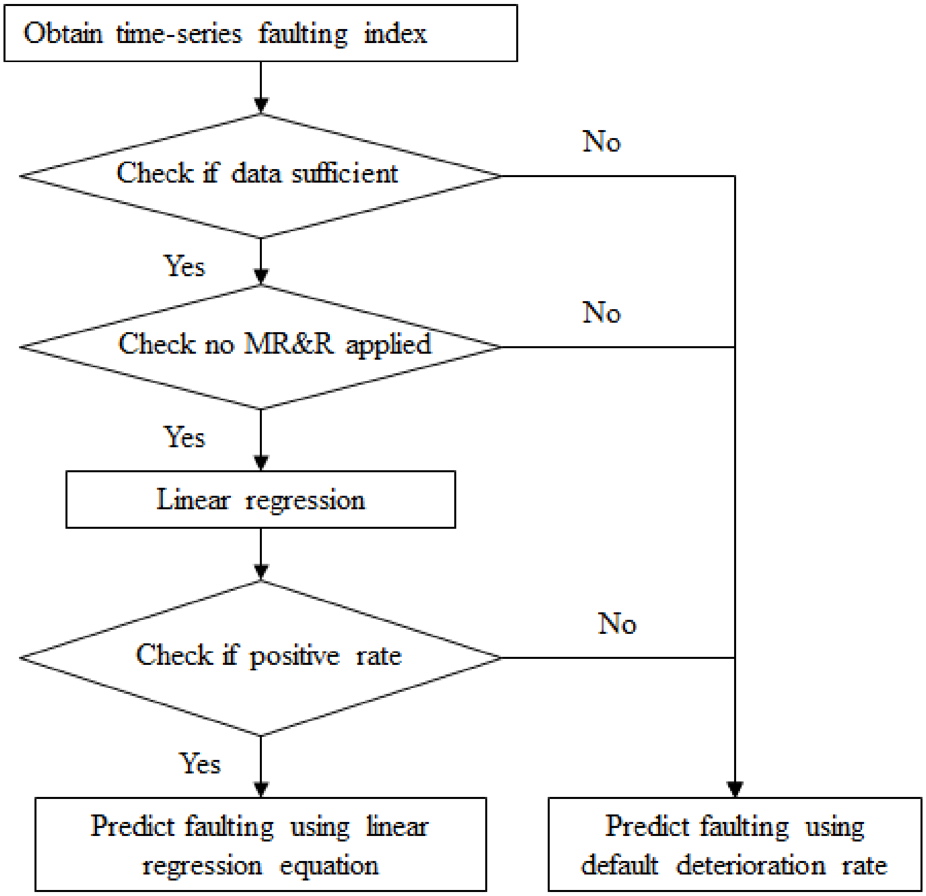


Figure 5.3 Segment-level dynamic regression model flow chart

- Obtain time-series 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 five years will be queried from the CPACES for further process.

- Check if data sufficient

  In this step, the number of faulting index in the time-series is checked to ensure the data is sufficient data (i.e., at least three faulting indexes) for performing further analysis.

- Check no MR&R applied

  It was observed in the CPACES data is that the faulting index in a certain year is abruptly decreased, most likely due to the MR&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. The CPACES database does not contain information on when MR&R were applied and, therefore, the decision as to whether the abrupt increase in the faulting index is due to MR&R or not has to be determined by logic using the data. Therefore, the faulting index is checked to determine if MR&R has been applied within three years. A significant drop in the faulting index is anticipated when MR&R actions such as diamond grinding and lane replacement are applied. Previous study (Tsai et al., 2012) found an increase of 7 in the faulting index indicates a MR&R may have been applied on the segment. This value (7) is used as the threshold for determining if MR&R has been applied.

- Linear regression

  In this step, a linear regression is then applied to estimate the deterioration rate of the faulting index. While the faulting index is expected to increase in time, fluctuation (increase and decrease) was observed in the faulting index reported in the CPACE. During this step, the major concern is the quality of the historical CPACES data. Errors in pavement evaluation data will have significant impact on the accuracy of the predicted values; however, they cannot be not be entirely eliminated, even though extensive efforts had been made to eliminate errors from the pavement condition evaluation database. Thus, the faulting index outside the 66% confidence interval will be removed from the linear regression.

