GEORGIA DOT RESEARCH PROJECT 15-02

FINAL REPORT

DEVELOPING A COMPREHENSIVE PAVEMENT CONDITION EVALUATION SYSTEM FOR RIGID PAVEMENTS IN GEORGIA

OFFICE OF PERFORMANCE-BASED MANAGEMENT
AND RESEARCH

15 KENNEDY DRIVE
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1. Report No.:
FHWA-GA-19-1502

2. Government Accession No.:

3. Recipient's Catalog No.:

4. Title and Subtitle:
Developing A Comprehensive Pavement Condition Evaluation System for Rigid Pavements in Georgia

5. Report Date:
February 2019

6. Performing Organization Code:

7. Author(s):
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8. Performing Organ. Report No.:
15-02

9. Performing Organization Name and Address:
Georgia Institute of Technology
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10. Work Unit No.:

11. Contract or Grant No.:
PI# 0013538

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 2015 – February 2019

14. Sponsoring Agency Code:

15. Supplementary Notes:
Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract:

The objective of this project is to develop standardized pavement condition evaluation systems for Georgia's rigid pavements, including continuously reinforced concrete pavement (CRCP) and jointed plain concrete pavement (JPCP). The research outcomes of this project include: 1) a first-ever CRCP pavement condition evaluation system (CRCPACES) that standardizes the condition survey of six distresses (including distress types, severity levels, extents, and measurement methods) using a windshield survey and a walkthrough survey and a rating system with distress deducts; 2) a tablet-based CRCPACES application to facilitate the data collection process and the implementation of CRCPACES; 3) an enhanced JPCP pavement condition evaluation system (JPCPACES) with a finer distress categorization to better monitor severe distresses in aged JPCP and refined treatment criteria based on today's JPCP condition; 4) a tablet-based JPCPACES application with features similar to the CRCPACES application to improve the data collection process by eliminating the existing pen-and-paper recording method; 5) new modern Georgia Faultmeters that are used for annual faulting measurement operations; and 6) a 2D-based faulting measurement method that safely and effectively measures faulting using 3D pavement data. CRCPACES, JPCPACES, and the modern Georgia Faultmeters have been validated and successfully implemented. In addition, the 2D-based faulting measurement method has been recommended for future faulting measurement operations.

17. Key Words:
Jointed plain concrete pavement; JPCP; Continuously reinforced concrete pavement; CRCP; Faultmeter; Faulting measurement

18. Distribution Statement:
No Restriction

19. Security Classification (of this report):
Unclassified

20. Security classification (of this page):
Unclassified

21. Number of Pages: 111

22. Price:

Form DOT 1700.7 (8-69)

GDOT Research Project No. 15-02

Final Report

DEVELOPING A COMPREHENSIVE PAVEMENT CONDITION EVALUATION SYSTEM FOR RIGID PAVEMENTS IN GEORGIA

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February 2019

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EXECUTIVE SUMMARY

Rigid pavements, including continuously reinforced concrete pavement (CRCP) and jointed plain concrete pavement (JPCP), are part of the state route system in Georgia. However, the Georgia Department of Transportation (GDOT) did not have a comprehensive pavement condition evaluation system for systematically monitoring CRCP and JPCP. Thus, GDOT decided to develop pavement condition evaluation systems for both CRCP and JPCP. In addition, applications and Georgia Faultmeters were developed to facilitate the condition survey and support faulting measurement operations. The outcomes of this research project are the following:

1. A CRCP pavement condition evaluation system (CRCPACES), including a distress protocol and a rating system, has been developed for GDOT. The CRCPACES standardizes the identification and quantification of six distresses (punchouts, patches, longitudinal cracks, longitudinal joint spall, shoulder distress, and transverse cracks) and deduct values for each distress.
2. A tablet-based CRCPACES application with tap-and-count features for easy data entry, embedded real-time data checking, and an integrated CRCPACES distress protocol was developed to facilitate the CRCP data collection process and the implementation of CRCPACES.
3. An enhanced JPCP pavement condition evaluation system (JPCPACES) was developed to monitor the severe distresses of aged JPCP. This included a finer distress categorization, improved faulting index calculation, and an enhanced rating system.

4. A tablet-based JPCPACES application with features similar to the CRCPACES application was developed to improve the JPCP data collection process by eliminating the current pen-and-paper recording method.
5. Eight modern Georgia Faultmeters were built so each district will have one faultmeter with which to effectively accomplish its annual faulting measurement operations.
6. A new 2D-based method that measures faulting as the elevation differences between two 2D-planes on each side of the joint was proposed as an alternative faulting measurement method. Lab and field tests showed the proposed method could successfully estimate faulting with an average error of less than 2/32 inch (Geary et al, 2018).

To ensure the implementation of pavement condition evaluation for rigid pavement, recommendations are as follows:

1. It is recommended that GDOT conduct annual statewide training on the newly developed CRCPACES and the enhanced JPCPACES.
2. It is recommended that GDOT develop applications to systemically determine the treatment methods for implementing the treatment criteria for JPCP.
3. A full-scale test of the 2D-based faulting measurement method is recommended to comprehensively validate this proposed method.
4. Further studies, including a pool-funded study to establish a national standard for an automatic faulting measurement that uses 3D pavement data, including noise removal, joint detection, and outliner removal, are recommended.

ACKNOWLEDGMENTS

We would like to thank the Georgia Department of Transportation (GDOT) for its support. The work conducted in this report was sponsored by the GDOT Office of Performance-Based Management and Research (Research Project 15-02). We would also like to thank Mr. David Jared and Mr. Binh Bui from the Office of Performance-Based Management and Research; Ms. Ernay Robinson, Mr. Larry Barnes, Mr. Sam Wheeler, Mr. David Sparks, Mr. Curtis Grovner, and many others from the Office of Maintenance, and Mr. Peter Wu from the Office of Materials and Testing for their strong support and heavy involvement in the project. We would like to thank the United States Department of Transportation (USDOT) for its support on the research project "Remote Sensing and GIS-enabled Asset Management System (RS-GAMS)," which enabled us to use emerging 3D pavement data with the Georgia Tech Sensing Vehicle (GTSV) for evaluating faulting measurement method. We would like to thank the GDOT District Engineer, Mr. Michael Taylor, and the District 3 survey team for their assistance with the field tests. We would like to thank Dr. Chengbo Ai, Blake Baklini, and Neeta Thawani for their work on the design and fabrication of the faultmeter. We would also like to thank the members of the research team at the Georgia Institute of Technology (Georgia Tech), including Georgene Geary, Anirban Chatterjee, and Geoffery Price, for their diligent work on data collection, processing, and analysis in this research project.

1. INTRODUCTION

1.1 Background and Research Need

Georgia's state route system covers 17,959 centerline-miles, of which 17,176 centerline-miles are asphalt pavements and 783 centerline-miles are rigid pavements (GDOT, 2017). The Georgia Department of Transportation (GDOT), has established an active, data-driven pavement management system to cost-effectively manage and preserve its asphalt pavements. This system includes the following: 1) a pavement condition evaluation system (PACES) that standardizes the distress survey (including distress types, severity levels, extents, and measurement methods) and a PACES rating; 2) criteria for determining adequate treatment methods; and 3) the standardized procedures for prioritizing maintenance and rehabilitation (M&R) projects and allocating funding by considering various risk metrics (Tsai & Lai, 2002). However, a similar system has not been developed for its concrete pavements, including continuously reinforced concrete pavement (CRCP) and jointed plain concrete pavement (JPCP).

GDOT does not have a pavement condition evaluation system for its CRCP. Consequently, it is difficult to determine the right timing for applying proper M&R due to a lack of condition data. Therefore, there is an urgent need to develop a CRCP pavement condition evaluation system to standardize the CRCP distress survey. GDOT's concrete pavement condition evaluation system (CPACES) was developed for its JPCP in the 1970s. Today, JPCP has aged tremendously (many pavements are now more than 40 years old) and has severe distresses. As identified in a previous study (Tsai et al., 2016), there is a need to revamp the existing CPACES to differentiate the severe distresses in aged JPCP to better support the M&R decisions; this is especially important when funding resources are limited. GDOT also faces challenges in conducting JPCP surveys. Due to the increase of damaged/non-functioning Georgia Faultmeters, GDOT does not have a sufficient number of Georgia Faultmeters to support its annual faulting measurement operations, which is required for JPCP surveys. In addition, the manual measurement of JPCP faulting using the Georgia Faultmeter is still time-consuming and unsafe, especially on roadways with heavy traffic. In summary, there is a need for developing a comprehensive pavement condition evaluation system to address the aforementioned challenges/issues and to improve the safety and efficiency of data collection by leveraging today's technologies

1.2 Research Objectives and Scopes

The objectives of this project are as follows:

1. To develop a CRCP pavement condition evaluation system, that standardizes the condition survey and a rating system quantifying the overall pavement condition.
2. To develop an application for CRCP to facilitate the data collection process and the implementation of a CRCP pavement condition evaluation system.
3. To enhance the existing JPCP pavement condition evaluation system to differentiate severe distresses in aged JPCP and to refine JPCP treatment criteria to better support maintenance and rehabilitation (M&R) decisions based on today's JPCP condition. This is especially important when funding resources are limited.

4. To develop an application for JPCP that will replace the existing pen-and-paper method and improve the data collection process.
5. To build a sufficient number of modern Georgia Faultmeters, which are required for annual JPCP faulting measurement operations.
6. To critically explore and assess alternative faulting measurement methods that can measure faulting safely and cost-effectively.

While the original scope of the study was to develop the pavement condition evaluation systems for CRCP and JPCP, the Georgia Tech Research Team made extra efforts to develop table-based data collection applications to facilitate the data collection process and the implementation of the developed pavement condition evaluation systems.

1.3 Organization of This Report

This report is organized as follows:

1. Chapter 1 introduces the background, the objectives, and the organization of this research project.
2. Chapter 2 presents the development of a CRCP pavement condition evaluation system (CRCPACES). A comprehensive review of CRCP distress protocols of various transportation DOTs (e.g., LTPP, Texas, Illinois, Virginia, and North Carolina) was conducted, and recommendations on GDOT's CRCP distress protocol were made. A new CRCPACES that standardizes a survey of six distresses and a CRCP rating with deduct values is presented.
3. Chapter 3 presents the development and implementation of a CRCPACES application that was designed to facilitate the data collection process and the

implementation of CRCPACES. The design, operation flow, and implementation of a tablet-based CRCPACES application are described in this chapter.

4. Chapter 4 presents an enhanced JPCP pavement condition evaluation (JPCPACE), which includes finer distress categorization to differentiate severe distresses of aged JPCP, improved faulting index calculation, and a refined rating system. This chapter also presents the refined treatment criteria for JPCP.
5. Chapter 5 presents the development and implementation of a JPCPACES application that uses the features similar to the CRCPACES application to eliminate the current pen-and-paper recording method and improve the data collection process.
6. Chapter 6 presents the design and fabrication of modem Georgia Faultmeters that use up-to-date sensors to replace outdated sensors. Lab and field tests were conducted to validate the newly built Georgia Faultmeters.
7. Chapter 7 presents the critical assessment of faulting measurement method using 3D pavement data. A review of current faulting measurement standards was conducted to identify issues in current standards. A 2D-based faulting measurement method was proposed, and a field test was conducted to validate the proposed method. Effects of different parameters on faulting values were also discussed.
8. Chapter 8 presents conclusions and recommendations for future research.

2 DEVELOPMENT OF CRCP PAVEMENT CONDITION EVALUATION SYSTEM (CRCPACES)

GDOT had only a limited amount of CRCP prior to 2000 and did not have a standardized condition survey. However, since 2000, GDOT has added over 400 lane miles of CRCP to its network (FHWA, 2012), more than doubling the amount of CRCP in the state. This creates a need for a CRCP pavement condition evaluation system (CRCPACES), including a distress protocol standardizing condition survey and a rating system quantifying the overall pavement condition. The distress protocol standardizes distress types, severity levels, extents, and measurement methods; the rating system associates deducts with specific distress type, severity, and extent combinations. This chapter presents the development of a first-ever CRCPACES for GDOT. First, a comprehensive literature review of existing distress protocols and rating systems for CRCP was conducted; from the findings and inputs from GDOT, the Georgia Tech Research Team drafted a distress protocol. Second, a field survey using the draft protocol was conducted to identify the refinements needed for GDOT's crews to carry out the survey in the field. Finally, a new CRCPACES has been developed for GDOT based on a literature review, results of a field survey, and consultation with GDOT engineers from the Office of Maintenance (OM) and the Office of Materials and Testing (OMAT).

2.1 Background

CRCP is a type of concrete pavement that is reinforced with transverse and continuous longitudinal steel. Due to the reinforcement, it does not need to have regularly formed joints, so it has a much lower number of transverse joints than jointed plain concrete pavement (JPCP). CRCP can have isolation joints and longitudinal joints, and it will have construction joints. Most states do not routinely construct CRCP, due mostly to the higher initial cost and/or lack of experience with this pavement type. A survey of all 50 states in the US only identified 15 that had a full understanding and commitment to CRCP, and 14 states were identified as having no experience with CRCP (FHWA, 2012).

Georgia is one of the states familiar with CRCP. A 2012 TechBrief document (FHWA, 2012) identified California, Georgia, Illinois, Louisiana, North Dakota, Oklahoma, Oregon, South Dakota, Texas, and Virginia as having experience with CRCP. GDOT was noted in the report as using CRCP as early as 1969. Unfortunately, some of those early pavements were placed on hydraulic fills and exhibited excessive settlement; CRCP was not used again in Georgia for some time. Prior to 2000, GDOT had only a limited amount of CRCP and did not have a standardized condition survey. In the 2000s, primarily due to the need for major interstate reconstruction on I-20, I-75, I-85, and I-95, GDOT added over 400 lane-miles of CRCP to its network, more than doubling the amount of CRCP in the state. This additional CRCP prompted GDOT to consider future asset management for all of its CRCP. While GDOT has had a concrete pavement evaluation system (CPACES) for JPCP since the 1980s, CPACES does not cover CRCP. Due to the differences between CRCP and JPCP, a new pavement condition evaluation is needed to specifically manage the CRCP.

2.2 Review of CRCP Pavement Condition Evaluation System

A comprehensive review was conducted to understand the CRCP distress protocols and rating systems used by other states. A limited number of states conduct CRCP surveys, and the distresses collected by each state are somewhat similar, and, in many cases, somewhat follow FHWA's Long Term Pavement Performance (LTPP) Distress Identification Manual (Miller & Bellinger, 2014). The consistencies and differences in the distress types, severity levels, and measures were summarized, and recommendations on GDOT's CRCP distress protocol were made. Literature discussing ratings used for CRCP was not as prevalent as for JPCP. Virginia DOT and Illinois DOT used methods for determining CRCP ratings similar to the way they determined JPCP ratings.

2.2.1 ***Distress Protocols***

Individual distress protocol manuals for CRCP were gathered from a number of states, including Virginia (Virginia DOT, 2012), California (Caltrans, 2015), Illinois (Illinois DOT, 2014), Texas (Texas DOT, 2015), Minnesota (Minnesota DOT, 2011), and Oregon (Oregon DOT, 2010). Many of these states' distress definitions and severity levels appeared to be based on FHWA's Long-Term Pavement Performance Distress Identification Manual (hereafter, LTPP) (Miller & Bellinger, 2014), which was established to collect research level distress data. The most common distresses identified for CRCP by the states reviewed are summarized in Table 2-1 and include punchouts, transverse cracking, longitudinal cracking, longitudinal joint spalling/condition, patches/patch deterioration, and shoulder distress. As shown in Table 2-1, all the common distresses used by the states are, also, part of the LTPP. Other measures that were noted as being used to rate the performance of CRCP were faulting of cracks, pumping, joint deterioration, blowups, and the international roughness index (IRI). A few states used average transverse crack spacing and cluster cracking. Most of the states evaluated used a manual or semi-automatic method, varying from in-house review of video to the use of consultant services. After consulting with the GDOT Office of Maintenance, a manual method was identified as the primary method for CRCP condition survey. The subsequent sections summarize the consistency and differences in the six common distresses listed in Table 2-1.

Table 2-1 Summary of CRCP distresses identified by states and the LTPP

Distress		Typical Measure	VA (2012)	CA (2015)	IL (2014)	TX (2015)	MN (2011)	OR (2010)	LTPP
Punchouts		# or # and area	Y	Y (3)	Y (3)	Y	Y[a]	Y (3)	Y (3)
Transverse Cracking		Transverse Cracking (#)	Y (3)	Y (3)	Y (3)	Y[b]	Y	Y (3)	Y (3)
		Average Transverse crack spacing (total #/segment length)	Y	Y	N[a]	Y	N	Y	N[a]
		Clustered Cracking (# and area)	Y (2)	N	N	N	N	N	N
Longitudinal Cracking		# and length	Y (3)	Y (3)	Y (3)	N[b]	N	Y (3)	Y (3)
L Joint Spalling/ Condition		length	Y	Y (3)	Y (3)	N	Y[c]	Y (3)	Y (3)
Patch/ Patch Deterioration		# or area	Y (3)	N	Y (3)	Y	Y	Y (3)	Y (3)
Durability "D" Cracking		# and area	N	N	Y (3)	Y[d]	Y	N	Y (3)
Surface Defects	Map Cracking	# and area	N	N	Y	N	N	N	Y
	Scaling	# and area	N	N	Y	N	N	N	Y
	Polished aggregate	area	N	N	Y	N	N	N	Y
Blow-ups		#	N	N	Y (3)	N	N	N	Y
Shoulder Distresses	Lane to Shoulder Dropoff	depth	Y (2)	Y (3)[e]	Y	N	N	N	Y
	Lane to Shoulder Separation	width	N	Y (3)[e]	Y	N	N	N	Y
Transverse construction joint deterioration		#	N	N	Y (3)	N	N	N	Y (3)
Pumping and Water Bleeding		# and area	N	N	Y (3)	N	N	N	Y

Y: Identified as being collected (number of severity levels)
N: Not Identified as being collected.
a: While LTPP and Illinois do not specify average transverse crack spacing in their manuals, they do record the number of transverse cracks per segment, so an average spacing could be computed.
b: Texas only counts spalled (>3" long spalled) transverse cracks (termed Spalled Cracks) and identifies longitudinal cracks longer than a foot and wider than 1 in as punchouts.
a: Minnesota categorizes punchouts and joint spalling together under a category called Localized Distress; the number of localized distress areas are recorded.
d: Texas does include D cracking in its JPCP distresses, but not in CRCP.
e: The CalTrans Manual lists shoulder distress under only JPCP, not CRCP

Punchouts

Punchouts are commonly described as localized distresses occurring between closely spaced transverse cracks in CRCP (CRSI, 2018). They can be caused by steel corrosion, an inadequate amount of steel, or excessively wide or close transverse cracks; they are considered a severe distress and the primary failure mode for CRCP. All six states and the LTPP include punchouts in their CRCP survey, as shown in Table 2-1. The LTPP identifies a punchout as “an area enclosed by two closely spaced (usually < 2 ft (or 0.6 m)) transverse cracks, a short longitudinal crack, and the edge of the pavement or a longitudinal joint,” as shown in Figure 2-1 (Miller & Bellinger, 2014); this is, also, a common definition used by many states. Since punchouts are considered localized distresses, the pattern is typically only considered a punchout when the area is less than ½ the width of the pavement, as shown in Cases 1 and 3 in Figure 2-1 (Miller & Bellinger, 2014). Both Oregon (Oregon DOT, 2010) and the LTPP specifically note that Y cracks are not considered punchouts unless they are spalled, as shown in Case 2 in Figure 2-1.

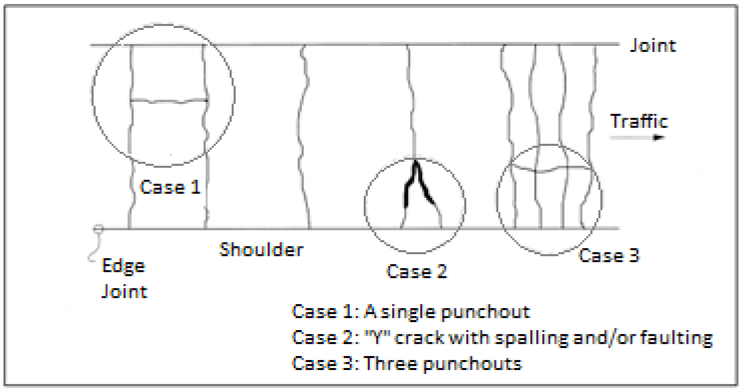


Figure 2-1 Example of CRCP punchouts (Miller & Bellinger, 2014)

The LTPP includes three severity levels for punchouts and recognizes 0.25 in of faulting as defining the line between low severity and medium severity. High severity punchouts are defined as heavily spalled (> 6 in) or faulted (> 0.5 in). Some other states do not use severity levels for punchouts. Virginia notes that punchouts will rapidly deteriorate, so they should be repaired when they are identified. Therefore, there is no need for a severity level. Virginia specifically defines a punchout as a slab that is broken (not just cracked) or a Y crack that is also spalled. Most states measure punchouts by counting the number of punchouts in a segment (i.e., a mile). A few states also measure the area of a punchout.

Since punchouts are the primary failure mode for CRCP and essential information for M&R, it is recommended punchouts be measured in GDOT's CRCP survey. The definition of a punchout is relatively standardized. Using a manual method, it is recommended that the number of punchouts (without a severity level) be recorded. The severity level and area, along with actual locations of punchouts, can be collected when a semi-automatic method is used.

Transverse Cracking

Transverse cracking refers to "cracks that are predominantly perpendicular to the pavement centerline" (FHWA, 2003). It is noted that transverse cracks in CRCP "are designed and expected to remain tight, and as such are not considered distress" (Gulden, 2013). All six states and the LTPP collect transverse cracking, as shown in Table 2-1. Most states (North Carolina, Virginia, Illinois, Texas, and Oregon) and the LTPP also specifically note that transverse cracking by itself is not truly a distress in CRCP because it is expected and normal, but they measure it to monitor the spacing and frequency. Although punchouts are typically found where the transverse crack spacing is between 1 ft and 2 ft, the average transverse crack spacing is not a good indicator of punchout potential in a segment because of the variability in crack spacing (Selezneva et al., 2013).

Transverse cracking is typically measured by counting the number of transverse cracks in a segment (i.e., per 100/200 ft section or per mile). Using the segment length, average transverse cracking spacing can be computed in most cases. Some states have identified three severity levels for cracking that are related to spalling, faulting, or both. Most states identify low-severity cracking as tight or closed cracks with no to low spalling. States that do not use severity levels have a minimum criterion to be considered a crack. California only counts cracks with an average crack width greater than 0.05 in, and Minnesota only counts cracks greater than ¾ in wide or cracks with faulting greater than ¼ in as transverse cracks. It was noted that Minnesota could not compute average transverse cracks due to transverse cracks only being counted if they are greater than ¾ in in width or faulted greater than ¼ in.

Due to the difficulty of counting transverse cracks in the entire segment (e.g., 1 mile), it is recommended that a 100-ft sample location is used for transverse cracking, similar to GDOT's practice in its COPACES survey. Since GDOT already uses transverse cracking and severity levels for JPCP, it is recommended that the same two severity levels be used for CRCP. This will provide consistency in GDOT's concrete pavement evaluations.

Longitudinal Cracking

Longitudinal cracks run parallel to the pavement centerline and can be inside or outside the wheelpath. They are caused by poor construction techniques or subgrade settlement and are typically localized. Four states and the LTPP collect longitudinal cracking, as shown in Table 2-1. Most states and the LTPPP measure longitudinal cracks by number and/or length (e.g., linear foot). Severity levels vary and can be defined by the amount of spalling (North Carolina; Virginia) and/or the average crack width (California). The LTPP, Illinois, and Oregon use spalling, faulting, and crack width to define severity levels. Oregon further differentiates between wheelpath and non-wheelpath longitudinal cracking.

Since longitudinal cracking may be localized, it would be best that it be captured throughout the entire segment (e.g., 1 mile), preferably noted as inside or outside the wheelpath and with a location reference, to support M&R decisions. However, it is questionable that this could be accurately accomplished using a manual method. Since GDOT already uses longitudinal cracking and severity levels for JPCP, it is recommended that the same two severity levels be used. Again, this will provide consistency in GDOT's concrete pavement evaluations.

Longitudinal Joint Spalling/Condition

Longitudinal joint spalling is any form of breaking or spalling of the CRCP within a short distance (e.g., 1 ft) of the longitudinal joint. "Spalls are primarily caused by high deflections, infiltration of incompressible materials, weak concrete, or the corrosion of reinforcing steel" (Gulden, 2013). Six states and the LTPP collect longitudinal joint spalling, although some call it "joint condition" (Oregon) or "centerline joint spalling" (Illinois). All measure spalling using length or percentage along the joint. The LTPP, Oregon, and Illinois each use the same criteria for severity levels for longitudinal joint spalling: low < 3 in spalling; medium 3-6 in spalling; and high > 6 in spalling. However, several others (e.g., California) do not consider severity levels. California does have criteria for minimum area of a spall (500 mm^2) to be identified as longitudinal joint spalling. Most states include information on the joint seal condition, either as part of the longitudinal joint spalling distress or as a separate distress.

Since GDOT already collects joint distress information with no severity level for JPCP to identify the need for maintenance, it is recommended that the percentage of joint distress be collected for CRCP. This will provide consistency in concrete pavement evaluation, make it easier for the raters to adjust to, and provide consistency in GDOT's concrete pavement condition evaluations.

Patches/Patch Deterioration

Properly constructed patches can restore CRCP to a functional condition and extend its service life. Deteriorated patches can be a sign of a deeper problem or be the result of improper patching; in either condition, deteriorated patches need to be identified and/or repaired. Five states and the LTPP identify patches or patch deterioration as a form of CRCP distress, as shown in Table 2-1. Most states record the number of patches, and some include length (Minnesota) or area (North Carolina and Virginia), as well. As was the case for the other CRCP distresses, while several states and the LTPP use severity levels for patches, several do not consider severity levels. All those that acknowledge severity levels identify low-severity patches as including any patch with no distress. Some states consider asphalt patches and concrete patches separately, either as different distress types altogether (North Carolina and Texas) or as distresses to be measured separately under the generic patching distress type (LTPP and Virginia).

Based on the M&R need, it is recommended that patches be collected with two severity levels. Level 1 is for patches in good condition (i.e., no need for maintenance) and Level 2 is for patches that require maintenance.

Shoulder Distress

Shoulder distress (i.e., lane-to-shoulder dropoff or separation) is caused by loss of support under the shoulder due to settlement or pumping of fines from under the pavement. Several states (e.g., California and Illinois) include shoulder distress in their protocols. The LTPP measures the depth and width of shoulder dropoff and separation, while states typically measure the percentage or length of shoulder distress.

Since GDOT already collects shoulder distress data with two severity levels for JPCP, it is recommended that the same two severity levels be used for CRCP.

2.2.2 ***Rating Systems***

The AASHTO Pavement Management Guide (AASHTO, 2012) identifies two main types of pavement condition indices that are used in rating systems: composite indices and individual indices. The PACEs values used by GDOT for asphalt and JPCP pavements are considered a composite index that combines different types of distresses into one rating value (a PACEs or CPACEs value). Composite indices are beneficial for making comparisons at the network level. Individual indices (like cracking or ride indices) can be beneficial in determining treatment methods, but they add complexity to network level management systems. Literature on ratings used for CRCP, especially the deduct values, was not as prevalent as for JPCP. The following section provides two examples of state rating systems for CRCP, in which Virginia uses individual indices (McGhee et al., 2002), and Illinois uses a composite index (ILDOT, 2012).

Virginia DOT

Virginia DOT uses a critical condition index (CCI) for both its asphalt and concrete pavements. The CCI is defined as the lowest of the individual overall indices. Virginia has two overall indices, the concrete punchout rating (CPR) and concrete distress index (CDR) for CRCP; the CCI is the lower of CPR and CDR (Heltzel, 2014). The two indices (CPR and CDR) are a combination of different distresses, as shown in Table 2-2 (McGhee et al., 2002). Each rating index is based on a 0-100 scale, with 100 being a pavement in perfect condition (the same as GDOT's PACES rating). Each distress is deducted from 100 based on a distress equation.

Table 2-2 Virginia DOT CRCP Indices (*McGhee et al., 2002*)

Concrete Punchout Rating (CPR)	Concrete Distress Rating (CDR)
Punchouts	Transverse cracking
Cluster cracking	Longitudinal cracking
Asphalt patching	PCC patching
	Longitudinal joint spalling

The equations used for the deduct values were developed with the intention of aligning them with the shape of the U.S. Army Corp of Engineers PAVER deduct curves (also found in ASTM D6433-11 (ASTM, 2011)). As an example, the deduct equation for punchouts and cluster cracking are given in Equations 4.1 and 4.2.

$$PunchoutDeduc\ t = 25 * (\%\ of\ Pavement\ Area\ Punched)^{0.5} \tag{4.1}$$

$$ClusterDeduct = 2.6 * (\%\ of\ Area\_Sev1)^{0.76} + 6.8 * (\%\ of\ Area\_Sev2)^{0.66} \tag{4.2}$$

Equation 4.1 was designed to provide a deduct value over 40 if 3% of the pavement is consumed with punchouts. In a similar manner, Equation 4.2, where cluster cracking is identified by two severity levels, provides a deduct value over 40 if 9% of each Level 1 and Level 2 clustering cracking occurs in CRCP. It is noted that the deduct values for each individual distress index are typically high compared to the deduct values for the same distress in a composite index (in which the distress deduct values need to sum up to find the composite rating). In either case, the CCI would be below 60, which places the pavement in a “poor” category based on Virginia DOT’s pavement condition categories (as shown in Table 2-3). Virginia considers pavements with CCI at 60 or below as deficient and in need of maintenance. In contrast, GDOT has historically used 70 as a maintenance cut-off rating. As GDOT uses different threshold values for pavement categories and M&R decisions, the deduct equations developed by Virginia cannot be directly adapted in Georgia.

Table 2-3 Virginia DOT’s Pavement Condition Definition (*McGhee et al., 2002*)

Pavement Condition	Index Scale (CCI)
Excellent	90 and above
Good	70-89
Fair	60-69
Poor	50-59
Very poor	49 and below

<u>*Illinois DOT*</u>

Illinois DOT’s CRCP index is similar to its JPCP and asphalt pavement indexes in that it uses a regression equation to compute a rating scale of 0 to 9; this is in contrast to GDOT’s CPACES, which uses 100. The equations Illinois uses for CRCP are provided in Equations 4.3 and 4.4 as follows:

$$Interstate = 9.0 - 0.007*IRI - 0.225*A - 0.317*B - 0.342*D - 0.254*E - 0.085*F - 0.103*J - 0.322*K \quad (4.3)$$

$$Non\text{-}Interstate = 8.204 - 0.003*IRI - 0.334*A - 0.226*B - 0.318*D - 0.049*F - 0.165*J \quad (4.4)$$

Where A to J represent the common distresses and their distress range:

A= D-cracking (1-5); B= transverse cracking (1-5); D=centerline deterioration (1-3); E= longitudinal crack (1-4); F=edge punchouts (1-3); J= popouts/high steel (1-3); K= patch deterioration (1-4)

It is noted that a punchout (considered a major distress in CRCP) has the lowest coefficient of any of the distresses (0.085 and 0.049 for interstate and non-interstate, respectively). This could be a function of relying on regression equations too heavily or the fact that D-cracking (a materials distress) is the cause of much more distress in CRCPs in Illinois than the typical CRCP punchout distress.

Since the regression equations are based on Illinois pavements, the equations cannot be adapted in Georgia, especially since Georgia does not have D-cracking aggregates. In addition, the regression approach is not recommended for Georgia because Georgia has limited data on the small amount of CRCP located in the state.

In summary, due to the differences in CRCP distresses, the pavement condition categories, and the rating scale and/or system (composite index vs. distress index) used, it is not advisable or recommended that a rating system from other states be adopted. GDOT should develop a rating system for CRCP that is similar to its JPCP rating system. Since GDOT has a limited number of CRCP pavements, it is recommended GDOT's deduct values be identified by using a method similar to Virginia's, in which existing curves or deduct values (i.e. GDOT's existing JPCP deduct values) are used to approximate change in the deduct values. The deduct values themselves can be adjusted to better correlate with GDOT's experience with CRCP.

2.3 Development of GDOT's CRCP Pavement Condition Evaluation System (CRCPACES)

A CRCP Pavement Condition Evaluation System (CRCPACES) was developed by 1) creating a draft distress protocol and rating system based on a review of existing distress protocols, rating systems, and inputs from GDOT, 2) conducting a field survey to gather feedback, and 3) refining the distress protocol and rating system based on the feedback.

The Georgia Tech Research Team developed a draft distress protocol based on a review of other states distress protocols for CRCP (Section 2.2.1), GDOT's existing concrete pavement condition evaluation system for JPCP, and consultation with the engineers from GDOT's Office of Maintenance (OM) and Office of Materials and Testing (OMAT). The draft report was submitted to OM for review in February 2016. Subsequently, a field survey was conducted and the draft distress protocol was refined based on the results of the field survey. It is noted that for consistency for the GDOT surveyors, the CRCP distress protocol and rating system were designed to match GDOT's existing JPCPACES system as much as possible because the same personnel would be doing the JPCP and CRCP surveys. The field survey, finalized distress protocol, and rating system are described in the subsequent sections. A Continuously

Reinforced Concrete Pavement Evaluation System (CRCPACES) Instructional Manual, was, also, developed to provide guidance on the survey on CRCP.

2.3.1 *Field Survey*

A field survey based on the draft distress protocol was performed to ensure it can be practically implemented in the field. To enhance the draft protocol, OM liaisons and the Georgia Tech Research Team conducted a field survey on two 1-mile CRCP sections of I-75 on March 24, 2016, to identify any ambiguities or necessary refinements. OM's liaisons were divided into two 2-person groups to conduct the survey, and the Georgia Tech Research Team recorded the distress data. Distresses were recorded with a survey form designed to collect the proposed CRCP distress values. During the windshield survey, one liaison drove the car while another observed the distresses in CRCP. At the 100-ft sample location, both liaisons measured and recorded transverse cracking separately. Thus, two surveys were conducted on each of the two miles, and four surveys were conducted at the 100-ft sample location. These multiple surveys were used to check for consistency and repeatability. At the end of each mile, liaisons were asked to provide their ratings of the surveyed mile for validating the rating system. The results of the field survey were used to improve the protocol and guidance and to answer some questions that the Georgia Tech researchers had developed based on the literature review. The issues and solutions identified are as follows:

Punchouts

The field survey confirmed the concern that Severity Level 1 punchouts would be difficult to identify; therefore, the definition of Severity Level 1 punchouts was clarified as Severity Level 1. In addition, Severity Level 1 punchouts were removed from the rating system.

Transverse Cracking

The field survey identified the difficulty in consistently identifying Severity Level 1 transverse cracks, even with a walking survey. The presence of water and the way the light shined on the pavement could influence the appearance of these tight cracks. To counter this condition and to improve repeatability, the distress protocol and rating system were changed to focus on distressed transverse cracks. In addition, per GDOT's Office of Maintenance liaisons' suggestion, a second 100-ft sample location, which was the "representative" location, was used for transverse cracking. Therefore, transverse cracking will be surveyed within two 100-ft sample locations (one fixed location and one representative location). The fixed location provides information on transverse cracking changing over time at the same location. The representative location represents the overall transverse cracking within the segment (not worst or best).

Longitudinal Cracking

The field survey did satisfy the researchers' concern that the longitudinal cracking could not be identified by length using just a windshield survey. The raters did not have a problem identifying distressed longitudinal cracks, but low- severity longitudinal cracks were not consistently identified. This was rectified by identifying a new severity level for longitudinal cracks. Level 1 remained a tight crack, Level 2 was defined as a crack with visible spalling, and Level 3 was defined as a crack > ¼ in wide. Previously, only Levels 1 and 2 were considered, with ¼ in width being the separation. The rating does not use longitudinal crack Severity Level 1 due to the difficulty in identifying it, but it is still collected in case it can be seen so as to differentiate it from Severity Level 2.

Punchouts and Patching

The field survey identified potential confusion between punchouts and patches. Additional guidance was provided in the manual to count an area (like the one shown in Figure 2-2) as a punchout; it was based on the condition that if more than ½ of the original concrete material remained in the area, it was a punchout; otherwise, it was a patch. It was also clearly noted that the distress condition could not be counted as both a patch and a punchout. It should also be noted that both a Severity Level 2 patch and a Severity Level 2 punchout have the same deduct effect on the pavement rating.

Figure 2-2 Severity Level 2 punchout

2.3.2 *Distress Protocol*

Based on the feedback from the field survey and consultation with the engineers from OM and OMAT, a CRCPACES distress protocol was developed. The final CRCPACES distress protocol includes a survey of six common distresses in CRCP that are important for M&R needs and a treatment method. This includes punchouts, patches, longitudinal crack, longitudinal joint condition, shoulder distress, and transverse cracks. Table 2-4 summarizes the distress types, severity levels, extents, and measurement methods. The survey is performed by using the combination of a walkthrough survey of two 100-ft sample locations for transverse cracks and a windshield survey of an entire mile (with 100% coverage) for the other five distresses. The two sample locations include one at a "fixed" location and another at the "representative" location identified by the surveyor. Within each 100-ft sample location, the number of transverse cracks is recorded based on the severity level. For the other distresses, the number, length, or percentage of each distress observed in the entire 1-mile segment is recorded. A CRCPACES instructional manual (Continuously Reinforced Concrete Pavement Condition Evaluation System (CRCPACES) Instructional Manual) with a description and photos of distress types, severity levels, extents, and measurement methods, was developed to provide guideline on conducting condition survey for CRCP. Each distress is briefly described in the following discussion.

Table 2-4 Summary of CRCPACES Distresses

Distress	Severity Level	Extent	Measurement Method
Punchouts	Level 1	Number per mile	1-mile section
	Level 2		
Patches	Level 1	Number per mile (minimum 1 ft X 1 ft)	
	Level 2		
Longitudinal Cracks	Level 1	Total Length per Mile	
	Level 2		
	Level 3		
Longitudinal Joint Spall	Level 1	Percent of Mile	
	Level 2		
Shoulder Distress	Level 1	Percent of Mile	
	Level 2		
Transverse Cracks	Level 1 Level 2	Number per 100 ft Closest Spacing (ft)	Two (2) 100-ft sample locations

There will be two 100-ft sample locations selected to represent the full mile for transverse crack spacing. These are selected per the following guidelines:

- The first section will be the first 100 ft of the mile, starting from the milepost. This is to provide a reference of the same spot over time.
- The second section will be a representative 100-ft section of the mile. Representative is defined as related to representative severity levels and number of transverse cracks.
  Drive the first ½ mile then select a representative section in the second ½ mile.

Punchouts

Punchouts are enclosed by two transverse cracks (usually less than 2 ft apart), the pavement edge, and a longitudinal crack. Punchouts are measured by the total number per mile. They have two severity levels:

- Severity Level 1

  Pavement that has a clear punchout pattern but no other distresses associated with the punchout.

- Severity Level 2

  Pavement that has a punchout pattern and other distresses associated with the punchout (spalling, cracking, or faulting), or a “Y” crack with spalling or faulting.

Patches

Patches include properly constructed and deteriorated patches that need to be identified and repaired. Patches are measured by the total number in a mile and have two severity levels:

- Severity Level 1

  Patch is in good condition and performing as anticipated.

- Severity Level 2

  Patch has distresses or patch is asphalt.

Longitudinal Cracking

These cracks run parallel to traffic and can be inside or outside the wheelpath. Longitudinal cracks are measured as a percent of the total mile. There are three severity levels:

- Severity Level 1

  A tight, closed crack with minimal spalling, faulting, and not very wide.

- Severity Level 2

  A crack with visible spalling OR faulting >1/4 in.

- Severity Level 3

  A crack with visible spalling in a wheelpath OR a width >1/4 in.

Longitudinal Joint Spall

Longitudinal spalled joints are measured as a percent of the mile that is spalled at two severity levels:

- Severity Level 1

  Patch is in good condition and performing as anticipated.

- Severity Level 2

  Patch has distresses or patch is asphalt.

Shoulder Distress

Shoulder distresses are usually presented as depressions or “potholes” where the edge of the pavement meets the shoulder. Shoulder distresses for CRCP are no different than for JPCP in the CPACES manual. Shoulder distresses are measured as a percent of the mile at the two severity levels:

- Severity Level 1

  Depressions next to the longitudinal joint on the shoulder. No pumping of material onto the shoulder; patching is not required. No more than a 1-in difference between the pavement and the shoulder elevation.

- Severity Level 2

  Large depressions next to the longitudinal joint on the shoulder. Pumping of material onto the shoulder; patching is required. The shoulder can be more than 1-in lower than the pavement.

Transverse Cracking

Transverse cracks are described by two severity levels and are measured in two 100-ft walking section samples. A fixed sample location is used to monitor the change over time, and another "representative" sample location is used to represent the overall transverse crack within the mile.

- Severity Level 1

  A tight, closed crack.

- Severity Level 2

  A crack with any spalling or faulting OR a wide (> ¼ in) crack.

2.3.3 ***Rating System***

A composite rating (scale 0-100) was developed to represent the overall condition of the CRCP per mile. Similar to GDOT's rating for asphalt pavement and JPCP, the CRCP rating is computed based upon the severity and extent of each distress—cracking, smoothness (IRI), longitudinal joint spalls, shoulder distress, patching, and punchouts, as shown in Equation 4.5. The deducts for each distress are specified using the distress deduct functions, which are approximated to GDOT's JPCP deduct functions. The distresses common to JPCP (smoothness and shoulder distress) were designated using the same criteria as JPCP. For example, smoothness and shoulder distress each have a maximum deduct of 40 and 10, respectively, in JPCP. The CRCP rating is the same for these two distresses. Punchouts are a major distress, but they also can be repaired by full depth repairs, so the number of punchouts is important more as an indicator of the rate of new punchouts. The deduct distress functions were adjusted using the results from the field survey to match the computed rating to the ratings given by the engineers.

The CRCP rating is computed using Equation 4.5 as follows:

$$CRCP\ Rating = 100 - D_{PO} - D_{SM} - D_C - D_{PA} - D_{SD} - D_{LJ} \tag{4.5}$$

Where the distresses associated with the deduct values are shown in Table 2-5 and Table 2-6.

Table 2-5 Deducts, Definitions and Maximum Values

Deduct	Category	Max Value	Deduct	Category	Max Value
D_{PO}:	Punchout	40	D_{PA}:	Patches	30
D_{SM}:	Smoothness (IRI)	40	D_{SD}:	Shoulder Distress	10
D_C:	Cracks	30	D_{LJ}:	Longitudinal Joint Spalling	10

$$D_{PO} = 2 * \#\ of\ SL2\ Punchouts\ (when\ less\ than\ or\ equal\ to\ 10\ punchouts)$$

$$= 3 * (\#\ of\ SL2\ Punchouts - 10) + 20\ (when\ greater\ than\ 10\ punchouts)$$

$$If\ D_{PO} > 40\ Then\ D_{PO} = 40$$

$$D_{SM} = Smoothness\left(\frac{IRI}{HRI}\right) deduct\ from\ Table\ 2-6$$

$$D_C = D_{CT} + D_{CL}$$

$$Where\ D_{CT} = \frac{\#\ Transverse\ SL2\ in\ 100ft}{4}\ and\ where\ \max D_{CT} = 10$$

$$D_{CL} = \frac{\%\ of\ mile\ with\ Longitudinal\ \ L2}{4}\ and\ where\ \max D_{CL} = 20$$

$$Therefore, if\ D_C > 30\ \ Then\ D_C = 30$$

$$D_{PA} = 2 * \#\ of\ SL2\ Patches\ (Up\ to\ 10\ Patches)$$

$$= 3 * (\#\ of\ SL2\ Patches - 10) + 20\ (For >\ 10\ Patches)$$

$$If\ D_{PA} > 30\ \ Then\ D_{PA} = 30$$

$$D_{SD} = \frac{\%\ SL1\ Shoulder\ Distress}{10} + \frac{\%\ SL2\ Shoulder\ Distress}{5}$$

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

$$D_{LJ} = \frac{\%\ SL1\ Spalled\ Long.Joints}{10} + \frac{\%\ SL2\ Spalled\ Long.Joints}{5}$$

$$If\ D_{LJ} > 0\ \ Then\ D_{LJ} = 10$$

Table 2-6 Smoothness (HRI or IRI) Deducts

HRI* (mm/km)	Deduct	IRI (mm/km)
500	0	625
600	0	750
700	0	875
800	0	1000
900	0	1125
1000	1	1250
1100	2	1375
1200	3	1500
1300	4	1625
1400	6	1750
1500	9	1875
1600	13	2000
1700	17	2125
1800	22	2250
1900	27	2375
2000	32	2500
2100	37	2625
2200	40	2750

*Note: Interpolate between these values, but use even numbers and round down; for example, an HRI of 1250 has a deduct of 3, but an HRI of 1350 has a deduct of 5.

3 DEVELOPMENT OF CRCPACES APPLICATION

A new CRCPACES distress protocol that documents the condition survey process and includes guidance on how to categorize and record distress types and severity levels was developed in Chapter 2. Through the observation of the current JPCP survey and in consultation with OM engineers, the use of a pen-and-paper method for recording data was identified as having many drawbacks that would hinder the implementation of CRCPACES. First, the data quality can be compromised because of human errors. Human errors can include misunderstanding of the CPACES calculations and mistypes. Second, after a condition survey using the pen-and-paper method, additional manual data entry is needed to transfer the data from paper to electronic format, which results in decreased productivity. However, the condition survey process can be improved to increase efficiency and data quality by using a computerized application. Therefore, the Georgia Tech Research Team developed a tablet-based CRCPACES application for the CRCP survey to ensure data quality, enhance productivity, and facilitate implementation of the CRCPACES distress protocol. This chapter presents the design, development, and implementation of the CRCPACES application.

3.1 Design of CRCPACES Application

Figure 3-1 illustrates the system architecture of CRCPACES. Four components (data collection, IRI entry, upload, and reporting) were required to support the entire condition survey process from data collection to submission of the data into a central database for use in pavement management decision-making. In the field, a Windows-based tablet PC will be used for data collection. Data input, therefore, can be easily accomplished by touching the screen with a stylus or fingers. After the survey has been completed, the data will be transferred to the District Offices, and the international roughness index (IRI), which is one of the distresses in CRCPACES, will be added (note that the IRI is collected by a different unit). The data will then be uploaded to the central database. Finally, application(s) can be developed to report the data, making it available for those who need to make informed pavement management decisions, such as determining treatment and prioritizing projects. A tablet-based CRCPACES data collection app and IRI entry app were developed in this project.