- Check if positive rate

  A positive (or increasing) rate is expected for the faulting index deteriorate without MR&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 follow 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 used for the segments with MR&R, missing data, or invalid data. A rate of 0.7 and 2.5 per year is used for the faulting index less than 15 and greater than or equal to 15, respectively. This rate was derived using the selected segments on I-16 and can be revised with a larger data set with different characteristics (e.g., AADT, joint spacing, dowel, etc.)

A case was conducted using the CPACES data on two 1-mile segments on I-16 (eastbound MP 12) to demonstrate the use of the proposed method for predicting faulting. Segment on eastbound MP 12-13 was built in 1968 with non-doweled JPCP, a 30-ft joint spacing, 9 in of PCC on top of 10 in stabilized cement base. Figure 5.4 shows the measured and predicted faulting index from 2000 to 2016. The faulting index measured on this segment is relatively high compared to an average faulting index of 10 at network level in 2016. 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 index 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 illustrate it is feasible to predicting the faulting index using the proposed method based on the historical CPACES data.

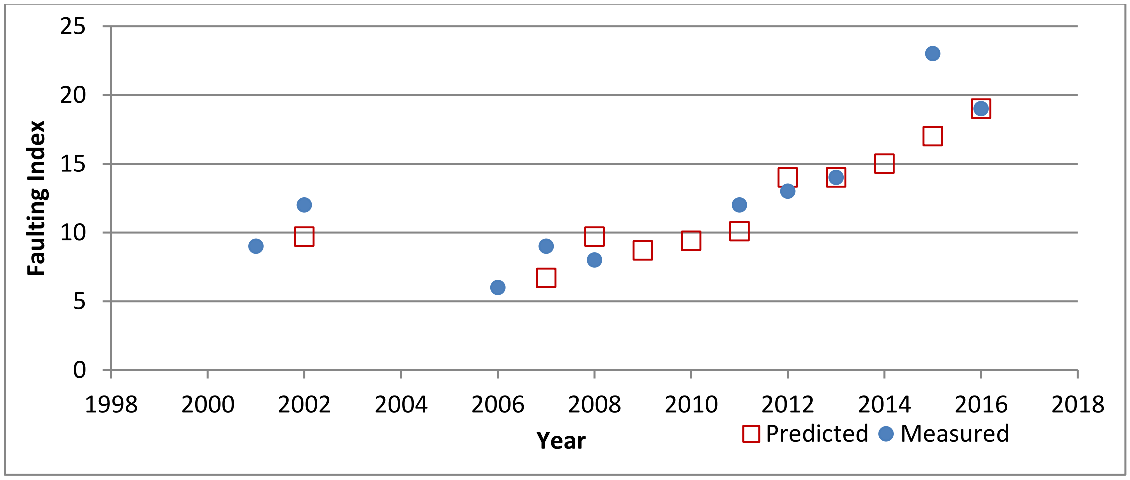


Figure 5.4 Example of predicted and measured faulting index

6.3 Summary

In this chapter, a review of faulting prediction models was conducted and summarized. The characteristics of different models and their advantage and disadvantages were compared and discussed. A dynamic linear regression model was developed for predicting the faulting on Georgia's JPCPs using CPACES data. 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. A case study was conducted on two 1-mile segments 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. The abrupt decrease in faulting index can be captured. This information can also be used to check the data for improving its quality. Comparison 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 recently 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. Some segments had invalid CPACES data and were deleted from the data analysis, as described in Chapter 3. Obviously, the linear regression model cannot be used to forecast faulting index without the historical faulting index data. For those segments, MEPDG results on typical JPCP designs can be used for forecasting a future faulting index.

The following are recommended for the future implementation of the proposed method.

- Apply to larger data set (more than 1 mile), especially apply to the incoming JPCP slab replacement plan and projects;
- Incorporate other distresses, such as IRI, broken slab and shattered slab, into the faulting prediction model; and
- Categorize the default faulting deterioration rates based on the age, design features, traffic, etc.

7. CONCLUSIONS AND RECOMMENDATIONS

Since the 1970s, GDOT has conducted its annual pavement evaluation on JPCPs based on the concrete pavement condition evaluation system (CPACES) and the data has been used for triggering treatment, determining treatment method, prioritizing projects, etc. However, the CPACES distress protocol has not been updated for many years. Today, GDOT is faced with the challenges of limited funding and the increasing needs for JPCP MR&R on its aging JPCPs that have been in service for more than four decades. There is a need to critically assess the CPACES process to ensure the data collected is of sufficient quality to support the JPCP program, including the pavement condition evaluation process, MR&R practices, and quantity estimation, to better support JPCP MR&R planning and programming. The research team had worked closely with the Office of closely to 1) refine the CPACES distress protocol, 2) develop an enhanced slab replacement quantity estimation method using 3D laser data to accurately estimate the needs, and 3) develop preliminary models for predicting segment-level faulting and broken slabs in support of future MR&R planning. The following are the major findings from this research project:

1) Several issues in the existing CPACES distress protocol were identified in a critical assessment of field distress survey, interviews with GDOT concrete pavement liaison Mr. Curtis Grovner, and reviews of historical CPACES data. It was found that the existing faulting index computation discounts the negative faulting readings; as a result, a lower faulting index (and higher rating) is being reported on these segments. Also, CPACES ratings were found to be inconsistent

because of the issues concerning inconsistency in handling negative faulting readings, inconsistency in faulting index computation, errors in rating computation, and missing or invalid distress. These issues can potentially delay the MR&R timing and underestimate MR&R needs and should be addressed to enhance MR&R decisions.

2) The modifications to the existing CPACES distress protocol, including refined slab definition, additional distress categorization, refined faulting index calculation, and data checking, were identified to address many of the issues identified in the current CPACES. The key changes are summarized as follows:
    - The broken slab was divided into three types of distresses to represent the distresses with different severity levels. The shattered slab was added to differentiate it from a broken slab because it requires a higher priority of treatment than a broken slab (e.g., single transverse crack). The corner break was added due to the potential for corner breaks to fault prematurely. The distress type definitions, severity levels, and measurement method, along with distress images, were detailed in this report.
    - The faulting index computation was modified as five times the average of "*absolute*" faulting readings ($\frac{5}{n} * \sum_{i=1}^{n} |Faulting\ Reading_i|$), to account for the negative faulting readings.
    - The CPACES rating computation was modified to include the additional distress categorization (including shattered slab and corner break). A "*null*" value will be assigned to the segments that miss the key distresses contributing to the deducts, including the international roughness index (IRI) and faulting

index. A rating of '105' will be assigned to sections of pavement under construction to denote that they are part of the system, but unavailable for rating.

3) The historical CPACES data was processed to have a consistent faulting index and rating. The analysis of FY 2015 data shows 22% of the segments with a rating less than 70. It is also noted that 15% of the segments had a rating less than 60. The majority of the segments with a low rating are on I-20 and I-16. It appears that recent budgetary and personnel restrictions have limited the capabilities to consistently maintain the JPCPs. Districts 2 and 3 had the highest percentage (34%) of segments with a rating less than 70, 61, and 53 miles, respectively.
4) An enhanced slab replacement quantity estimation method was developed and successfully demonstrated a promising capability to effectively identify distresses and accurately estimate slab replacement quantities using 1-mile 3D laser data collected on I-285. Results show a significant improvement (approximately 26%) on the accuracy of slab replacement quantity estimation compared to the current windshield survey. This method is capable of simulating different slab replacement alternatives, e.g., replacing only the severe distresses (e.g., shattered slab) or all distressed slabs, and calculating corresponding costs. This allows OM to analyze MR&R alternatives based on different treatment criteria and estimate corresponding costs.
5) A preliminary model for reliably predicting segment-level broken slab (i.e., severities) using 3D laser data was developed in support of segment-level MR&R forecasting. A case study, using three years of 3D laser data (2013, 2014, and 2015) collected in a 1-mile section on I-16, shows transition probability matrixes can be

derived using the detailed distress information derived from the 3D laser data. The proposed method is potentially promising in predicting slab replacement needs for the future.