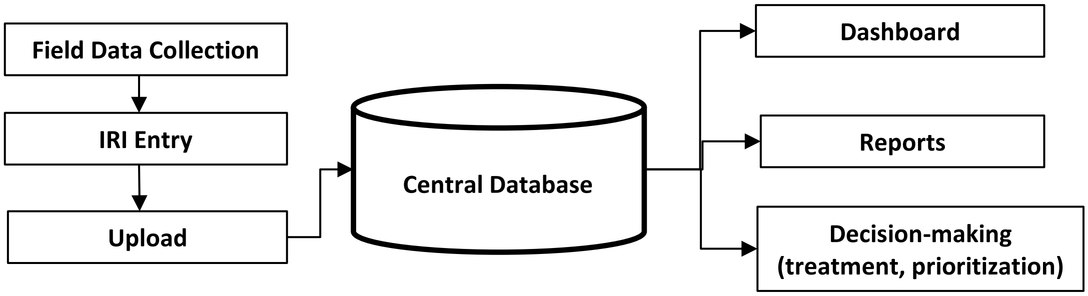


Figure 3-1 CRCPACES system architecture

The data collection app serves as a replacement for the pen-and-paper method. The data collection app is to be used in combination with a windshield survey and a walkthrough of two 100-ft sample locations. Therefore, the data collection app is a Windows 8 app optimized for tablet use. Windows 8 applications use the .NET framework. The delivered application runs on the Windows 8 and Windows 10 operating system. Microsoft Surface tablets were used for testing and deployment. Tablets were used because of their portability, lightweight, low power consumption, and touch-based interface, which is particularly useful inside a vehicle. The touch-based interface can eliminate the inconvenience of using a conventional mouse and keyboard. Tablets also provide the desired performance much more cost-effectively than laptops. Smartphones were not used because the screen size was too small to conveniently conduct the survey. Also, the cellular capabilities of tablets open up possibilities for future improvements. The IRI entry was designed as a Windows 8 application optimized for desktop use in the office.

The data collection app was designed with features such as tap-and-count and embedded real-time data checking to provide a user-friendly interface. The design of the data collection app for CRCP was adapted from the app developed for JPCP. The features were designed based on the observation of current JPCP survey and discussion with the JPCP survey crew. A review of the current JPCP survey process and the design of the features are discussed in Section 5.2.

3.2 Development of CRCPACES Application

The CRCPACES application was developed with special features (such as tap-to-count, real-time data checking, an embedded CRCPACES distress protocol, etc.) to streamline the data collection process while enhancing productivity and ensuring data quality. A detailed user's manual for data collection app and IRI entry component can be found in CRCPACES/JPCPACES Application User Manual and IRI Entry User Manual, respectively. Note that the user manual can also be used for JPCPACES application (Section 5.2) because the user interfaces for both CRCPACSE and JPCPACES are similar to provide user consistency. This section presents the operation flow and some major functions.

Step 1: Conduct the condition survey

While performing a condition survey, the user will use the data collection app on a tablet PC for recording data and, if necessary, access the CRCPACES distress protocol. Figure 3-2 shows the operation flow of the data collection app. Users will conduct the survey as described in Steps 1.1, 1.2, and 1.3.

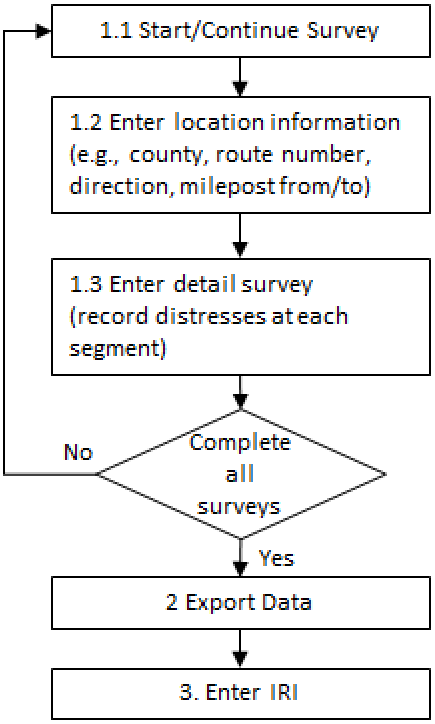


Figure 3-2 Operation flow of the CRCPACES application

- Step 1.1. Start/Continue Surveys: Users start the data collection app, as shown in Figure 3-3. The app can be used entirely via the touchscreen. Buttons are enlarged to make data entry easier in a moving vehicle. The user clicks/taps "Start/Continue Surveys" to start a new survey or continue an existing survey.

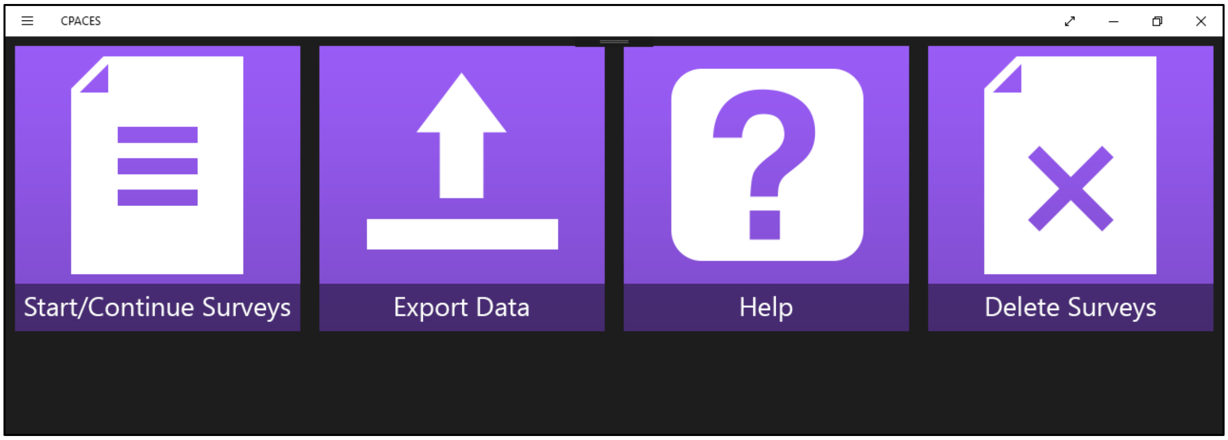
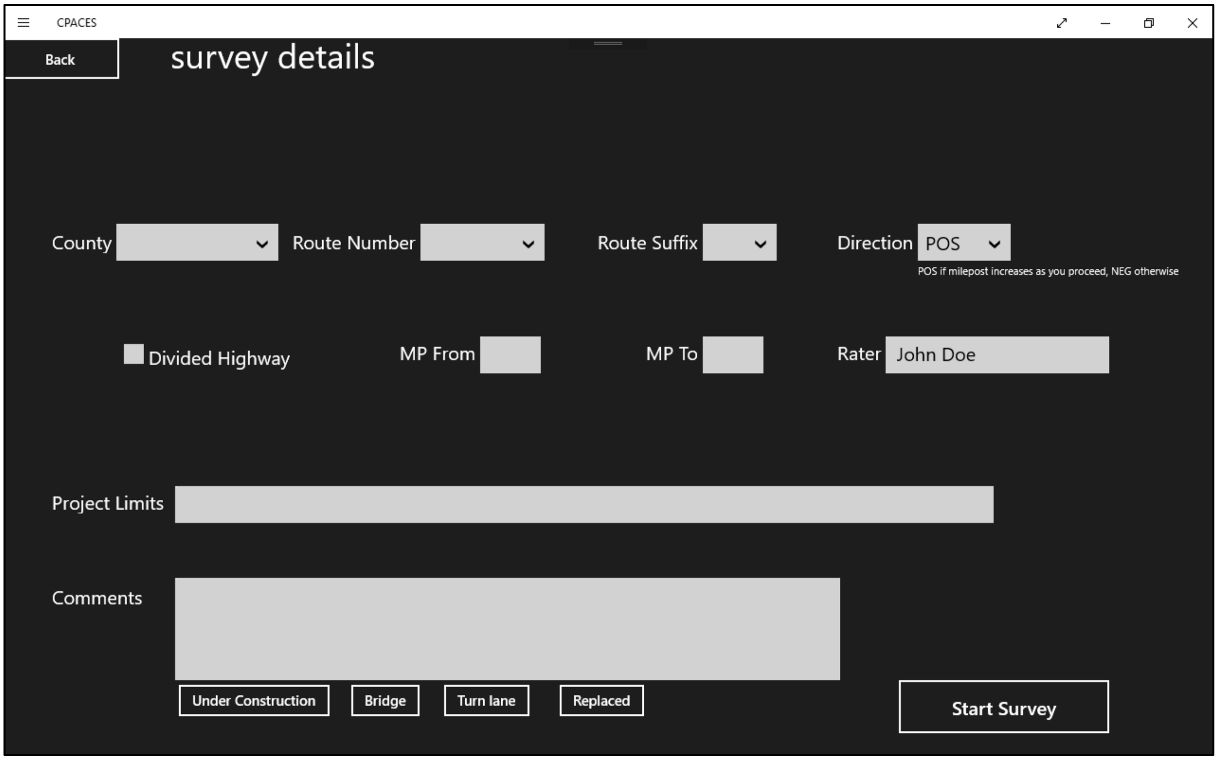


Figure 3-3 Homepage of the CRCPACES data collection app

- Step 1.2. Enter Location Information: A survey refers to a stretch of roadway consisting of one or more 1-mile segments. The location is defined by a county, a route number in the county, and the mileposts at the ends of the survey stretch. Once users choose to create a new survey, they are navigated to the survey details page, shown in Figure 3-4. On this page, the user can enter all the information that is common for the entire survey. This removes the repetition found in the current GDOT JPCP survey. Several data validation checks are also in place to ensure that the entered information is complete and valid. For example, using lookup tables ensures that the user enters only valid values for the county name and corresponding valid values for the route number, route suffix, and milepost. Using drop-down menus and constrained values ensures that the correct location data can be entered conveniently. After valid and complete details have been filled in, the user can press the “Start Survey” button to go to the Detailed Survey page.



Direction POS

POS if milepost increases as you proceed, NEG otherwise

Rater John Doe

Figure 3-4 Location information page of the CRCPACES data collection app

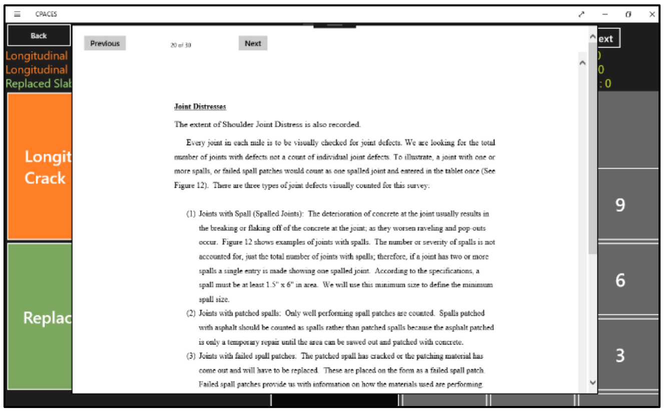
- Step 1.3. Enter Detailed Survey: The survey page (as shown in Figure 3-5) is the main data entry interface for the data collection app. At the top, the current segment being surveyed is displayed; from here, the user can navigate to other segments. Below that, counters show the number of distresses measured up to that point for that segment. The colored distress buttons are used for recording distresses. The buttons are kept as large as possible to optimize the interface for data entry. Tally mark distresses, such as punchouts and patches, can be entered using the buttons on the screen. The user just taps the button as a surveyor observes the distresses (e.g., a punchout) during the windshield survey. These buttons are color-coded to match the counters at the top. Shoulder distresses are aggregated at the end of the mile, and they can be entered using the slider at the bottom of the page. Any changes are automatically saved to an internal database as soon as they are made. Mistakes can be undone by using the "UNDO" button. Tapping the "HELP" button in the top middle of the survey page opens a document listing the distresses in the CRCPACES distress protocol. Tapping on any of the distresses opens up the CRCPACES manual definition for that distress (as shown in Figure 3-6). This serves as a quick reference for survey personnel to reduce subjectivity during the survey. The data is saved at every entry, so users can simply close the app once the survey has been completed.

County: 157 Route: 332 00 MP: 2.0 to 6.0

Long. Cracks 1: 0
Long. Cracks 2: 0
Long. Cracks 3: 0
Lo. Crk. 1 Len: 0 ft
Lo. Crk. 2 Len: 0 ft
Lo. Crk. 3 Len: 0 ft
Tran. Crks Sec1 Lvl1: 0
Tran. Crks Sec1 Lvl2: 0
Tran. Sec1 Avg Spc: -
Tran. Crks Sec2 Lvl1: 0
Tran. Crks Sec2 Lvl2: 0
Tran. Sec2 Avg Spc: -
Patches 1: 0
Patches 2: 0
Punchouts 1: 0

Shoulder Distress 0%
Longitudinal Joint Spalling 0%

Figure 3-5 Survey details page of the CRCPACES data collection app



Joint Distresses

The extent of Shoulder Joint Distress is also recorded.

Every joint in each mile is to be visually checked for joint defects. We are looking for the total number of joints with defects not a count of individual joint defects. To illustrate, a joint with one or more spalls, or failed spall patches would count as one spalled joint and entered in the tablet once (See Figure 12). There are three types of joint defects visually counted for this survey:

(1) Joints with Spall (Spalled Joints): The deterioration of concrete at the joint usually results in the breaking or flaking off of the concrete at the joint; as they worsen raveling and pop-outs occur. Figure 12 shows examples of joints with spalls. The number or severity of spalls is not accounted for, just the total number of joints with spalls; therefore, if a joint has two or more spalls a single entry is made showing one spalled joint. According to the specifications, a spall must be at least 1.5" x 6" in area. We will use this minimum size to define the minimum spall size.

(2) Joints with patched spalls: Only well performing spall patches are counted. Spalls patched with asphalt should be counted as spalls rather than patched spalls because the asphalt patched is only a temporary repair until the area can be sawed out and patched with concrete.

(3) Joints with failed spall patches: The patched spall has cracked or the patching material has come out and will have to be replaced. These are placed on the form as a failed spall patch. Failed spall patches provide us with information on how the materials used are performing.

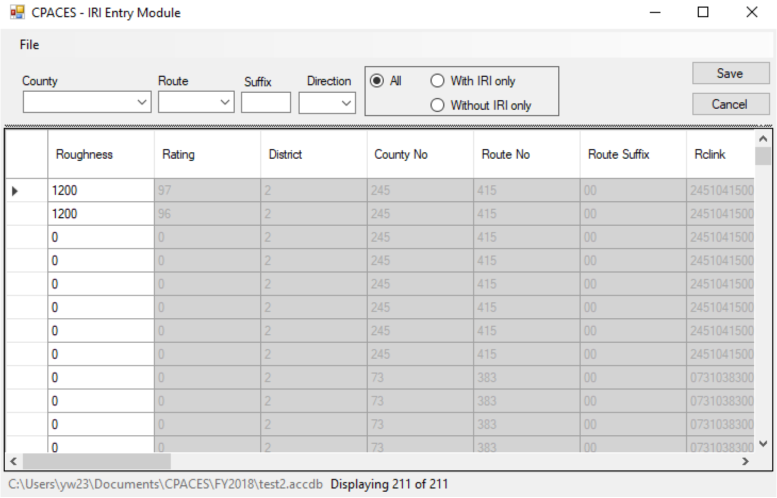
Figure 3-6 CRCPACES distress protocol integrated into the data collection app

Step 2: Export data

Once the survey has been completed, the survey data can be exported in the form of comma-separated values (csv) files from the home page (as shown in Figure 3-3). The user only needs to export the data at the end of the survey season when all surveys have been completed.

Step 3: Enter IRI

Typically, after all surveys in a district have been completed in a fiscal year, the data collected by the CRCPACES data collection application has to be transferred for further data entry (i.e., IRI). This processing step cannot occur inside the data collection app during a field condition survey, as IRI data is collected by a different unit. The IRI Entry component on the desktop will be used for entering IRI data (see Figure 3-7). The user can query the survey data by county, route, suffix, and direction, then enter IRI data for each segment. Note that the CRCP rating is automatically computed once IRI data is entered. The user manual for IRI Entry is in IRI Entry User Manual.



● All ○ With IRI only ○ Without IRI only

Roughness	Rating	District	County No	Route No	Route Suffix	Rclink
1200	97	2	245	415	00	2451041500
1200	96	2	245	415	00	2451041500
0	0	2	245	415	00	2451041500
0	0	2	245	415	00	2451041500
0	0	2	245	415	00	2451041500
0	0	2	245	415	00	2451041500
0	0	2	245	415	00	2451041500
0	0	2	245	415	00	2451041500
0	0	2	73	383	00	0731038300
0	0	2	73	383	00	0731038300
0	0	2	73	383	00	0731038300
0	0	2	73	383	00	0731038300

C:\Users\yw23\Documents\CPACES\FY2018\test2.accdb Displaying 211 of 211

Figure 3-7 IRI entry form

3.3 Implementation of CRCPACES Application

Two training sessions were conducted for implementation of CRCPACES. First, training for the liaisons was conducted October 25, 2016, in Forest Park, Georgia. Second, statewide training was conducted on November 13, 2017, in Macon, Georgia. More than forty engineers from seven districts attended the training, as shown in Figure 3-8. The data collection app was installed on their tablet-PCs, and the engineers simulated the data recording process in-house. Feedback from GDOT personnel was strongly positive. The CRCPACES application has been successfully deployed and will be used for conducting condition surveys for CRCP.

Figure 3-8 CRCPACES statewide training on November 13, 2017, in Macon, Georgia

4 ENHANCEMENT OF JPCP PAVEMENT CONDITION EVALUATION SYSTEM (JPCPACES)

GDOT has conducted annual pavement evaluation on JPCP since the 1970s based on its concrete pavement condition evaluation system (CPACES), and the data has been used to support its M&R decision-making. The CPACES was last revised in the 1990s. In the meantime, JPCP has continued to age, and severe distresses have developed in JPCP slabs. A previous study (Tsai et al., 2016) identified and recommended the enhancements necessary for the CPACES based on the analysis of historical CPACES data. The recommended enhancements included 1) a finer distress categorization for properly differentiating the most severely distressed slabs of the aged JPCP, 2) a refined faulting index computation to address negative faulting values, and 3) a revised rating to incorporate the finer distress categorization. This chapter presents the implementation of the enhancements, including a brief introduction to GDOT's JPCP and CPACES, a review of the enhancements necessary for the CPACES (including distress protocol and rating system), and the development of a JPCPACES manual with the aforementioned modifications to support GDOT's JPCP survey and training.

4.1 Background

Jointed plain concrete pavement (JPCP) is designed with contraction joints to control the location of expected natural cracks and does not use any reinforcing steel. GDOT has used JPCP since the 1960s, and many interstates (e.g., I-20, I-75, and I-16) were originally constructed as JPCP. Today, GDOT maintains approximately 950 centerline miles of JPCP on it interstate highways (HPMS, 2014). GDOT has a long history of conducting pavement evaluations of its JPCP. The first statewide faulting measurement was conducted on interstate highways in 1971 as part of the data collection effort for a research project to study concrete pavement faulting (Gulden, 1974). Since then, GDOT has been conducting an annual pavement condition evaluation on its JPCP. The data has been used to enhance its concrete pavement design by studying the performance of various design features (e.g., doweled vs. undoweled, joint spacing, and joint orientation) and to support its M&R decisions. For example, Gulden and Brown (Gulden, 1974; Gulden & Brown, 1983) studied the causes of faulting on Georgia's interstate highways and recommended improvements for load transfer in JPCP. In the 1990s, a concrete pavement condition evaluation system (CPACES) was developed to standardize the JPCP survey in terms of distress types and severity levels, and a CPACES rating was also developed to provide an overall assessment of concrete pavement condition. Treatment criteria were developed at the time, but it was not well documented.

The CPACES and treatment criteria have not been updated for the past two decades. In the meantime, JPCP has continued to age; a majority of Georgia's JPCPs have been in service for more than thirty years. Severe distresses (e.g., two or more cracks on a slab) have developed in aged JPCP slabs. In 2016, Tsai et al. (2016) conducted a study analyzing the trend of CPACES distresses (e.g., broken slab and faulting index) using historical CPACES data. During the process, it was identified that the existing CPACES distress types cannot differentiate the most severely distressed slabs (e.g., slabs with multiple types of cracking) from the slabs with a single crack. Irregular data (e.g., zero faulting index) and trends (e.g., increase in rating without treatment) were also observed in the data. As result, recommendations were made to use 1) a finer distress categorization for properly differentiating the most severely distressed slabs of the aged JPCP, 2) a refined faulting index computation to address negative faulting values, and 3) a revised rating to incorporate the finer distress categorization. There is a need to implement the recommended enhancements to provide quality and consistent data that can better support GDOT's M&R decisions.

4.2 Review of CPACES and Recommended Enhancements

CPACES and the recommended enhancements by Tsai et al. (2016) are reviewed in the subsequent sections.

4.2.1 *Review of CPACES Distress Protocol*

GDOT has conducted an annual survey of its JPCP using CPACES since the 1970s. The CPACES survey consists of measuring joint faulting and counting eight types of distresses in the outside lanes for each mile of JPCP in Georgia (GDOT, 1993). The faulting of every eighth joint is measured using a Georgia Faultmeter, which was developed and built by the Office of Materials and Research (GDOT, 1991). The faultmeter measures the faulting down to 1/32 in. The rest of the survey consists of a windshield survey counting broken slabs, longitudinal cracks, replaced slabs, failed replaced slabs, spalled joints, patched joints, failed spall patches, and shoulder distress. Table 4-1 summarizes the distress type, severity level, sample location, and measure for the distresses in the current CPACES. A brief description of each distress is also provided in the subsequent paragraphs.

Table 4-1 Types of Distresses in CPACES (Tsai et al., 2016)

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

- Broken slabs in the outside lane of each mile are manually counted. Surface cracks do not count; the slab must be, in the surveyor's opinion, actually broken. There are two severity levels for broken slabs:
    - Severity Level 1 - The broken slab has a hairline and tight working crack, regardless of its length.
    - Severity Level 2 - The broken slab has a moving crack that may be wide, spalled, and needs to be sealed; in the surveyor's opinion, the slab is actually broken.
- Longitudinal cracks normally start at a transverse joint and, generally, run parallel to the traffic flow. These cracks can occur inside or outside the wheel path. There are two severity levels for longitudinal cracks:

    - Severity Level 1 - The longitudinal crack is a hairline and "tight" working crack.
    - Severity Level 2 - The longitudinal crack is a moving crack, generally wider than the crack described in Severity level 1, maybe spalled, and needs to be sealed.
- Replaced slabs will be marked in each mile as they occur. It is noted that some replacements are not obvious because the color and texture are similar to slabs that have not been replaced. This is especially true after the pavement has been ground for some time.
- A count of all failed replaced slabs will be made. Knowing how many replacements have previously failed provides GDOT with necessary information about how the materials are performing.
- There are three types of joint defects visually counted for this survey. They are joints with spall, joints with patched spalls, and joints with failed spall patches.
- The shoulder joint will be visually inspected for distress. The distress takes the form of a depressed pothole at the joint. The distress might have advanced to the extent of being a large hole at the joint and base material may be pumped out onto the shoulder. There are two severity levels for a shoulder joint distress:
    - Severity Level 1 - Obvious depressions adjacent to transverse joints. Depressions are not large enough to require patching. No "pumping" of base material onto the shoulder is present.
    - Severity Level 2 - Large, deep depressions adjacent to transverse joints. Depressions are large enough to require patching. The "pumping" of base

material onto the shoulders should be rated Severity Level 2 without considering the depression size.