6) A preliminary dynamic linear regression model has been developed to predict a segment-level faulting index using historical CPACES data. In conjunction with the broken slab prediction model, GDOT can better plan for future MR&R (e.g., diamond grinding and slab replacement).

Further research is recommended as follows:

1) It is recommended that the CPACES manual with the aforementioned modifications (e.g., additional distress categorization) be developed and that a computerized data collection module to implement the changes in faulting index, rating, and data checking be developed to have quality and consistent CPACES data.
2) It is recommended that statewide training is conducted on the enhanced CPACES distress protocol, especially on the additional distress categorization and slab definition, to implement the changes and to ensure consistent data being collected in the future.
3) The slab replacement quantity estimation method can be applied to a larger data set (more than 1 mile). Especially, it can be applied to an incoming JPCP slab replacement project to simulate different alternatives.
4) The preliminary broken slab prediction model needs to be expanded to include a larger data set with JPCPs in different categories by pavement deterioration stage, pavement design, and traffic.

5) It is recommended that the faulting prediction model is validated using a large data set (including the data collected in 2017) on different routes with different conditions (e.g., pavement design and traffic).

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APPENDIX A: HISTORY OF CPACES

The Georgia DOT has been conducting yearly pavement condition surveys of all jointed concrete pavement in the state for many years. The survey objectively rates roads to obtain an accurate record of the existing deterioration for each mile of pavement. The faulting at the joints is measured and visual distresses are tallied by the field survey crews. This data is then summarized in a yearly report. Pavement friction and roughness values are also included in this summary. By knowing the rate and extent of deterioration, areas needing maintenance, rehabilitation or reconstruction can be determined. The data can help establish schedules for repair, estimate contract quantities and determine the effectiveness of rehabilitation procedures. Therefore, the survey needs to be as accurate as possible.

Many of Georgia's older concrete pavements (pre-mid 1970s) were designed and built without dowels at the joints to assist with load transfer. This combined with the presence of free water under the slabs and some of the base types used have spelled trouble. Water gets under the slabs through cracks and failed joints and with the passage of heavy trucks a pumping action begins. This erodes the base material creating a void under the slabs. The slabs crack, joints and cracks spall, joint faulting or step-offs occur and shoulders adjacent to the pavement will sag and crack. Maintenance is then required to replace the broken slabs, fill the voids with grout, patch the shoulders, reseal joints and repair any spalling at the joints. Rough pavement or excessive joint faulting may require grinding or resurfacing. GDOT started collecting faulting measurements in 1971 due to these concerns, and as noted by Mr. Thomas Moreland (Previous GDOT Commissioner) the results of this testing provided the information needed to change the design standards back to require dowels in jointed concrete pavements in the mid-1970s.

An annual concrete pavement survey had been conducted since 1971, although it has changed over the years (Tsai et al., 2012). A brief history of the changes is as follows:

1971-1976: Faulting measured in outside lane only (During 1981-1994 the inside lane was also tested for faulting)

1977: Added slab distresses (cracked slab, replaced slab)

1995: Changed slab distresses (broken slab, longitudinal crack, replaced slab, joint distresses)

1996: CPACES rating developed, including CPACES program to store data

2016: Changed slab distresses (transverse crack, longitudinal crack, corner crack, shattered slab) and modified CPACES rating to JPCPACES rating. Faulting Index computation changed to address negative faulting. JPCPACES tablet program developed to gather field data.

APPENDIX B: FAULTING AND IRI DEDUCT TABLES

Faulting Index 1/32 in.		IRI mm/km	
1	0	450	0
2	0	500	0
3	0	600	0
4	0	700	0
5	0	800	0
6	1	900	0
7	3	1000	1
8	4	1100	2
9	5	1200	3
10	6	1300	4
11	8	1400	6
12	9	1500	9
13	10	1600	13
14	11	1700	17
15	13	1800	22
16	14	1900	27
17	15	2000	32
18	16	2100	37
19	18	2160	40
20	19		
21	20		
22	21		
23	23		
24	24		
25	25		