4.2.2 *Discussion of Recommended Enhancements*

The recommended enhancements by Tsai et al. (2016) are discussed in this section.

Finer distress categorization

As shown in Figure 4-1 , in the CPACES survey, two types of cracking distresses (broken slab and longitudinal crack) are used. “Broken slab” is defined as a slab with transverse cracks having one of two severity levels. However, in CPACES, a broken slab having Severity Level 2 also refers to a slab that is “actually broken.” A slab with longitudinal cracking is defined as a slab having longitudinal crack(s) rated at one of two severity levels. Through a review of historical CPACES data and an interview of the survey crew, Tsai et al. (2016) identified ambiguity in these two distress types. A slab with multiple, severe longitudinal cracks can be identified as a broken slab (Severity Level 2) by one surveyor’s interpretation of the distress description in CPACES or a longitudinal cracked slab (Severity Level 2) by a different surveyor. In addition, a wide range of distresses ranging from a single traverse crack to a slab broken into pieces with multiple cracks (as illustrated in Figure 4-1) can be classified as a broken slab at Severity Level 2.

Figure 4-1 Various broken slabs rated at Severity Level 2 (Tsai et al., 2016)

A review of other states' distress protocols finds "divided" or "shattered" being used to identify slabs with several different types of cracking, as shown in Table 4-2. California identifies similarly distressed slabs as 3rd stage cracking. While most states do not have severity levels for shattered slabs, they typically consider a slab in this condition to be in need of replacement. Some states have different severity levels (dependent on the number of shattered pieces) associated with this category. ASTM D6433 defines the severity levels based on the degree of crack faulting in the slab.

Table 4-2 Summary of Divided/Shattered Slab Definitions

Distress Type	State	Description	Severity Level
Divided Slab	VA		L- 3 pieces M- 4 pieces H- 5 pieces
	ASTM D6433/ PCI	4 or more pieces	L- <10mm (0.375") M 10-20mm H > 20 mm (0.75")
Shattered Slab	NC & OR	4 or more pieces	Levels (Needs to be replaced)
3rd Stage Cracking	CA	Slab with at least two cracks	

Based on the review and recommendations by Tsai et al. (2016), the definition of a broken slab was divided into three types of distresses to represent different severity levels. The term "broken slab" was changed to "transverse crack." The category of "shattered slab" was added to differentiate it from transverse cracking because a shattered slab requires a higher priority of treatment than a slab with a single crack. The term "corner break" was also added due to the potential for corner breaks to fault prematurely.

Faulting Index

A positive faulting reading, which occurs when the leaving side of a joint is lower than the approaching side (as shown in Figure 4-2), is typically expected at a joint. A negative faulting indicates the leaving side of the joint is higher. According to Mr. Wouter Gulden, who developed CPACES, during the early development of CPACES, a negative faulting value was considered rare and, sometimes, the result of a reading taken with a faultmeter facing in the wrong direction. This is especially true when continuous negative faulting readings were reported within a segment. Therefore, negative faulting values are recorded but considered as zero when computing faulting index, which results in a lower faulting index that is not representative of the actual condition. However, negative faulting can develop in an aged JPCP slab, and negative faulting values can cause safety issues that need to be fixed. Therefore, the faulting index computation was modified as five times the average of “absolute” faulting readings to take negative faulting into account.

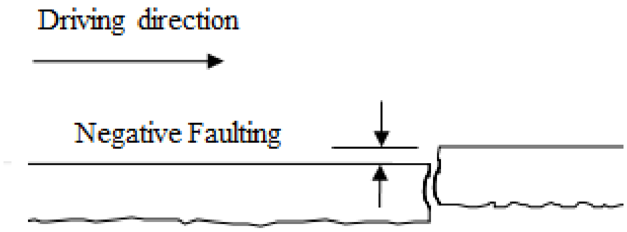


Figure 4-2 Example of negative faulting (Tsai et al., 2016)

Other recommendations include 1) a clear definition for a slab after it is repaired and divided into 2-3 small slabs and 2) clear instruction on measuring faulting at every 8th original joint to ensure consistent readings.

4.2.3 *CPACES Rating*

A performance rating (CPACES rating) scale of 0-100 is computed for each mile based on all the distresses collected, including IRI. The rating was modified to include the changes in the distress categorization (i.e., the additional distress categories of shattered slab and corner break). It was recommended that shattered slabs, corner breaks, and transverse cracks rated at Severity Level 2 be 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. A "null" value should be assigned to the segments with missing data (e.g., faulting index and/or IRI). This is because a zero deduct will be assigned for a missing faulting index and/or IRI, which results in a higher rating that does not represent the actual pavement condition. Thus, it is recommended that a null value be assigned to such segments with missing data. In addition, similar to COPACES, a rating of "105" will be assigned to sections of JPCP under construction to clearly denote that the pavements are part of the system but unavailable for rating.

4.3 Development of GDOT's JPCP Pavement Condition Evaluation System (JPCPACES)

The CPACES manual was available only in hard copy. Thus, a jointed plain concrete pavement condition evaluation system (JPCPACES) manual incorporating the aforementioned enhancements (including a finer distress categorization, a revised faulting computation, a definition for identifying a slab, and guidelines on selecting joints for faulting measurement) was developed to provide guidelines for the survey. In addition, the research team worked closely with OM engineers to refine the description for each distress type and its severity levels to clarify ambiguity and update the distress photos and illustration figures to provide better examples. A JPCP manual, Jointed Plain Concrete Pavement Condition Evaluation System (JPCPACES) Instructional Manual, was developed. The subsequent sections summarize the key changes in the distress protocol and rating computation.

4.3.1 ***Distress Protocol***

The three distresses (shattered slab, corner break, and transverse crack) that were added (or, updated), as well the as faulting index computation, are briefly described below. See Jointed Plain Concrete Pavement Condition Evaluation System (JPCPACES) Instructional Manual for all distresses in JPCPACES.

<u>Shattered slab</u>

A slab that is cracked in multiple locations and separated into 3 or more pieces is categorized as a shattered slab. In this category, the concrete block(s) may pop out and pose safety concerns to road users. Previously, there was no shattered slab category in CPACES. Although the number of shattered slabs will be counted and recorded, there is no severity level for shattered slabs. Figure 4-3 shows examples of shattered slabs.

Figure 4-3 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. Because it may deteriorate faster, a "corner break" is separated from longitudinal and transverse cracks. This type of distress might lead to a popout. There is no severity level for a corner break. Figure 4-4 shows examples of corner breaks.

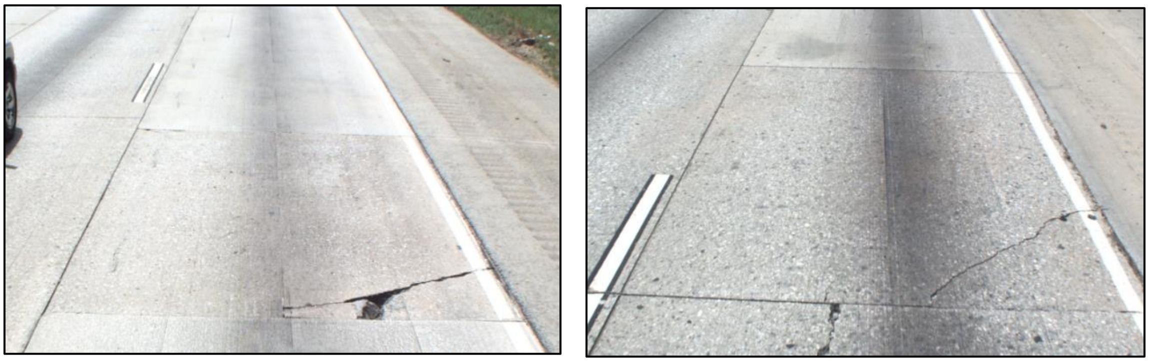


Figure 4-4 Examples of corner break

Slab with transverse cracking

Previously, a slab with transverse cracking only was considered as a broken slab, but now it will be termed as transverse cracking in the enhanced distress protocol. There are two severity levels: Severity Level 1 is categorized as a hairline crack and a tight working crack. Severity level 2 is categorized as a moving crack, which is generally wider than a hairline or tight working crack and maybe spalled. Figures 4-5 (a) and (b) show transverse crack Severity Levels 1 and 2, respectively.


6/24/2003
6/24/2003

Figures 4-5 Example of transverse cracking, Severity Levels 1 and 2

Faulting Index

The faulting index is computed at five times the average of “absolute” faulting readings, as shown in Equation 4.1, to account for the negative faulting readings.

$$Faulting\ Index = \frac{5}{n} * \sum_{i=1}^{n} |S_i| \tag{4.1}$$

It is noted that the final faulting index is always rounded to the nearest integer (e.g., 5.09=5 and 5.74=6). An example of the faulting index computation is provided as follows:

S_i	1	2	3	2	-3	6	4	2	3	5	3	0	0	2	-4	-2	2	3

There are 18 faulting readings, and the sum of those reading is 47. Therefore, the faulting index is 13 (47/18*4=13.06, rounded to 13).

4.3.2 *Rating System*

The rating was revised to incorporate the finer distress categories (shattered slab, corner break, and transverse crack). The revised rating is computed based on Equation 4.2.

$$\text{Rating} = 100 - D_{FI} - D_{SM} - D_{CS} - D_{LC} - D_{SD} - D_{SP} \tag{4.2}$$

- D_{FI}: Deduct value for Faulting Index (see JPCPACES Instructional Manual)
- D_{SM}: Deduct value for Smoothness (see JPCPACES Instructional Manual)
- 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 4-3 lists the maximum deduct value and associated extent for each distress. For example, 30 shattered slabs will reach a maximum deduct value of 30. This means the rating cannot be lower than 70 with just cracked slabs.

Table 4-3 JPCPACES Maximum Deduct Values and distresses

	Max Deduct	Distress extent and deduct
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.

An example of rating computation is shown in Table 4-4. A segment with the listed distresses would have a rating of 71. The deduct value for each distress is determined based on the extent; a rating is then calculated using Equation 4.2.

Table 4-4 An example of Rating Calculation

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

4.4 JPCP Treatment Methods and Criteria

This section reviews the treatment methods and criteria used for JPCP. Based on the findings from the review and consultation with OM engineers, treatment criteria based on GDOT’s distresses were proposed,

4.4.1 *Review of JPCP Treatment Methods*

Treatment methods used by various states for JPCP are much more uniform than the pavement condition distresses and indices. Table 4-5 lists the individual treatment method, its use, and expected service life.

Table 4-5 JPCP Treatment Methods

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

Each treatment method is briefly described as follows:

- Partial Depth Repair (PDR) involves removing less than half the thickness of a slab. The minimum repair area recommended is 10-in long and 4-in wide. The repair area should be extended at least 3 in into sound material. It is important to remove the damaged area completely without damaging the surrounding concrete. Another important aspect of these types of repairs is the proper bond between the old concrete and the repair material; a grout or similar material is used to assist in bonding to the repair material. The repair material can be typical concrete or a number of proprietary, rapid-setting repair materials.

- Full Depth Repair (FDR) involves removing the full thickness of the slab and typically includes full lane width. A minimum repair length of 6 ft is needed to provide a stable portion for a slab. This results in a minimum repair area of 6 ft long by 12 ft wide. SHRP2 estimates that FDR may not be appropriate if the extent of cracking is over a certain percentage. States use different percentages, ranging from 5% to 20%. California considers FDR as an alternate up to 20% cracking, but it also requires an LCCA analysis to make that determination for cracking between 10-20%. The MEPDG recommends a default cracking percent of 10-20% in its performance criteria limits, depending upon the type of route (interstate=10%, primary=15%, secondary=20%).
- Dowel Bar Retrofit (DBR) is typically performed on a project basis on undoweled JPCP that is still in relatively good condition. As the slabs become more distressed, DBR is less effective. DBR is performed by cutting slots in which to place dowel bars at the joints. The construction of the slots, placement of the bars, and placement of the replacement concrete or repair material are all crucial parts of the repair. It is noted that GDOT does not currently use DBR.
- Joint Reseal/Crack Seal extends the life of the pavement by reducing the amount of moisture that can get to the base or subgrade, and it prevents incompressible material from getting deposited into the cracks or joints that could cause distress due to movement at these locations. Different methods and different materials for joint and crack sealing are in use. Both cold-applied and hot-applied materials are

available. The trial and error method has historically been used to identify methods and materials that work best for a particular state. Some states are now constructing very narrow joints and not sealing the joints at all. Although this may work in some situations, materials, aggregate type and size, and, climate are all factors to consider when making decisions about sealing or not sealing joints.

- Diamond Grinding is used to restore rideability to a surface. It is commonly performed after PDR, FDR, or DBR work to provide a smooth surface and remove any additional bumps or irregularities introduced through the repair process. The process uses a milling machine with closely spaced blades to grind off typically less than ¼ in of the surface. SHRP2 identified that diamond grinding lasts, on average, 8 to 15 years and can be performed up to 3 times without adversely affecting the structure.
- Slab Stabilization/Slab Jacking are similar techniques in that a material is pumped under the slab to seal or lift (jack) the slab. Slab stabilization is used to fill voids under a slab. Slab jacking is used to level a slab that has settled due to soil consolidation (i.e., at the end of bridges or over culverts). Typically, a cement-grout mixture or a polyurethane component is used. Slab stabilization/jacking is best performed before a slab exhibits distresses. It is, also, typically performed with other measures, such as DBR, drainage, shoulder improvements, and/or joint resealing to address the causes of the voids.
- Lane Replacement is a combination of continuous, full-depth repair, and total reconstruction. It is used when one lane, typically the truck lane, is distressed to a level that repair of individual slabs would either be cost prohibitive and/or

unsightly. One lane is removed and replaced, and a new lane is placed in a manner similar to new construction using a standard paver and dowel baskets or dowel bar inserters.

- Overlay is actually adding structural capacity to the pavement. Either asphalt or concrete can be placed on top of the existing pavement for a new riding surface. The existing pavement needs to be repaired to the point that it is stable for an overlay. Asphalt overlays tend to experience reflective cracking at the joints from bottom-up cracking. Because of this, asphalt overlays tend to be either very thin or very thick. Concrete overlays can be bonded or unbonded. Unbonded overlays are more common and consist of placing a new concrete slab and a bond breaker over the existing pavement. Unbonded overlays can be used over existing pavement that is in poor condition as long as the existing pavement is intact enough to provide consistent support. Bonded overlays involve actually bonding new concrete to the old concrete that is still in relatively good condition. Therefore, bonded overlays are mainly used to repair surface distresses (e.g., excessive scaling or map cracking, texture issues).

4.4.2 ***Treatment Criteria***

A comprehensive review was conducted to understand the treatment criteria used by other states. Table 4-6 summarizes the treatment criteria used for common treatments, including slab replacement, diamond grinding, lane replacement, and overlay.

Table 4-6 Summary of Treatment Criteria by States

	Maintenance/Preservation			**Rehabilitation/ Reconstruction**	
	Joint Reseal Seal Cracks	**Repair Slabs (PDR/ FDR)**	**Diamond Grinding**	**Replace lane**	**Overlay**
California Cracking	>25% slabs with crack btw ¼ ” and ¾”	<15% with cracks wider than ¾”	Average Faulting > ¼” or IRI >170 for over 50% of the project	>15% with cracks wider than ¾”	Slabs with cracks wider than ¾”
California 3rd Stage Cracking	>20% slabs with 3rd stage cracking btw ¼ ” and ¾”	<10% with 3rd stage cracks wider than ¾”		>10% with 3rd stage cracks wider than ¾”	Slabs with 3rd stage cracks wider than ¾”
Georgia		SL2 BS>10 & F.I.<20 & IRI<1100	F.I. > 15 or IRI>1100		
Illinois		<12% new patching, no D cracking and <24% total patching		N/A	>12% new patching Or <12% new patching & >24% total patching Or <12% new patching & D cracking
Indiana		<8% patching LCCA to be performed for >8% patching		N/A	>30% patching
Maryland		<25% patching		N/A	>25% patching
New Jersey		<10% cracked and 95<IRI<170		N/A	>10% cracked
Washington			Faulting >1/8” for 25% extent or IRI>220		>15% slabs w/multiple cracks, > 60% have 1 crack, > 47% have 25% patching or 73% have high spalling

- Most states do not clearly identify the criteria for joint seal. California uses 20% to 25% for crack seal based on the type of cracks. After consulting with OM engineers, a 20% of joint defects was selected to use as the trigger for using joint seal.

- Distress slabs need to be repaired (PDR or FDR) to prevent the slab from further deterioration. However, JPCP may reach a point when there are many distressed slabs, and it needs lane replacement or overlay. Thus, most states use certain criteria to distinguish the need for slab repair and rehabilitation/reconstruction. Percent of slabs cracked, the severity level of cracking, IRI, and patching are often used as criteria. For example, California considers rehabilitation if greater than 15% of the slabs have single cracks with the highest severity level (3/4 in) but will consider rehabilitation if greater than only 10% of the slabs have multiple cracking (3rd stage cracking) with the highest severity level. Illinois considers patching needed in its evaluation, which is related to the presence of cracking or spalling in the slabs and their need for repair. They have a decision tree that considers new patching, old patching, and D-cracking and includes a provision for LCCA. New Jersey, also, considers IRI but includes a maximum IRI criterion, recognizing that if the IRI is very poor, then slab repair may not solve the underlying problem alone. In the past, GDOT used the number of broken slabs, faulting index, and IRI for identifying the need for slab repair and rehabilitation/reconstruction. Slab replacement is recommended when the number of distressed slabs (shattered slab, transverse crack Severity Level 2, and longitudinal crack Severity Level 2) is greater than 10, the faulting index is less than 20, and IRI is less than 1100 mm/km.
- The criterion for diamond grinding is typically based on faulting and/or IRI. As noted earlier, diamond grinding is typically performed as part of a complete concrete pavement restoration (CPR) that includes slab repair and dowel bar

retrofit as appropriate. The trigger points noted by states varies; California uses 0.25 in (8 mm). The trigger points for faulting and IRI recommended in the Concrete Pavement Preservation Guide (CPPG) are faulting > 0.08 in (2 mm) and IRI > 160-220 in/mile (2.5-3.5 m./km) (Smith & Harrington, 2014). A faulting of 0.08 in is approximately a faulting index of 15. This was the trigger point GDOT used in the 1980s and 1990s when there were sufficient resources/funding. Given the funding level and higher faulting on Georgia's JPCP, using a faulting index of 20 is recommended for triggering the need for diamond grinding.

- In summary, the following criteria are recommended for JPCP MR&R.

Table 4-7 Refined Treatment Criteria

Maintenance/Preservation			**Rehabilitation/ Reconstruction**	
Seal Cracks	**Repair Slabs (PDR/ FDR)**	**Diamond Grinding**	**Replace lane**	**Overlay**
>20% of joint seal failed	SS+TR L2 >10 (~5% slabs cracked) & F.I.<20 (1/8"/4mm) & IRI<1100	F.I. > 20 (1/8 in/ 4 mm) or IRI>1100	SL2 BS >33% slabs cracked	Slabs with cracks wider that ¾ in

5 DEVELOPMENT OF JPCPACES APPLICATION

Since the 1970s, GDOT has been conducting annual surveys for its JPCP using a pen-and-paper based data collection operation. Today, technological advancements have opened up avenues for improvement of this operation to enhance productivity and data quality. GDOT has previously embraced technologies in its pavement data collection. A computerized pavement condition evaluation system (COPACES) was successfully implemented in 1998 for collecting data for asphalt pavement (Tsai & Lai, 2001). As a result, it has significantly improved the operation efficiency for the field data collection with an estimated saving of 120 men-month (60 engineers * 2 months) while enhancing the data quality (Tsai & Lai, 2002). With this successful implementation, the Georgia Tech Research Team is convinced the current JPCP survey process can be greatly improved to increase efficiency and data quality through the use of a computerized programming. Therefore, a tablet-based JPCPACES application was developed to facilitate the implementation of JPCPACES and improve the existing data collection operation. This chapter presents a review of the current survey process and the design, development, and implementation of a JPCPACES application.

5.1 Review of CPACES Survey Practice

The existing CPACES data collection operation was observed during an inspection of a 4-mile section on I-16 in Georgia. The data collection operation is summarized as follows:

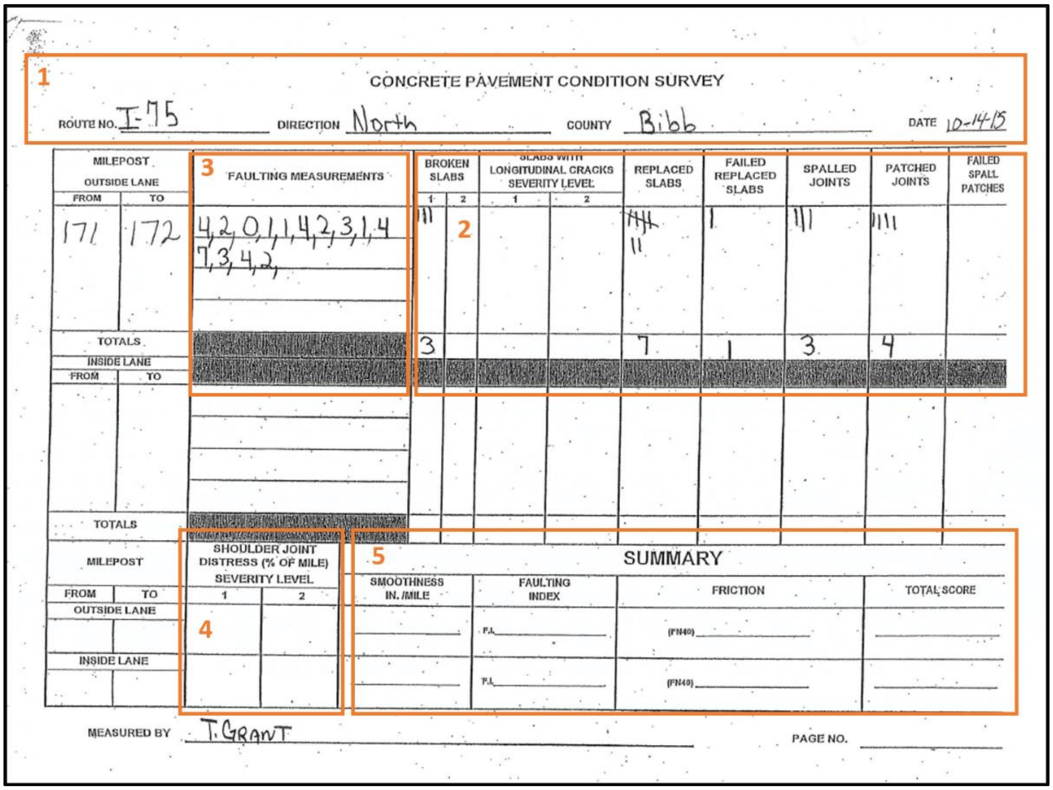
- The CPACES survey crew consists of four members and two vehicles. The first vehicle is a van with a team conducting the survey (as shown in Figure 5-1 (a)). The second vehicle is a buffer truck (as shown in Figure 5-1 (b)) that provides temporary traffic control. The four members consist of a driver for each vehicle, one member in the van who records observations during the survey (further referred to as the recorder), and one person on foot who operates the fault meter used to measure faulting between slabs.

(a) (b) (c)

Figure 5-1 CPACES survey procedure

- The distresses observed during the survey are recorded on a paper form, as shown in Figure 5-2. A separate form is required for every one-mile segment. Location information has to be entered into each individual form in Box 1, which often remains the same for a section of the road within a county. The recorder keeps track of the slabs and adds tally marks for observed distresses in Box 2. For example, if a slab is broken with a tight transverse crack, a tally mark is added to the column titled broken slab Severity Level 1. Faulting is measured by a Georgia Faultmeter and the value is hand-signaled to the recorder (as shown in

Figure 5-1 (c)). All faulting readings are entered into the form in Box 3. At the end of the segment, total shoulder distress is aggregated and entered in Box 4.



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 5-2 Data collection form used by GDOT

- The roughness (in Box 5) is entered later in the office because it is collected by a different unit. The time taken to complete a 1-mile survey varied from 17 to 26 minutes. The faulting measurement was clearly the bottleneck controlling the speed of the survey. The variance in survey time can be explained by the presence of bridges and ramp areas (bridges and ramp areas are skipped in the CPACES surveys).
- After the survey is complete, the distresses on the paper forms and associated roughness have to be manually entered into a database. For one district, copying the survey forms and entering the data into a computer takes about one week to

complete. According to Mr. Curtis Grovner, approximately 280 man-hours are spent entering the data for all seven Georgia districts each year.

From the Georgia Tech Research Team's observations of the current CPACES data collection operation and interviews with the survey team, the following inferences were drawn which would lead to the design of JPCPACES features:

- Manual data entry after the survey should be eliminated. Manual data entry leads to human errors (e.g., typo and misunderstood handwriting) in the data, which compromises the data quality. Data validation should occur as soon as values are entered in the field so that the recorder can be informed of erroneous entries immediately and corrections can be made on the spot.
- Inputs should be constrained to a range of feasible values. For example, faulting measurement cannot be less than -20 or more than 20. This applies to nominal values, as well. For example, the name of the county being surveyed should be verified using a lookup table.
- Prompts should be given if the required data is not provided. For example, the route number must be provided for the survey data to be of any use. The recorder must be prompted to enter a valid route number at the beginning of the survey.
- The distress protocol with distress type, severity level, and photos should be readily available for reference during the survey to minimize subjective evaluations of the pavement condition.
- The process of entering data should be easy, leaving the recorder free to concentrate on observing pavement distresses. Computations should be automated as much as possible.

5.2 Design of JPCPACES Application

The JPCPACES application shares the same system architecture with the CRCPACES application. Refer to Section 3.1 for the system architecture and the choice of device and development platform. This section describes the features designed to address the issues identified through the review of the current survey process and discussion with the survey crew to provide a user-friendly interface. The features are summarized as follows:

- Reduction of repetitive data entry, such as county name and route number when conducting a survey on one route in the same county.
- Recording of all observations included in the proposed CRCPACES distress protocol.
- Embedded, real-time error-checking to ensure user inputs are valid.
- Tab-and-count features, such as automatically tallying distresses and including time of collection, for easy data entry distresses.
- Automatic saving at every entry. Users can continue an earlier survey.
- Undoing of accidental entries.
- Addition of comments or tags for individual segments or surveys.
- A built-in manual and the CRCPACES protocol for quick reference in the field.
- An export function for transferring the collected data.

5.3 Development of JPCPACES Application

The JPCPACES application was developed with special features (such as tap-to-count, real-time data checking, an embedded JPCPACES distress protocol, etc.) to streamline the data collection process while enhancing productivity and ensuring data quality. A detailed user's guide for data collection app and IRI entry can be found in CRCPACES/JPCPACES Application User Manual and IRI Entry User Manual. The operation flow and major functions are similar to the ones in the CRCPACES application (see Section 3.2) by design to provide consistency; the differences are in the distress entry step. The three steps (conduct the condition survey, export data, and enter IRI) are briefly discussed in subsequent paragraphs with a focus on the distress entry.

Step 1: Conduct a condition survey

During a condition survey, the user will use the data collection app on a tablet PC for recording data and, if necessary, access the JPCPACES distress protocol. Note that the user interfaces are similar to the CRCPACES by design to provide consistency to the user.

- Step 1.1 Start/Continue Surveys: On opening the app, the user starts at the home page shown in Figure 5-3, which is the same as the CRCPAES data collection app.

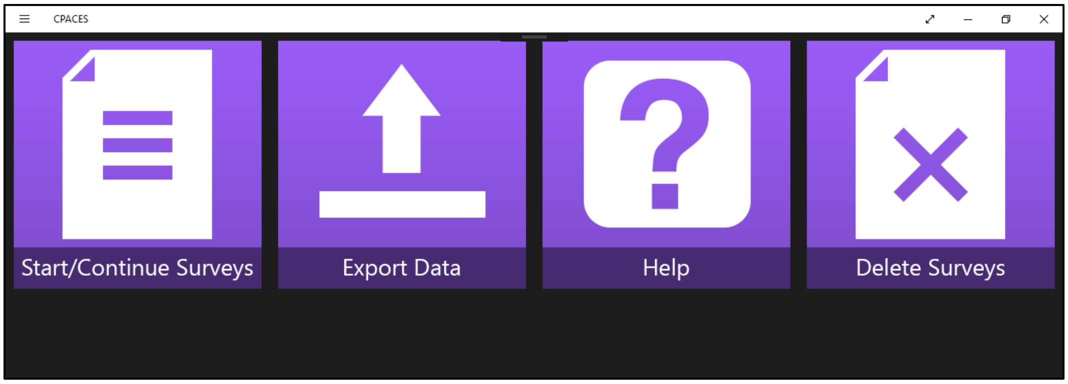
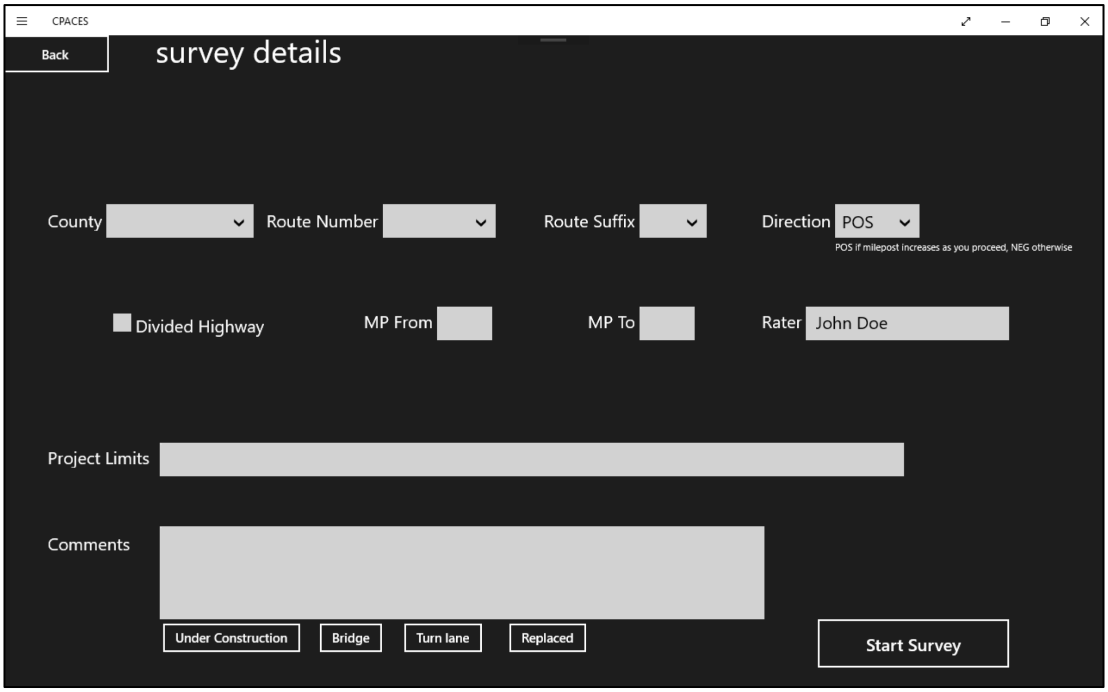


Figure 5-3 Homepage of the JPCPACES data collection app

- Step 1.2 Location Information: Again, the location information page (as shown in Figure 5-4) is the same as the CRCPACES data collection app. The user can enter the location in the same manner.



Direction POS

POS if milepost increases as you proceed, NEG otherwise

Rater John Doe

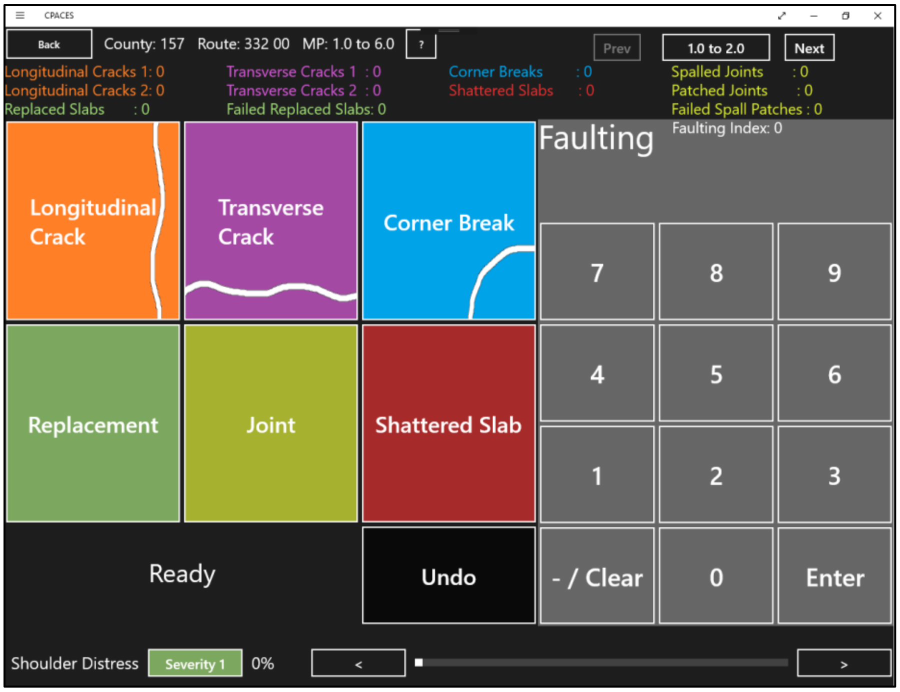
Figure 5-4 Location information page of the JPCPACES data collection app

- Step 1.3 Detailed Survey: Figure 5-5 shows the detailed survey page for recording distresses. At the top, the current segment being surveyed is displayed; from here, the user can navigate to other segments. Below that, counters show the number of distresses measured up to that point for that segment.

On the right, a numeric keypad is simulated on the screen for the user to enter faulting readings. The user can enter the faulting reading as it was measured in the field. The faulting index will be automatically calculated as soon as a faulting reading is entered. Inputs are constrained using lookup tables wherever possible to ensure high-quality data at the time of data entry itself. This mitigates manual errors and also makes it easy to verify information in the field during the survey itself.

The colored distress buttons on the left are used for recording distresses. Tally mark distresses, such as shattered slabs and corner breaks, can be recorded by tapping/clicking the buttons on the screen. The user just taps the button as a surveyor observes the distresses (e.g., shattered slabs) in the windshield survey. These buttons are color-coded to match the counters at the top. Shoulder distresses are aggregated at the end of the mile, and they can be entered using the slider at the bottom of the page. Any changes are automatically saved to an internal database as soon as they are made.

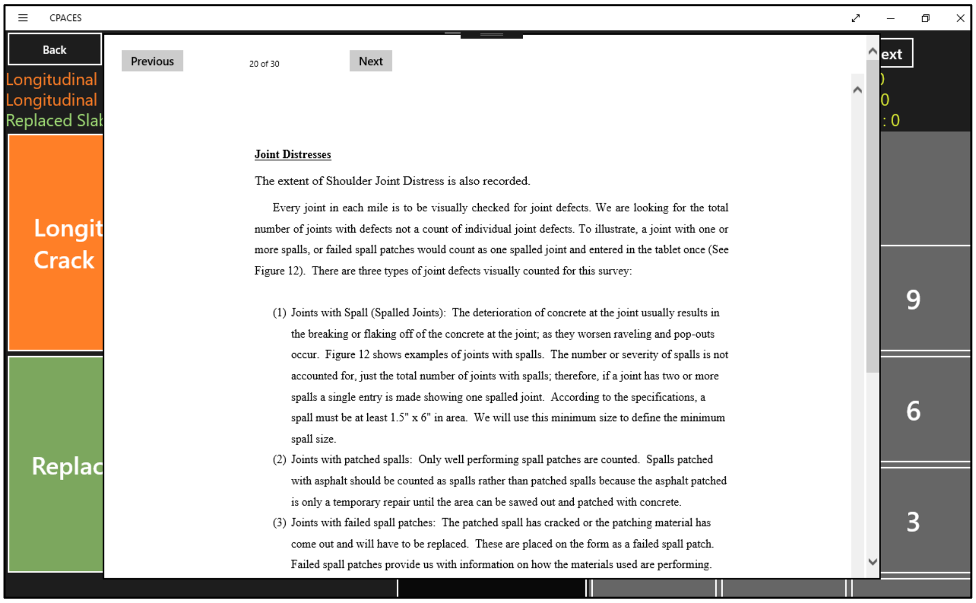
The “HELP” button in the top middle of the survey page opens a document listing the distresses in the JPCPACES distress protocol. Tapping on any of the distresses opens up the CRCPACES manual definition for that distress (as shown in Figure 3-6). This serves as a quick reference for survey personnel to reduce subjectivity during the survey.



County: 157 Route: 332 00 MP: 1.0 to 6.0

Longitudinal Cracks 1: 0
Longitudinal Cracks 2: 0
Replaced Slabs : 0
Transverse Cracks 1 : 0
Transverse Cracks 2 : 0
Failed Replaced Slabs: 0
Corner Breaks : 0
Shattered Slabs : 0
Spalled Joints : 0
Patched Joints : 0
Failed Spall Patches : 0
Faulting Index: 0
Shoulder Distress Severity 1 0%

Figure 5-5 Survey details page of the JPCPACES data collection app



Joint Distresses

The extent of Shoulder Joint Distress is also recorded.

Every joint in each mile is to be visually checked for joint defects. We are looking for the total number of joints with defects not a count of individual joint defects. To illustrate, a joint with one or more spalls, or failed spall patches would count as one spalled joint and entered in the tablet once (See Figure 12). There are three types of joint defects visually counted for this survey:

(1) Joints with Spall (Spalled Joints): The deterioration of concrete at the joint usually results in the breaking or flaking off of the concrete at the joint; as they worsen raveling and pop-outs occur. Figure 12 shows examples of joints with spalls. The number or severity of spalls is not accounted for, just the total number of joints with spalls; therefore, if a joint has two or more spalls a single entry is made showing one spalled joint. According to the specifications, a spall must be at least 1.5" x 6" in area. We will use this minimum size to define the minimum spall size.

(2) Joints with patched spalls: Only well performing spall patches are counted. Spalls patched with asphalt should be counted as spalls rather than patched spalls because the asphalt patched is only a temporary repair until the area can be sawed out and patched with concrete.

(3) Joints with failed spall patches: The patched spall has cracked or the patching material has come out and will have to be replaced. These are placed on the form as a failed spall patch. Failed spall patches provide us with information on how the materials used are performing.

Figure 5-6 JPCPACES distress protocol integrated into the data collection app

<u>Step 2: Export data</u>

Once the surveys have been completed, the survey data can be exported in the form of comma-separated values (csv) files at the home page (Figure 3-3). The user only needs to export the data at the end of the survey season when all surveys have been completed.

Step 3: Enter IRI

The IRI Entry on the desktop will be used for entering the IRI for both JPCPACES and CRCPACES.

5.4 Implementation of JPCPACES Application

With the JPCPACES application, the need for manual data entry into the database after returning from the survey is eliminated. The data collected through the data collection app can be easily exported and uploaded to the database. Hence, 280 man-hours of work formerly required to enter the data per year is saved. The data collection app fills data automatically wherever possible (e.g., the date and time of survey), checks the data in real-time, and calculates faulting index automatically to improve efficiency and data quality.

Several training sessions were conducted for implementation of JPCPACES. Statewide training was conducted on August 18, 2016, and November 13, 2017, in Macon, Georgia. More than forty engineers from seven districts attended the training. The data collection app was installed on their tablet-PCs, and the engineers simulated the data recording process in-house. Feedback from GDOT personnel was strongly positive. The JPCPACES application has been successfully deployed and will be used for conducting condition surveys for JPCP. The survey crew with a tablet (e.g., District 2) has used JPCPACE application for the survey.

Further improvements of the data collection app are listed as follows:

- Voice recognition can be used to make data entry more convenient. This will free users from having to constantly shift their attention between observing the pavement condition and entering data.
- With location services, GIS features can be added to the data collection app. Users can be provided with a dynamic map of their location and distresses can be geotagged. Geotagged distress information can be very useful for paneled studies and can be used as reference during maintenance operations.

6 DEVELOPMENT OF GEORGIA FAULTMETER

GDOT currently uses the Georgia Faultmeter (GFM) to measure joint faulting on jointed plain concrete pavement (JPCP) during its annual concrete pavement condition evaluation. The GFM, as shown in Figure 6-1, is a hand-held device that measures the vertical displacement between two slab edges across a transverse joint in JPCP. The GFM was originally designed, developed, and built by GDOT's Office of Material and Research in the 1980s, and, since then, it has been used by GDOT to measure faulting (Stone, 1991). It was also later adopted by the Long-Term Pavement Preservation (LTPP) program and many states for measuring faulting (Miller & Bellinger, 2003). Due to the extensive use of the devices since the 1980s when they were originally manufactured in-house by GDOT, the GFMs have been reported as damaged or non-functioning more frequently in recent years. Recently, there has not been a sufficient number of units that function properly. Some districts have to share GFMs for condition surveys, which hinders GDOT's annual faulting measurement operations. Thus, there is an urgent need to fabricate sufficient number of GFMs to support faulting measurement operations.

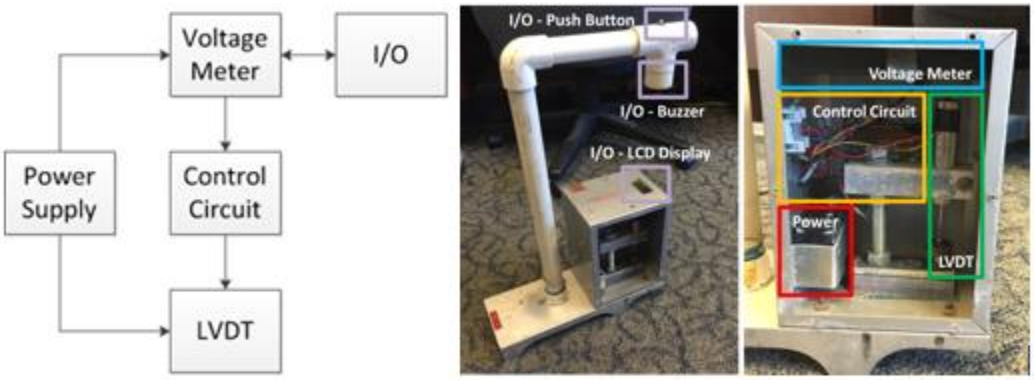
Figure 6-1 Field data collection using the GFM

Although the design, operation, and maintenance of the original GFM have been well-documented by the Office of Materials and Research (Stone, 1991), the sensors and devices, especially electronics used in the original GFM, have become obsolete. Consequently, it has become technically challenging to replicate an original GFM unit by following the original documentation. Therefore, the Georgia Tech Research Team developed a new GFM by studying the functions and design of the original GFM and by exploring options to implement the same functionalities using the most up-to-date electrical components. Instead of exactly replicating the original GFM, the research team improved the design of the electronics and the mechanics to make a new GFM that is more convenient to operate, more robust, and more capable of sustaining frequent routine operations. In this chapter, the detailed design and development of the new GFM are presented. The calibration (i.e., lab testing) and validation (i.e., controlled-environment testing and field testing) of the new GFM prototype are also presented. Some of the suggestions for future designs are also provided.

6.1 Design of Modern Georgia Faultmeter

To maintain the operational consistency for the field engineers, the new GFM prototype was intended to keep the original exterior design, but the interior was redesigned to accommodate new electronics. Both the operational flow and the reading format of the original design were retained, and additional functions were added to improve the performance of the GFM. In this section, both the electronics and fabrication of the new GFM prototype are presented. The detailed instruction for the operation of the new GFM prototype can be found in Appendix A.

The original electronic design of the GFM provides convenient operation for users to measure concrete slab faulting using a single trigger. When the user presses the button for triggering a measurement, the measurement will be performed using a single linear variable differential transformer (LVDT). The reading is then displayed with a range between -13 and 19 (i.e., -13/32 in to 19/32 in). The original design consists of five primary components: the voltage meter, the control circuit, the power supply, the LVDT, and the input/output (I/O). Figure 6-2 (a) shows the flow of the power and command control among these components, while Figure 6-2 (b) shows the detailed images of these components. See Appendix B for the design of GFM base and control circuit.



(a) (b)

Figure 6-2 The electronic design of the original GFM

- Voltage Meter: The original design of the GFM includes an off-the-shelf voltage meter that measures the voltage and the display in decimals.
- Control Circuit: The control circuit amplifies the actual voltage disturbance produced by the LVDT into a large range of voltages between -13.0 volts and 19.0 volts so that the voltage meter could directly display the value in units of 1/32 in

- Power Supply: The power supply sustains the power consumption by the LVDT and the voltage meter within the GFM. In the original design, eight AA batteries were used for the power supply. Also, due to the high voltage from the control circuit, a protection fuse was inserted between the power supply and the control circuit.
- LVDT: The LVDT converts the linear distance measurement into a stimulation of voltage disturbances and outputs to the control circuit.
- I/O: The input of the GFM includes a single pushbutton for triggering the GFM for measurement, a faulting measurement from the voltage meter displayed on a liquid crystal display (LCD), and a buzzer to indicate the successful operation of the GFM.

To preserve the functions of the original GFM and to streamline the controls of the GFM using off-the-shelf components, a new electronic design of the GFM was proposed and implemented by the Georgia Tech team. Figure 6-3 shows the schematic designs of the original GFM and the new GFM. Instead of supplying power for every component of the GFM, power is only provided to the control circuit, and then the control circuit will drive the power to the I/O component and the measurement component (i.e., potentiometer). In addition, instead of using a voltage meter, the control circuit is designed to process the readings from the measurement component (i.e., potentiometer) and display onto an LCD because the voltage meter used in the original design is no longer available. The new electronic design consists of four components, including the control circuit, the power supply, the potentiometer, and the I/O.

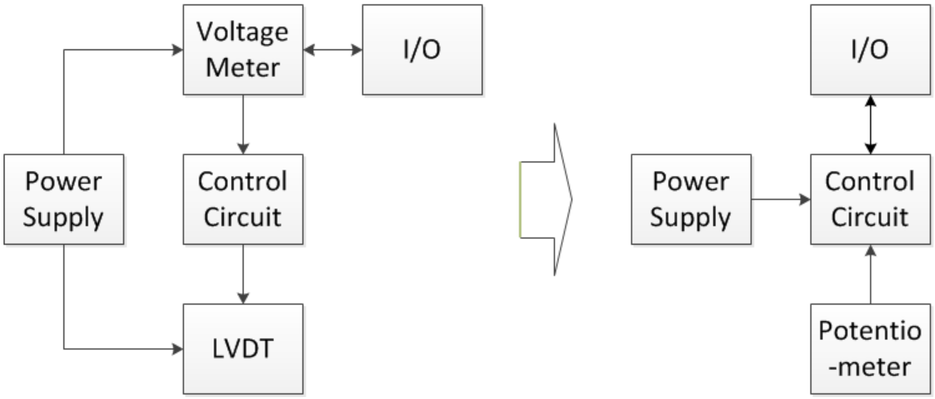


Figure 6-3 Schematic designs of the original GFM and the new GFM

- *Control Circuit*: The new control circuit is operated by a single-chip computer called Arduino Uno. The control circuit integrates all the primary functions of the GFM, including power management, LCD, read button trigger, trigger buzzer, and conduct faulting measurement. The control circuit is controlled by the code developed under an Arduino development environment.
- *Power Supply*: The power supply sustains the power consumption of the control circuit and all the peripheral devices. In this new design, a power bank with a capacity of 22000mAh is used to provide a desirable battery life, i.e., 140 hr. /charge. The power bank is rechargeable through a recharging port on the side of the new GFM prototype, so the user does not need to replace the battery.
- *Potentiometer*: The potentiometer has a function similar to the LVDT; it converts the linear distance offset into an electronic parameter. Different from the LVDT, the potentiometer converts the linear distance into the change of resistance instead of voltage. A potentiometer is used instead of the original LVDT because it is less expensive and provides similar distance measurement accuracy.
- *I/O*: The I/O component retains the design of the original GFM, including the pushbutton trigger, the buzzer indicator, and the LCD.

Figure 6-4 shows the layout of the electronics of a prototype unit and the corresponding detailed schematic layout of the pins on the control circuit and the peripheral devices.

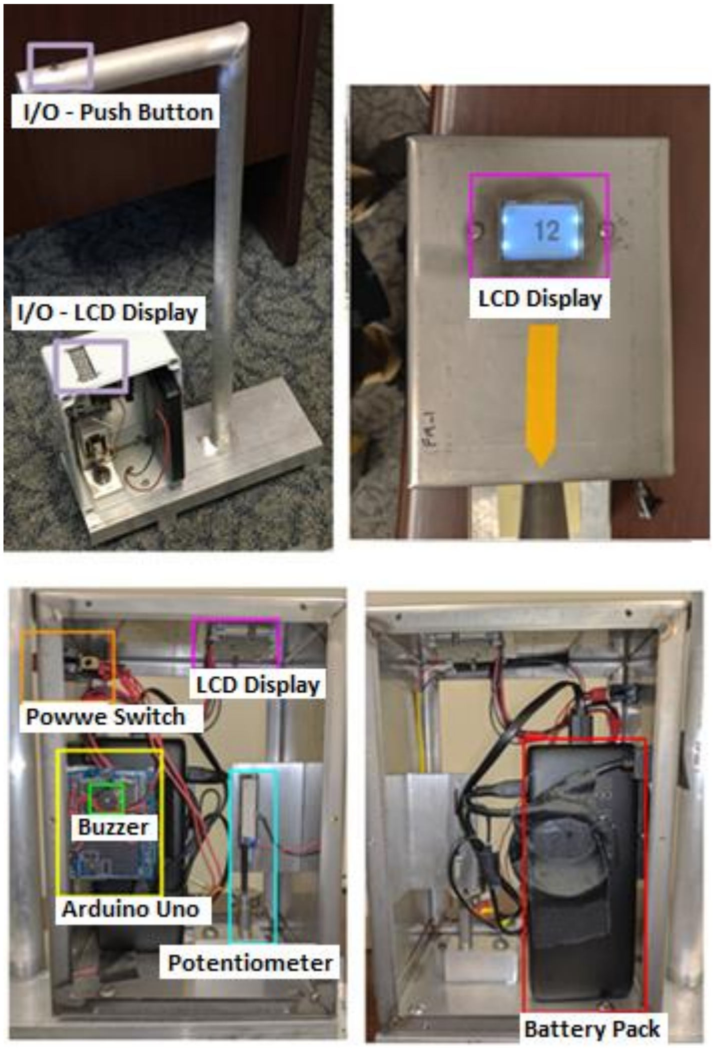


Figure 6-4 The electronic design of the new GFM and the corresponding schematic layout

6.2 Fabrication of Modern Georgia Faultmeter

The original design of the GFM includes an AutoCAD drawing of the enclosure and mounting kit. The new design of the GFM retains most of the original design. A few iterations of the enclosure, stand, and base plates were prototyped and tested to balance the weight, robustness, and usability of the new GFM. Figure 6-5 (a) shows some of the iterations of the prototype. Based on the feedback from the concrete pavement liaison and the field engineers, the final prototype, shown in Figure 6-5 (b), was implemented.

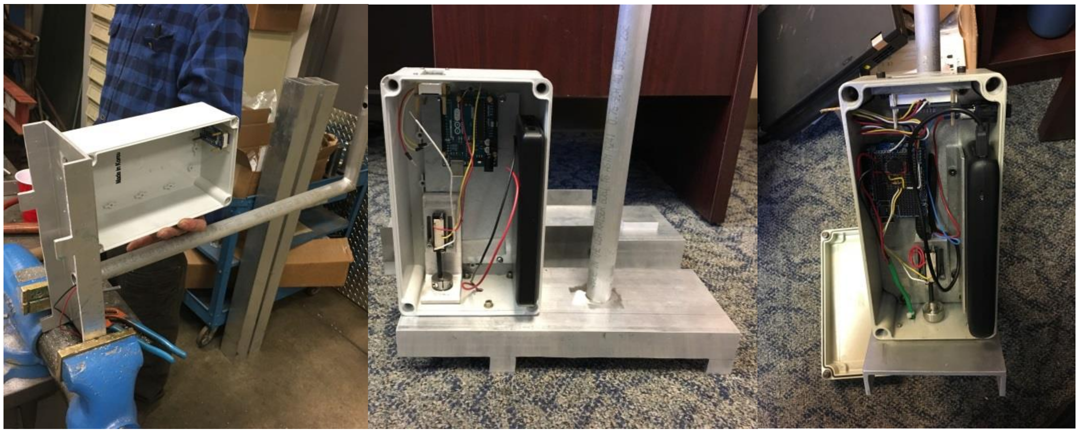


Figure 6-5 Example of the fabrication iterations of the new GFM prototype

6.3 Calibration and Validation

This section describes both lab and field tests conducted for calibrating and validating the new faultmeters.

6.3.1 *Lab Test*

The objective of the lab calibration is to calibrate the parameters for the potentiometer for each new GFM prototype so that the resistance measurement can be correctly translated into a distance measurement and, subsequently, into the faulting number between -13 and 19 (i.e., -13/32 in and 19/32 in). Although the potentiometer used in the new GFM prototype has an excellent linearity, as reported by the vendor's specification, the research team still rigorously calibrated the reading at each measurement between -13 and 19. Certified depth calibration block was used to simulate the faulting at the interval of 1 for conducting a reliable calibration. Figure 6-6 (a) shows the calibration block, and Figure 6-6 (b) shows the calibration using the blocks. By stacking the blocks one by one, the faulting number is generated by the new GFM prototype. The corresponding resistance measurement provided by the potentiometer was recorded and produced a regression line between the measured resistance and the expected faulting number as indicated by the calibration block. By conducting such a calibration, the new GFM prototype can achieve accurate measurements.

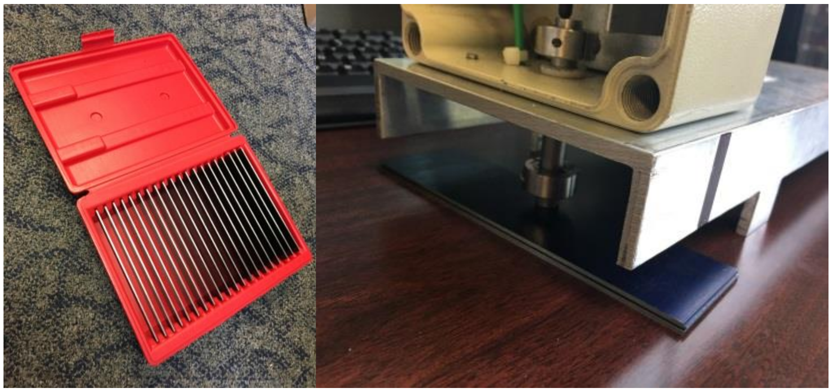

(a) (b)

Figure 6-6 Lab calibration process. (a) Calibration block; (b) Calibration example

Besides the measurement calibration, an exhaustive battery test was conducted for each new GFM prototype unit. It is estimated that each charge can be sustained for more than a month by efficiently using the power switch. A full charge of the selected battery can still sustain more than 140 hours of continuous operation based on the exhaustive battery testing.

6.3.2 *Field Test*

The Georgia Tech Research Team conducted a controlled-environment test on the Georgia Tech campus to evaluate the performance of the new GFM prototype by comparing it with the original GFM performance (provided by GDOT's District 2). The objective of the lab testing was to provide the initial validation of the new GFM prototype in preparation for the field test performed by GDOT survey crew. Figure 6-7 shows a few images of the lab testing.

Figure 6-7 The controlled-environment testing using the original GFM and the new GFM prototype

The Georgia Tech Research Team conducted a field visit with GDOT's District 2 survey crew on I-16 (EB MP 6-7 and WB MP 15-14) on February 27, 2017. The field trip focused on the faulting measurement portion of the concrete pavement condition evaluation system performed in the CPACEs survey. Faulting measurements were taken with one of the original GFMs and with the new GFM prototype constructed by Georgia Tech. The field test was not a typical CPACEs survey, as the test was focused on faulting measurements only, and it did not follow the stratified sampling plan (every 8th slab) used in CPACEs. This field test compared the original GFM and the new GFM prototype and accurately marked locations of faulting measurements for later analysis and comparison using 3D technology. For these reasons, the sampling locations were chosen to provide a range of values and a range of potential conditions for faulting. The actual field testing was conducted as if it were a CPACES survey; it used a buffer truck and a survey vehicle located upstream of the testing sites.

A total of 40 slabs were measured using the original GFM and the new GFM prototype. Each joint that was to be tested was marked prior to the faultmeter testing. A template was used to provide marks for the placement of the faultmeters (outside edges) and the probe (cross-hatched section on the upstream (approach) slab). A sequence of this operation is shown in Figure 6-8. Each site was selected by the research team prior to testing. Black spray paint was used to outline the template and probe locations in Figure 6-8 (b) and (c). Orange paint was used to mark the joint location transversely and numbered to identify the test locations 1-40. The operators placed the faultmeter on the pavement and aligned it with template markings. The template was used to improve the accuracy of placing each faultmeter at the same location. The template markings were also used to identify the location along the slab where the reading was taken, so analysis of the 3D data could be aligned with the location of the joint where the test was made. Two DOT employees each took faultmeter readings at each location, one with the original GFM and the other with the new GFM prototype. One measurement from each faultmeter was taken for the first 7 slabs. For slabs 8-40, three readings were taken with each piece of equipment at each slab and recorded, as shown in Figure 6-9. The operator placed the faultmeter, took a measurement, picked up the gauge, and set it back down. This was performed several times using each piece of equipment so that 3 readings were taken by each machine at each slab location (8-40). After 20 slabs, the operators switched pieces of equipment so they each could provide feedback on potential improvements to the new GFM prototype.

(a) Joint identification (b) Template placement and painting

(c) Location marking (d) GFM reading

Figure 6-8 Sequence of the field validation

	GDOT Existing Faultmeter			Ga Tech New Faultmeter		
1	4			3		
2	8			7		
3	8			7		
4	5			6		
5	6			7		
6	6			8		
7	6			7		
8	7	7	5	6	5	6
9	5	4	4	4	4	4
10	4	5	4	6	6	5
11	5	5	5	5	6	5
12	5	5	5	4	4	5
13	4	4	4	4	4	4
14	5	4	5	5	5	4
15	6	5	4	4	4	4
16	4	4	4	4	4	5
17	-1	0	0	-1	0	0
18	5	4	4	5	4	4
19	9	9	9	8	7	8
20	6	5	6	5	6	5

Figure 6-9 Field data collection example

The testing started just after MP 6 eastbound on I-16 (MP 6-7). This section of pavement consisted of 30-foot slabs on 90-degree joints. The original GFM and the new GFM prototype were each tested for calibration using a calibration board prior to testing. The first few consecutive slabs were tested, and then the intermittent testing continued until 20 tests were complete. The second set of testing started after MP 15 westbound on I-16 (MP 15-14). This section of pavement consisted of slabs at a random spacing (17 ft,-23 ft,-22 ft,-16 ft) with joints skewed at 10 degrees. Slabs were identified that showed a higher range of distress and greater faulting than the EB section of pavement. A particularly cracked section was identified between Measurement 33 and 34 (Station 660+00 was also noted on the pavement in this area).

During the testing, at Slab 31, a negative reading of -8 was reported by the original GFM. The new GFM prototype recorded -1. It was identified that the new GFM prototype was limited to reading up to -1, since most readings are positive. The new GFM prototype was further revised based on the feedback provided by the field engineers.

In most cases, the original GFM and the new GFM prototype provided readings within 1 reading (1/32) of each other. Slab # 31 had the highest difference due to the negative value limitation and was removed from the analysis. Another discrepancy identified was that the original GFM truncated any decimal values instead of rounding it. Therefore, a reading of 2.9 would be seen as 2 and recorded as 2 instead of 3 for the original GFM. It was noted that a reading of 2 and 3 at slab #30 was read as a negative 0 (-0) instead of just zero, indicating that the reading was actually between 0 and -1. The new GFM prototype rounds values so that a 2.6, for example, would be a 3. The actual values and an analysis of the data are provided in Table 6-1 and Figure 6-10.

Table 6-1 Field data collection Results

	GDOT				GT				
Slab #	GD1	GD2	GD3	GDOT Ave	GT1	GT2	GT3	GT Ave	Ave GD-GT
1	4				3				1
2	8				7				1
3	8				7				1
4	5				6				-1
5	6				7				-1
6	6				8				-2
7	6				7				-1
8	7	7	5	6.3	6	5	6	5.7	0.7
9	5	4	4	4.3	4	4	4	4.0	0.3
10	4	5	4	4.3	6	6	5	5.7	-1.3
11	5	5	5	5.0	5	6	5	5.3	-0.3
12	5	5	5	5.0	4	4	5	4.3	0.7
13	4	4	4	4.0	4	4	4	4.0	0.0
14	5	4	5	4.7	5	5	4	4.7	0.0
15	6	5	4	5.0	4	4	4	4.0	1.0
16	4	4	4	4.0	4	4	5	4.3	-0.3
17	-1	0	0	-0.3	-1	0	0	-0.3	0.0
18	5	4	4	4.3	5	4	4	4.3	0.0
19	9	9	9	9.0	8	8	8	8.0	1.0
20	6	5	6	5.7	5	6	5	5.3	0.3
21	4	4	4	4.0	4	3	4	3.7	0.3
22	6	6	6	6.0	4	5	5	4.7	1.3
23	5	5	5	5.0	5	5	4	4.7	0.3
24	3	3	3	3.0	2	2	3	2.3	0.7
25	5	5	5	5.0	3	3	3	3.0	2.0
26	5	5	5	5.0	5	5	5	5.0	0.0
27	2	1	1	1.3	0	1	2	1.0	0.3
28	3	3	3	3.0	3	2	3	2.7	0.3
29	0	1	1	0.7	-1	-1	-1	-1.0	1.7
30	0	-0	-0	0.0	-1	-1	-1	-1.0	1.0
31	-8	-9	-9	-8.7	-1	-1	-1	-1.0	-7.7
32	0	0	0	0.0	-1	-1	-1	-1.0	1.0
33	12	12	12	12.0	12	11	12	11.7	0.3
34	16	16	16	16.0	16	16	17	16.3	-0.3
35	17	17	17	17.0	16	15	16	15.7	1.3
36	15	16	16	15.7	15	15	15	15.0	0.7
37	5	5	6	5.3	3	5	5	4.3	1.0
38	4	4	4	4.0	4	3	3	3.3	0.7
39	5	5	4	4.7	3	4	4	3.7	1.0
40	5	5	6	5.3	5	4	5	4.7	0.7

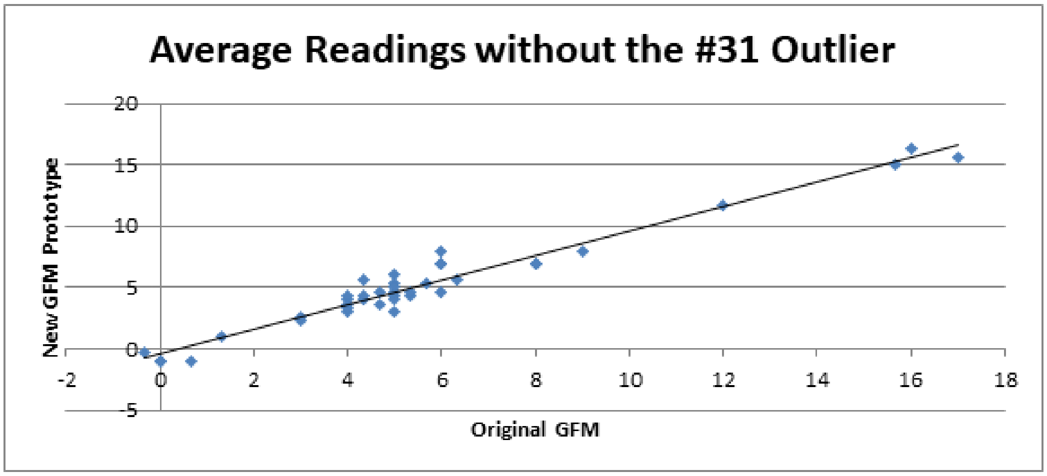


Figure 6-10 Analysis results between the reading from the original GFM and the new GFM prototype

6.4 Summary

The GFM is essential for measuring faulting, one of the important distresses on JPCP. While the original GFM works well for the current CPACES, there is an insufficient number of units in GDOT due to the damage of the units over the years. Although the design of the original GFM is well documented and was adopted by the LTPP program, the components of the original GFM have become obsolete. Therefore, the research team at Georgia Tech redesigned and fabricated a new GFM prototype for GDOT. The new GFM keeps the operation flow and the functions of the original GFM design while streamlining the electronic control of the units and using off-the-shelf components that are commonly available. Each new GFM unit has been tested for battery consumption and calibrated for accurate measurement. The validation results show that the new GFM prototype is as consistent in reading faults as the original GFM, and it improves some of the readings over the original GFM (e.g., decimal truncation).

7 ASSESSMENT OF FAULTING MEASUREMENT METHODS

Faulting is one of the three performance measures (i.e., faulting, cracking, and IRI) recognized by the Code of Federal Regulations (CFR) for jointed concrete pavements. FHWA rules developed for the CFR require state DOTs to use the AASHTO Standard R 36 (AASHTO, 2017), Standard Method for Evaluating Faulting of Concrete Pavements, for measurement of faulting. R 36 allows both manual testing using a faultmeter and automatic testing using a high-speed inertial profiler (HSIP). However, there is a concern in the literature (Simpson et al., 2017) that the HSIP methods are not accurate enough for network level testing of faulting.

Recent studies have also shown that 3D laser technology is showing promise for providing more accurate faulting measurements. Still, there currently is not a specific method in R36 that utilizes 3D pavement data for gathering faulting measurements. Therefore, this chapter presents a critical assessment of an alternative faulting measurement method that takes full advantage of the full-coverage capabilities of 3D pavement data to measure faulting. First, a review of faulting measurement standard and methods is presented. Next, a new 2D-based faulting measurement method is proposed to provide accurate and consistent faulting measurement. In addition, the field test is described, and the impacts of various parameters in the proposed method on the faulting values are discussed. The result was presented at the 2018 Transportation Research Board Annual Meeting and accepted for publication (Geary et al., 2018)

7.1 Background

Faulting, cracking, and IRI are the three performance measures recognized in the Code of Federal Regulations (CFR, Part 490) for JPCP. State DOTs must report these pavement performance measures to FHWA starting in 2018. As part of the recent regulation changes, the percent of roadways in Good and Poor condition will be monitored by the federal government, and each state DOT use of federal funding will be impacted by these measurements. All three pavement measurements must fall into a good performance region for a section of road to be rated Good (FHWA, 2017). Therefore, each of these measurements is critical for recognizing what constitutes good performance in jointed concrete pavements.

IRI measurements are well defined, and a number of well-vetted standards are used for IRI, such as the American Association of State Highway and Transportation Officials (AASHTO) Standards M-328, R-54, R56, etc. Certification programs are also available for the high-speed inertial profiler (HSIP) equipment used to measure IRI (CalTrans, 2017).

Cracking, while somewhat more nebulous than IRI, now has a clear standard definition in the latest Highway Performance Monitoring System Field Manual (HPMS). The HPMS Field Manual considers the cracking of a slab be transverse cracking when it extends at least ½ the width of the lane (FHWA, 2011). Cracking is not measured per se but is considered as yes or no per slab for classification purposes, so the measurement of cracking is not subject to much measurement uncertainty.

Faulting, on the other hand, while it has been performed by the Long-Term Pavement Performance program (LTPP) and many state DOTs for over 20 years, and although a simple concept, it is not as defined as a measurement as is IRI or cracking.
FHWA rules developed for the CFR require state DOTs to use the AASHTO Standard R 36, “Standard Method for Evaluating Faulting of Concrete Pavements,” for measurement of faulting (FHWA, 2017). AASHTO R 36 provides both manual and automatic methods to compute faulting (AASHTO, 2017). However, the manual method is not realistically a viable option due to the FHWA requirement of measuring every joint on the network every year. The manual method described in the R 36 standard is also not equivalent to the manual faultmeter equipment that has been used for over 20 years. The 2012 ASTM International report on pavement performance measures reported, “Currently, no such manual devices have been built to meet the requirements in AASHTO R 36-12” (ASTM, 2012). The Florida DOT recently constructed and tested a faultmeter that meets the R 36 requirements, which will be described later in this chapter.

ASHTO R 36 also includes two automatic methods that use the longitudinal profile from the same HSIP equipment that is used for IRI. While the HSIP equipment has been widely used and validated for IRI measurements, it has not been as extensively tested for faulting measurements, and when it was tested, there have been accuracy concerns. A 2016 report developed for FHWA (Simpson et al., 2016) noted a concern with collecting reliable and repeatable faulting data with HSIP equipment alone and suggested that 3D methods be pursued. Some DOTs that use HSIP for faulting, such as Illinois DOT, specifically refer to using manual faulting equipment in the field to check on unusual measurements due to the concern for “inaccuracy and misrepresentation” of automatic faulting measurements (ILDOT, 2010). Thus, there is an urgent need for a new method that can provide accurate, consistent, and reliable faulting measurements at the network level.

7.2 Review of Faulting Measurement Standard and Methods

This section presents a review of faulting measurement standard and methods.

7.2.1 *How is Faulting Measured*

Faulting is the difference in elevation of an approach slab as compared to the elevation of a leave slab at a joint or crack. Manual faulting measurements have long been performed using a Georgia Faultmeter (GFM), which was first built by the Georgia DOT in 1987. Georgia DOT also built the first modified version used by SHRP for LTPP testing in the late 1980s.

Figure 7-1 shows how a faulting measurement is taken with the GFM. The legs are placed on the leave slab and the probe measures the faulting from the approach slab. The GFM reads out in positive or negative integer readings (i.e. -2, -1, 0, 1, 2) that are equivalent to 1/32 in (0.03 in or 0.8 mm) measurements. It can measure positive and negative faulting. Positive faulting is a drop in elevation along the direction of travel, and negative faulting is a rise in elevation in the direction of travel, as shown in Figure 7-1. Positive faulting is considered the expected change due to traffic effects. Negative faulting, while still possible, has been linked to data errors, such as measuring faulting at cracked or repaired areas, excessive joint sealant, placing the GFM in the wrong direction, or being due to the accuracy of the measurement itself when the actual elevation difference is near 0 (Selezneva et al., 2000). The range of the GFM reading is from -20 to +20 or ±20/32 in (±0.6 in or ±16 mm), and it has a clear space between the closest leg to the probe and the probe of 50 mm (2 in).

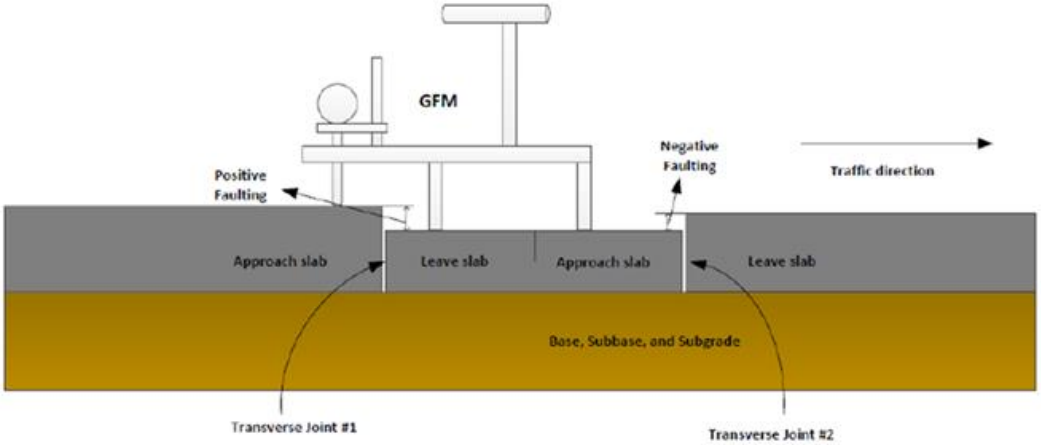


Figure 7-1 LTPP faultmeter operation (Agurla and Lin, 2015)

The SHRP faultmeter (SFM) is basically the same as the GFM, except it was modified to read out in millimeters to the nearest millimeter (0.04 in or 1 mm.), and it was also modified to have 100 mm (4 in) clear spacing between the closest leg and the probe so it could also be used for shoulder drop-off readings (Stone, 1991). Minnesota DOT also made changes to the footprint of the faultmeter for the MNROADs test sections to improve repeatability. Minnesota DOT found that a three leg “bolt” system was more stable than the four long legs used in the GFM, but they also found that marking where the exact location measurements were taken along the joint was also crucial to repeatable measurements (Worel and Clyne, 2009). Of course, manual faulting measurements can be time-consuming and labor-intensive, and they can cause safety concerns. Therefore, automatic methods have been developed using longitudinal profiles from high-speed inertial profilers, which will be discussed in the next section in relation to the current faulting standard.

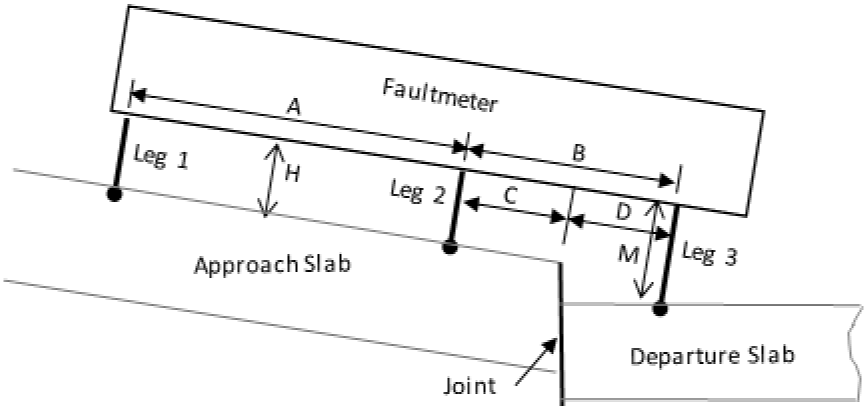


Figure 7-2 Generic Faultmeter from AASHTO R 36 Standard (AASHTO, 2017)

7.2.2 *Current Faulting Standard*

AASHTO R 36, “Evaluating Faulting of Concrete Pavements,” is the only current standard for faulting measurements. R 36 currently provides three methods to measure the faulting value: manual, automatic Method A, and automatic Method B. The schematic for manual measurements in AASHTO R 36 is different from the current GFM or SFM. The dimensions for the distance between the probe and the joint and the joint and the front legs (C and D, as shown in Figure 7-2) are each noted to be between 76 and 226 mm (3 in to 8.9 in). Therefore, the R 36 generic faultmeter has a clear space between the closest leg to the probe and the probe of 152 to 452 mm (6 to 17.8 in) as compared to 50 mm (2 in) for the GFM and 100 mm (4 in) for the SFM. In addition, the probe in R36 is on the departure slab and the legs are on the approach slab, while the probe for the GFM and the SFM (see Figure 7-1) is placed on the approach slab, and the legs are placed on the departure slab. The automatic methods both use one longitudinal profile from a high-speed inertial profiler (HSIP) to compute faulting.

Method A

Automatic Method A uses a regression line for the approach and departure slab to identify elevation measurements on each side of the joint. The regressed length is 1219 mm (4 ft) on each side of the joint. The difference in elevations for a section consisting of a distance of 76 mm to 226 mm (3 in to 8.9 in) from the joint are averaged.

Method B

Method B is similar to Method A in that it averages the values between 76 mm to 226 mm (3 in to 8.9 in), but it uses the actual profile points and measures the elevation difference at 300 mm (11.8 in) horizontal locations. Both methods have inherent issues. Using a 1219 mm (4 ft) regression will include the effect of profile roadway slope. Measuring elevation differences as Method B does will provide different results for a roadway on a constant slope than a section that is on a changing slope, even if the faulting is the same.

Recently, comparison of manual and automatic faulting measurement accuracy using R36 20 equipment and longitudinal profile data was documented by Florida DOT. It used its newly-developed faultmeter that reads out to 0.01 mm and met R36 requirements; Florida DOT concluded that its faultmeter was repeatable to 0.42 mm in the field and that its automatic method was repeatable to 0.6 mm when the same HSIP was used, although the results increased to 0.9 mm when different HSIPs were used. Nonetheless, Florida DOT experienced issues with joint identification of the 93 joints marked and manually tested; only 39 were consistently picked up with the HSIP profilers, and, therefore, they were the only joints compared for faulting, putting somewhat of an unknown bias into the analysis (Mraz et al., 2012). Florida DOT also identified a bias in the automatic method as compared to the manual faulting with a confidence limit of 0.2 mm (0.01 in) to 0.7 mm (0.03 in). It should also be noted that 36 of the 39 manual readings that were used measured 29, less than a 4 mm difference (0.125 in) in elevation.

7.2.3 *Concerns with Current Faulting Methods*

GFMs are historically considered to only be accurate to ± one reading (1 mm or 1/3 in). Minnesota DOT made modifications to the original GFM to improve repeatability of their faulting measurements. By replacing the 4 legs with 3 bolt feet and adding an offset rod, it noticed a change in the faulting trends. Minnesota DOT y further marked the actual locations on the pavement when it felt that repeatability due to surface texture could be an issue (12). Although these improvements are applicable to a static accelerated test facility, like MNRoads, they cannot be incorporated into actual network level surveys. Manual GFM readings are time-consuming, and since it is necessary to place the equipment in the travel lane to get a measurement, they can also impede traffic. There is always a safety issue when physically encroaching into a travel lane.

Automated methods that use a single longitudinal profile can be affected by surface texture, since the depth of typical tining is on the order of 4 mm (0.125 in) (Rasmussen et al., 2011), measuring faulting to less than 1 mm (0.03 in) is a challenge over using longitudinal profiles alone. A recent study performed for FHWA on collecting network level data for the Highway Performance Monitoring System (HPMS) noted that the HSIP used found an average of 0.4 joints as compared to 3.4 using 3D pavement data. Florida DOT experienced a similar issue with their HSIP readings not picking up every joint using a longitudinal profile. This is a concern with HSIP and longitudinal profiles and is a known challenge (Agurla and Lin, 2015; Chang et al., 2010). While this study does not address automatic joint location, only faulting measurements, 3D pavement data naturally would lend itself to easier identification of joints because it covers the full-lane-width (instead of one longitudinal profile).

7.3 Proposed Faulting Measurement Method Using 3D Pavement Data

3D pavement data has the benefit of being able to identify joints and also provides a 3-dimensional view of the edge of the pavement that can be used to smooth out irregularities, like spalling, while also being able to measure as close to the joint as possible to remove curl, warp, and longitudinal profile aspects. Preliminary studies of faulting measurements using 3D data performed by Tsai et al. (2011; 2012) and others (Wang et al., 2014) have shown potentially improved results over HSIP methods.

7.3.1 *Description of the Proposed Method*

The placement and functionality of a GFM were considered in developing a method to measure faulting using 3D data. The GFM places a probe on the approach side, as shown previously in Figure 7-2. It rests on the departure side, essentially creating a plane. With manual placement, the operator can observe spalling or other irregularities and place the device so that it does not include those areas. With an automatic method, that is not possible, so to address that issue, a rectangular area was chosen (instead of a point location) to represent both the approach and departure slab. In this manner, any irregularities can be smoothed out or identified by averaging the data from several points within the area and identifying the standard deviation of the data.

Therefore, the proposed faulting measurement method using 3D data involves measuring within a smoothed rectangular shaped area on each side of the joint, as shown in Figure 7-3 (a). The rectangular box shown in the figure is located 120 mm from the lane line and 10 mm from the center of the joint, and the box is 20 mm longitudinally by 200 mm transversely. The concept is similar to Method B in R36 in which the values are averaged, although, in contrast to R36 where the values are averaged along the longitudinal profile, the elevation differences are computed at 5 points within the box and then averaged transversely along the joint. Five measurements are taken within each smoothed box, and each elevation difference is computed (X2-X1); then the average is computed for each joint, as shown in Figure 7-3 (b). The standard deviation is also computed for each joint, which can be checked for anomalies.

A program was developed in MATLAB to read the 3D files and allow for changing the size and location of the measurement box and computing the elevation difference at a number of points within the area. The area is located in reference to the center of the joint and the lane marking. The results were compared to the ground truth determined by a GFM, and the field test is described in the next section.

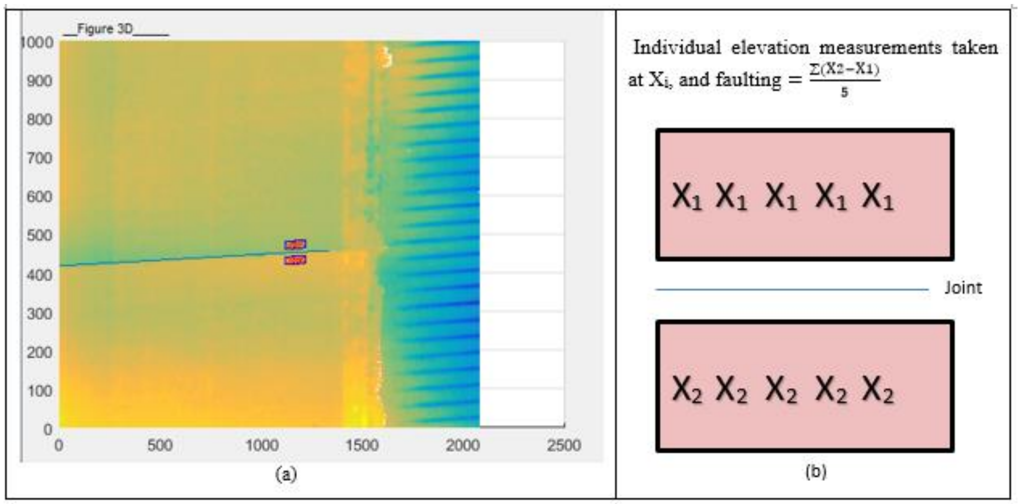


Figure 7-3 Smoothed area method used to calculate faulting

7.3.2 *Field Test*

A field test was performed February 27, 2017, on Interstate 16 in central Georgia to compare manual GFM measurements to faulting from 3D pavement data. Faulting at 20 joints (joints 1-20) was measured between eastbound MP 6-7, and faulting at 20 joints (joints 21-40) was measured between westbound MP 15-14. MP 6-7 consists of 30 ft slabs on 90-degree joints. MP 15-14 consists of slabs at a random spacing (17 ft; 23 ft; 22 ft; 16 ft) with joints skewed at 10 degrees. Both sections were originally constructed in the 1970s with transverse tining but now have a diamond-ground surface. The actual joint locations within the two miles were chosen to get the widest range of faulting possible. The GFM readings varied from -9 to +17 (negative 9/32 in to positive 17/32 in) or -7 mm to +13.4 mm. A GFM in use by the Georgia DOT was used, and Georgia DOT personnel that normally do the manual surveys for GDOT operated the GFM. The GFM was checked for calibration at the beginning of each mile section. The GFM reads out in whole numbers. It was identified that the GFM truncates readings instead of rounding (i.e. an actual reading of 2.9 would be seen as 2 and recorded as 2 instead of 3 for the GFM). Three readings were taken at locations 8-40, while one reading was taken at locations 1-7. The joint locations were marked with a template to allow for a consistent, repeat reading with the GFM and to locate the exact joints tested. The Georgia Tech Sensing Van collected 3D pavement data over the sections the same day after all the manual readings were taken.

As noted, three replicates were taken at 33 of the 40 joints. Although a template was used and the faultmeter was placed back within the template markings each time, the GFM readings for each set of the faultmeter did vary. Of the 33 readings with 3 replicates, only 18 consistently read the same GFM value for each of the three times. This could be due inherent variability due to the measurement increment (0.8 mm) and pavement irregularities or, potentially, due to rounding of the GFM value as noted earlier. The 3D faulting data was first computed by identifying the location of the probe marking in the image (the black dot inside the template, as shown in Figure 7-4), from the distance from the shoulder and using a 20 mm by 200 mm rectangular box with 5 measurements taken in the box. The box was located 10 mm off the joint on each side, which provided an area measurement located between 10 and 30 mm off the joint to match the 25 mm probe to joint measurement used by the GFM. The comparisons of the GFM and 3D elevation differences derived this way are shown in Figure 7-4 (note: the GFM values were converted to mm). The GFM readings are shown by the dots, and the 3D reading is shown by the X. When more than one GFM reading was recorded at a location, a vertical line is shown depicting the range of the GFM readings. An apparent bias between the

GFM and 3D readings is displayed. Ninety percent of the 3D readings are lower than the average GFM readings. An average bias of 0.6 mm was observed.

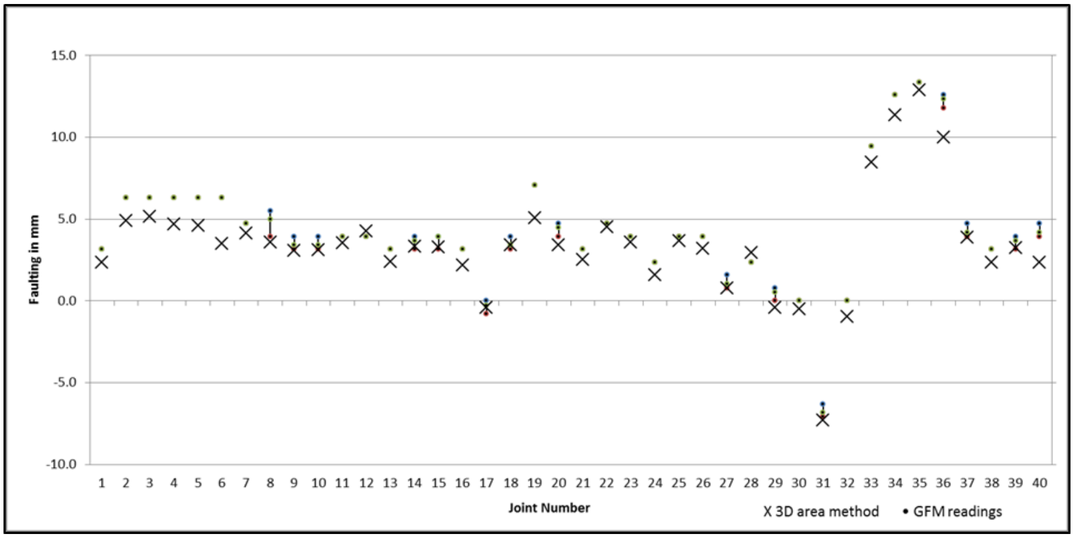


Figure 7-4 GFM readings vs. 3D method for 40 joint field test

The size of the rectangular box was increased, but the best results were found when the box size was maintained at 20 mm by 100 mm. Next, the location of the box was varied. The box was located at a consistent distance of 120, 220, 320, 420, and 640 mm off the lane line (shoulder). The box was also moved away from the joint at distances of 10, 20, 40, 60, 80, 100, 200, and 300 mm. Figure 7-5 shows an example of the locations of the boxes for the different measurements. The photo shows only approximately half of the lane. The shoulder is on the right side of the photo, and the outside lane marking is directly to the left of the shoulder. The approach slab is in the bottom of the picture, and the departure slab in the top. The joint is mirrored by the boxes representing the different locations of the tests for the sensitivity analysis. The values shown are in millimeters. The results of this sensitivity analysis are further described below.

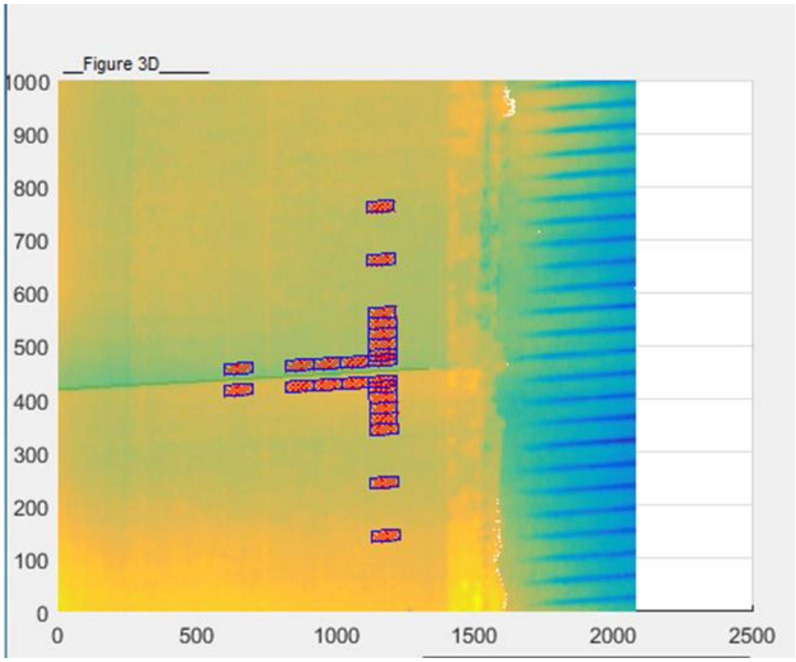


Figure 7-5 Showing varying locations of measurements taken

<u>Sensitivity Analysis - distance from the Shoulder</u>

The elevation differences when placing the box 120 mm, 220 mm, 320 mm, 420 mm, and 640 mm from the lane line were calculated for all the joints. For clarity, only a portion of the data is shown in Figure 7-6. The figure shows some of the joints that had the highest and least positive and negative difference between the 120 mm reading and the 640 mm reading. These two readings were chosen, as the GFM is typically measured around 120 mm from the shoulder and the wheelpaths are considered between 300 mm and 750 mm from the shoulder. Some of the joints showed a higher faulting value at the edge, and some showed a higher value further from the edge. Joints not shown here were similar to the ones shown; they varied in values, but no consistent trend was identified overall. As can be seen, the values did not vary by more than 1 mm either way for most of the joints shown. This was also the case for all the joints where the average absolute difference between the elevation difference at 120 mm and 640 mm was 0.57 mm. This result is consistent with SFM readings at the edge and wheelpath, which were performed using LTPP data in a faulting study published by FHWA in 2000. In that study, it was found that 90% of the joints that they compared from the LTPP database had less than a +/- 1 mm difference in faulting readings between the edge and the wheelpath of the same joint. The authors feel that the variation was more related to the accuracy of the equipment used to measure faulting than true elevation differences (Simpson et al., 2016).

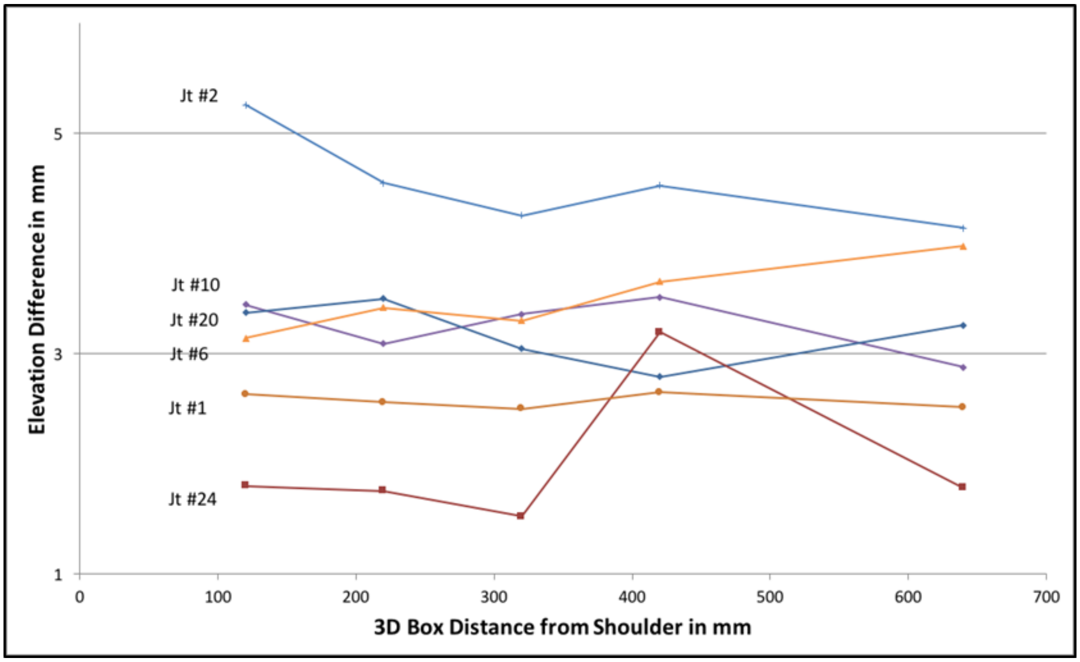


Figure 7-6 Variability in faulting readings based on distance 2 from shoulder

Sensitivity Analysis - distance from the Joint

As expected, the elevation difference computed at different locations away from the joint varied more than in the case of the transverse distance from the shoulder. Changes in elevation related to distance from the joint can come from curl and warp of the slabs, profile elevation changes, or cracking of the slabs. For the first section (the first 19 joints) the elevation difference computed at each location farther from the joint of the box is shown in Figure 7-7. It shows an almost consistent trend of the measured elevation difference becoming smaller as the measurement is taken further from the joint. Once again, this would tend to indicate that measuring faulting closer to the joint should provide more conservative faulting values. A 3D depiction of Joint #6 is shown in the next figure (Figure 7-8) to illustrate the differences more clearly.

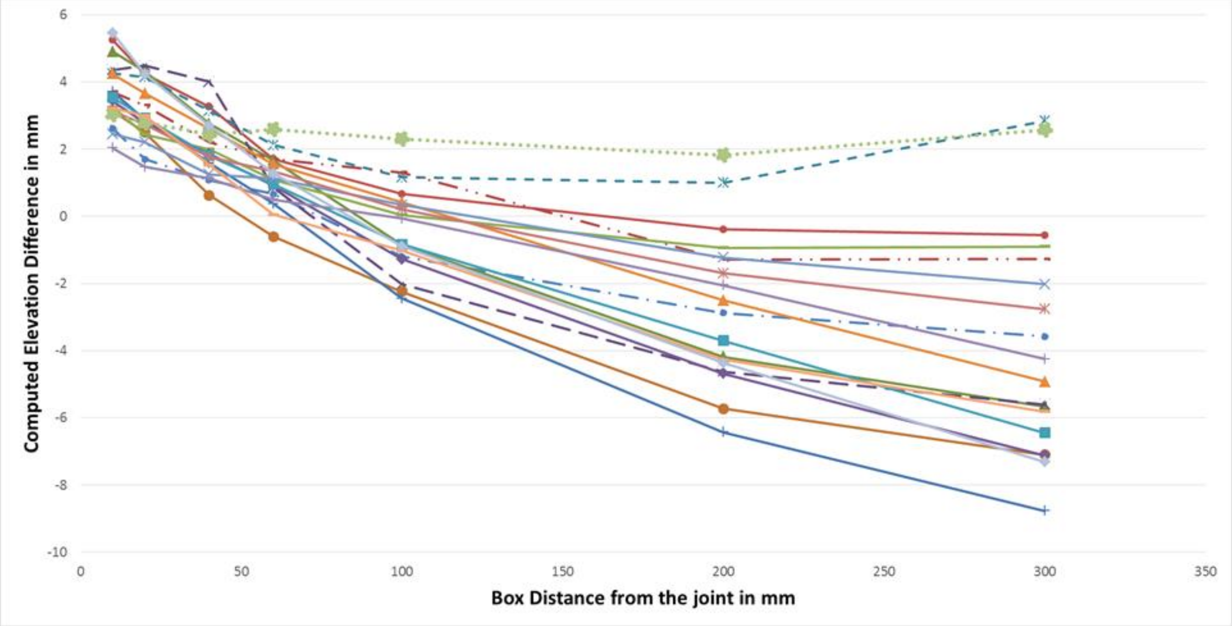


Figure 7-7 Elevation differences determined at locations

Figure 7-8 illustrates why the elevation difference is getting smaller and, even, negative, as the measurement is taken farther from the joint. At the joint (located at a horizontal distance of 300 mm in the figure) the approach slab clearly is higher than the departure slab, but if readings are taken farther from the joint, the departure slab is at a higher elevation than the approach slab, providing a negative elevation difference. The three axes shown here are in millimeters.

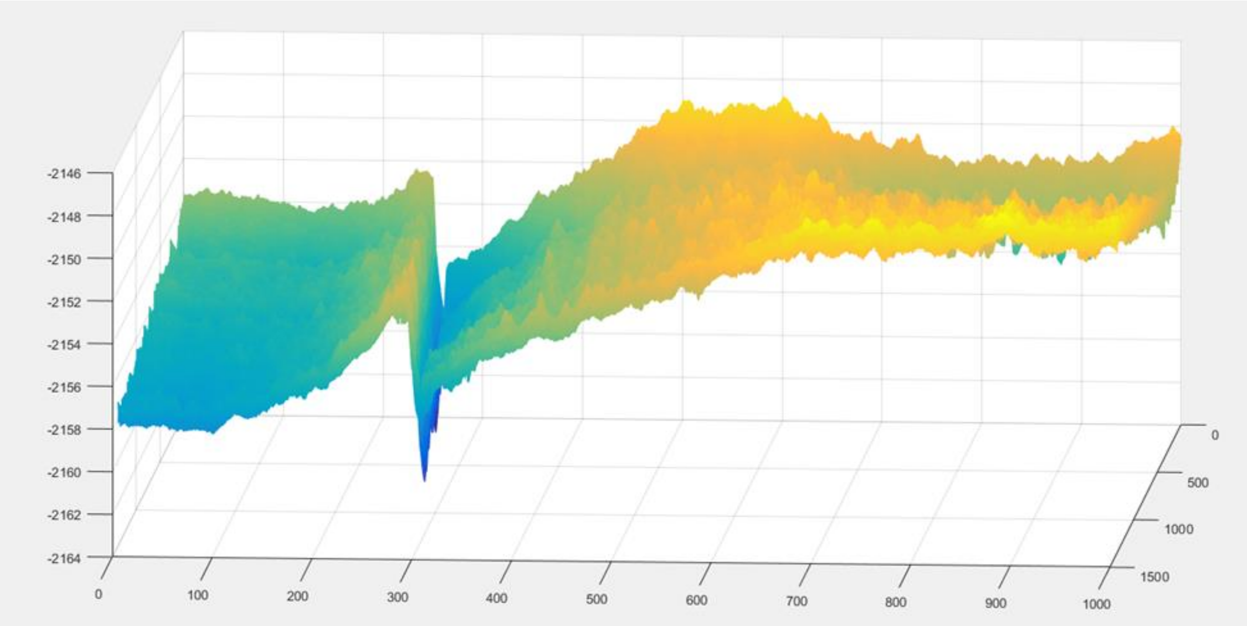


Figure 7-8 3D view of Joint 6 (joint at 300 mm)

7.4 Summary

While this study was performed on a limited sample (only two locations having similar textures), it did showcase a wide range of faulting values and two different joint orientations. The 2D-based faulting measurement method proposed in this chapter provides a different way to measure faulting using 3D pavement data. Relatively consistent results were gathered when compared to manual GFM readings. Analysis of different locations for testing showed that the most comparable faulting measurements to the GFM are between 10 and 20 mm from the joint. The measurements closest to the joint also provided the most conservative values of faulting. AASHTO R 36 currently does not address 3D pavement data for faulting measurement, so this proposed method could be developed into an alternative Method C. This method was presented to the AASHTO Technical Subcommittee 5a Pavement Measurement and Performance

Measures on August 2018 and was recommended to be added as a 3D pavement data method for measuring faulting in R 36, the current AASHTO Faulting Standard. For future research, further test on different textures, additional joint spacings, and different joint widths would be beneficial. Also, 3D pavement data needs to be collected at different temperatures to check repeatability under conditions of curl and warp.

8. CONCLUSIONS AND RECOMMENDATIONS

Rigid pavements, including continuously reinforced concrete pavement (CRCP) and jointed plain concrete pavement (JPCP), are critical for efficient freight logistics and need to be properly maintained to support freight logistics. GDOT does not have a standardized pavement condition evaluation system or treatment determination criteria for CRCP, and the concrete pavement condition evaluation for JPCP has not been updated for the past two decades. There is a need for developing a comprehensive pavement condition evaluation system for CRCP and JPCP to support M&R decisions, especially when funding is limited. The tablet-based CRCPACES and CRCPACES applications were developed to facilitate implementation for the condition evaluation systems and to improve productivity and data quality. The outcomes of this research project are the following:

1. A CRCP pavement condition evaluation system (CRCPACES), including a distress protocol and a rating system, has, for the first time, been developed for GDOT. The distress protocol standardizes the identification and quantification of six distresses using a walkthrough survey (for transverse cracking) and a windshield survey (for the other five distresses). Table 1 summarizes the distress types, severity levels, extents, and measurement methods. A CRCP rating (scale 0 to 100) and deduct values for each distress were developed to provide a quantitative performance indicator for CRCP. Both the distress protocol and rating system were validated and calibrated based on GDOT engineers' inputs from a field survey of two 1-mile sections on I-75. A CRCPACES instructional

manual with the distress protocol and rating system was developed to provide guidelines for the CRCPACES survey.

2. A tablet-based CRCPACES application with tap-and-count features for easy data entry, embedded real-time data checking, and an integrated CRCPACES distress protocol was developed to facilitate the CRCP data collection process and the implementation of CRCPACES.
3. An enhanced JPCP pavement condition evaluation system (JPCPACES) was developed to monitor the severe distresses of aged JPCP. This included a finer distress categorization, improved faulting index calculation, and an enhanced rating system. The JPCPACES instructional manual was updated to incorporate all the changes above, and distress photos were updated to support JPCPACES surveys and training. In addition, in consultation with GDOT engineers, refined JPCP treatment criteria were developed based on a review of states' treatment methods and criteria.
4. A tablet-based JPCPACES application with features similar to the CRCPACES application was developed to improve the JPCP data collection process by eliminating the current pen-and-paper recording method.
5. Eight modern Georgia Faultmeters were built so each district will have one faultmeter with which to effectively accomplish its annual faulting measurement operations. The modern Georgia Faultmeters were designed as replacements for old faultmeters and fabricated with modern, up-to-date sensors. Lab and field tests were conducted to validate the accuracy of the modern faultmeters by comparing their fault readings to the fault readings of

the existing, old Georgia Faultmeters. Results show the readings from the modern faultmeters are comparable to the existing, old faultmeters, having a difference of less than 1 mm

6. An alternative faulting measurement method using 3D pavement data that can be operated safely and effectively on high-volume roadways was also explored and assessed. A review of AASHTO R36 showed its faulting measurement method was not compatible with the Georgia Faultmeter's footprint; tests also showed the use of a single profile cannot produce a reliable faulting measurement. Thus, a new 2D-based method that measures faulting as the elevation differences between two 2D-planes on each side of the joint was proposed. Lab and field tests showed the proposed method can successfully estimate faulting; the new method has an average error of less than 2/32 in (Geary et al, 2018). This method was presented to the AASHTO Technical Subcommittee 5a Pavement Measurement and Performance Measures on August 2018 and was recommended to be added as a 3D pavement data method for measuring faulting in R 36, the current AASHTO Faulting Standard.

Implementation of the research outcomes and recommendations are as follows:

1. To establish its annual CRCP survey, it is recommended that GDOT conduct annual statewide training on the newly developed CRCPACES and the tablet-based CRCPACES application for data collection. Statewide training was initially conducted on November 13, 2017 in Macon, Georgia.

2. To ensure the implementation of JPCPACES, it is recommended that GDOT conduct annual statewide training on the enhanced JPCPACES (with a focus on the refined distress types) and the tablet-based JPCPACES application for data collection. Again, statewide training was initially conducted on November 13, 2017, in Macon, Georgia. According to Mr. Curtis Grovner, the estimated savings are approximately 280 man-hours because of the elimination of in-office data entry.
3. It is recommended that GDOT develop applications to systemically determine the treatment methods for implementing the treatment criteria for JPCP.
4. A full-scale test of the 2D-based faulting measurement method (including a wide range of faulting, various distress severities, different temperatures, and different speeds) is recommended to comprehensively validate this proposed method. Such an automatic faulting measurement method will promote GDOT's ability to collect data in support of the pavement performance measurement required by FHWA in a safe and cost-effective way.
5. Further studies, including a pool-funded study to establish a national standard for an automatic faulting measurement that uses 3D pavement data, including noise removal, joint detection, and outliner removal (e.g., at cracked locations), are recommended.

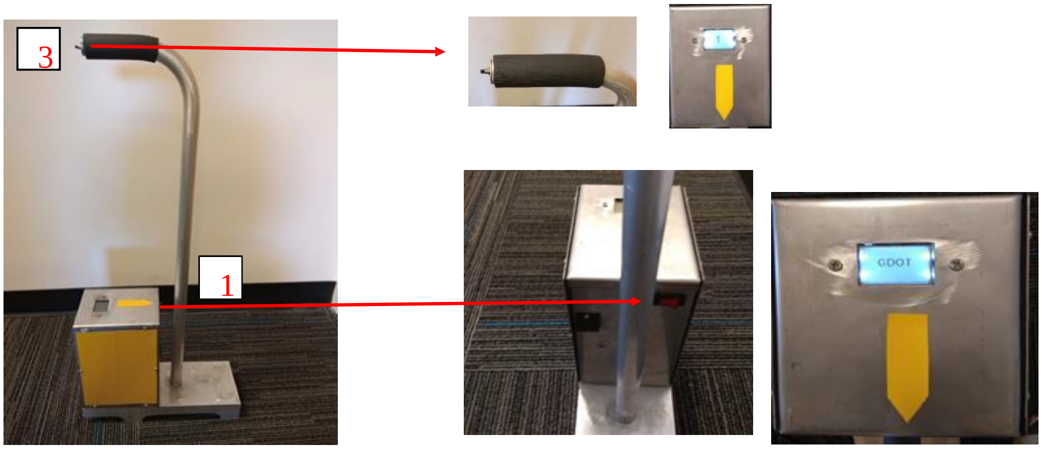
REFERENCES

1. AASHTO R36-17, Evaluating Faulting of Concrete Pavements. Standard Specifications for Transportation Material and Methods of Sampling and Testing, AASHTO. 2017.
2. The AASHO Road Test, Report 5, Pavement Research. Special Report 61E, National Academy of Sciences- National Research Council, Washington, D.C., 1962.
3. Agurla, M., and S. Lin. LongTerm Pavement Performance Automated Faulting Measurement. US DOT, FHWA-HRT-14-092. McLean, Virginia, 2015.
4. CalTrans. Smoother Pavements: Certification Location. California. http://www.dot.ca.gov/hq/maint/Pavement/Offices/Pavement_Engineering/Certification_Location.shtml, Accessed 2017.
5. Chang, G., A. Nazef, J. Watkins, and S. M. Karamihas. Automated Fault Measurement (AFM) in Proval. Pavement Evaluation 2010 Conference. Roanoke, Virginia, 2010.
6. FHWA. TechBrief: Continuously Reinforced Concrete Pavement Performance and Best Practices. Federal Highway Administration, Washington, D.C., 2012.
7. Geary, G., Tsai, Y., and Wu, Y. An Area-Based Faulting Measurement Method Using 3D Pavement Data. Transportation Research Record, Washington, D.C. (in press).
8. GDOT. 441 Report - County Mileage Of Public Roads in Georgia By Surface Type for 2017. Georgie Department of Transportation, Atlanta, GA. 2017.
9. Gulden, W., Investigation into the Causes of Pavement Faulting on the Georgia Interstate System. Georgia Department of Transportation, Atlanta, GA, 1974.

10. Gulden, W. and D. Brown. Improving Load Transfer in Existing Jointed Plain Concrete Pavements. Office of Materials and Research, Georgia Department of Transportation, Atlanta, GA, 1983.
11. Highway Performance Monitoring System Field Manual, FHWA. OMB No. 2125-0028, 2014.
12. ILDOT. Chapter 53- Pavement Rehabilitation, Bureau of Design and Environment Manual. Illinois DOT, 2010.
13. Roesler, J., Hiller, J., and Brand A. Continuously Reinforced Concrete Pavement Manual – Guidelines for Design, Construction, Maintenance, and Rehabilitation. FHWA-HIF-16-026. Federal Highway Administration, Washington, D.C. 2016
14. U.S. DOT, FHWA. Transportation Performance Management Website: Two Performance Management Final Rules Take Effect. Washington. D.C. https://www.fhwa.dot.gov/tpm/rule.cfm, Accessed 2017.
15. Simpson, A. L., G. R. Rada, B. Visintine, and J. Groeger. Interstate Pavement Condition Sampling Final Report. FHWA-HIF-17-022, Washington, D.C., 2016.
16. Selezneva, O., J. Jiang, and S. D. Tayabji. Preliminary Evaluation and Analysis of LTPP Faulting Data - Final Report. FHWA-RD-00-076. McLean, Virginia, 2000.
17. Stone, J. Design, Operation, and Maintenance Manual for Georgia Digital Faultmeter. Publication SP 9010, Georgia Department of Transportation, Atlanta, GA, 1991.
18. Smith, K. and Harrington, Pierce, L., Preshant, R. and Smith, K. Concrete Pavement Preservation Guide (Second Edition). FHWA-HIF-14-014, Federal Highway Administration, Washington, D.C., 2014.

19. Tsai, Y. and Lai, J. S. A Framework and Strategy for Implementing An IT-based Pavement Management System”, Journal of The Transportation Research Record, No. 1816, pp. 56-64, National Academy of Sciences; Washington, DC., 2002.
20. Tsai, Y. and Lai, J. S. Utilization of Information Technology to Enhance Asphalt Pavement Condition Evaluation Program. The International Journal of Pavement Engineering, Vol. 2(1):17-32, 2001
21. Tsai, Y. C., Wu, Y., and Ai, C. Critical Assessment of Measuring Concrete Joint Faulting Using 3D Continuous Pavement Profile Data. Journal of Transportation Engineering, Volume 138 Issue 11, 2012.
22. Wang, K. C. P., Li, L. and Li, J. Q. Automated Joint Faulting Measurement Using 3D Pavement Texture Data at 1 mm Resolution. ASCE T&DI Congress, 2014.
23. Worel, B. and Clyne, T. MnROAD Faultmeter. Minnesota Road Research, 2009.
24. Zimmerman, K. NCHRP Synthesis Report 501: Pavement Management Systems: Putting Data to Work. Transportation Research Board, Washington, D.C., 2017.

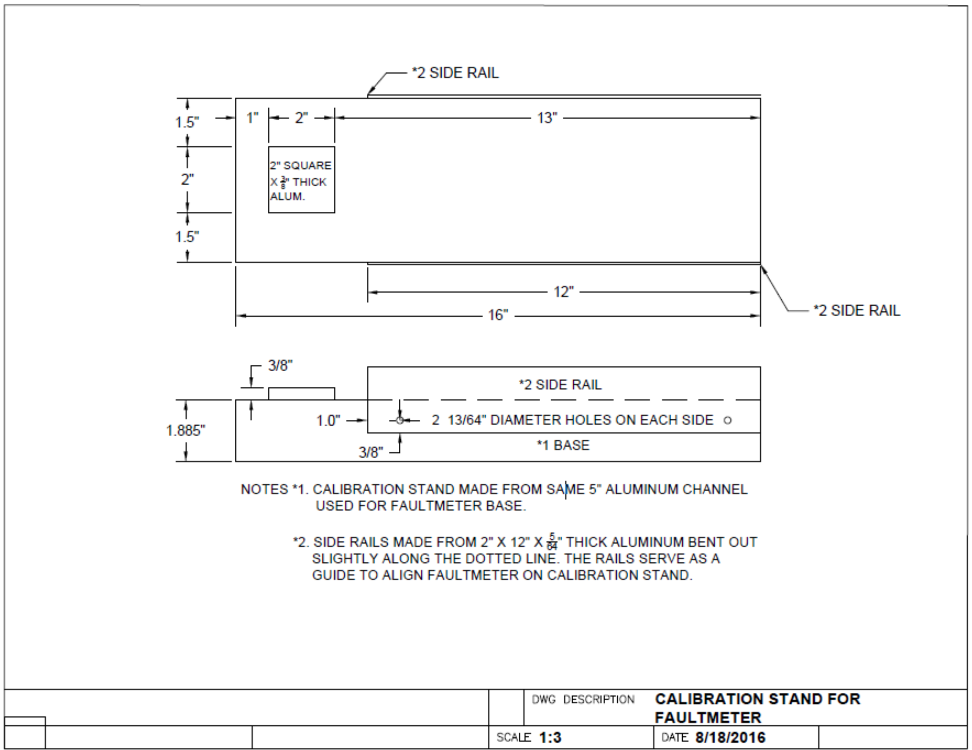
APPENDIX A GEORGIA FAULTMETER OPERATION MANUAL



- ➢ Turn on Power. You will see “GDOT” on the screen.
- ➢ Place the faultmeter at the joint.
- ➢ Press the button to measure faulting.
- ➢ Turn off Power when finish the survey.
- ➢ Charge the battery every week using the cable provided.

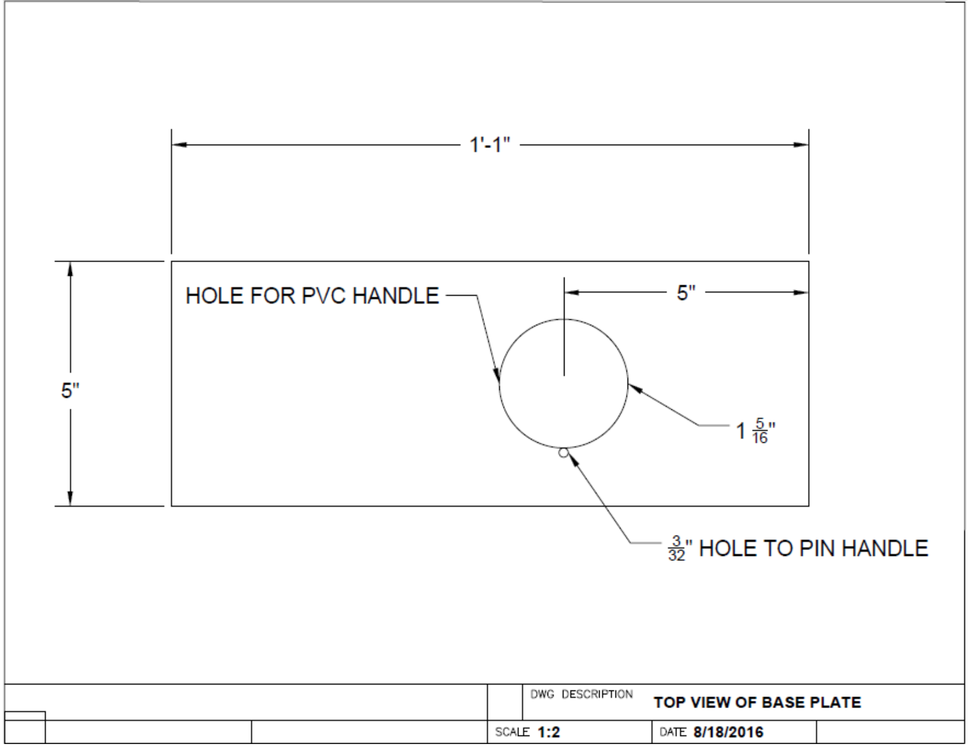
APPENDIX B DESIGN OF GEORGIA FAULTMETER

- Design of GFM stand and base plate

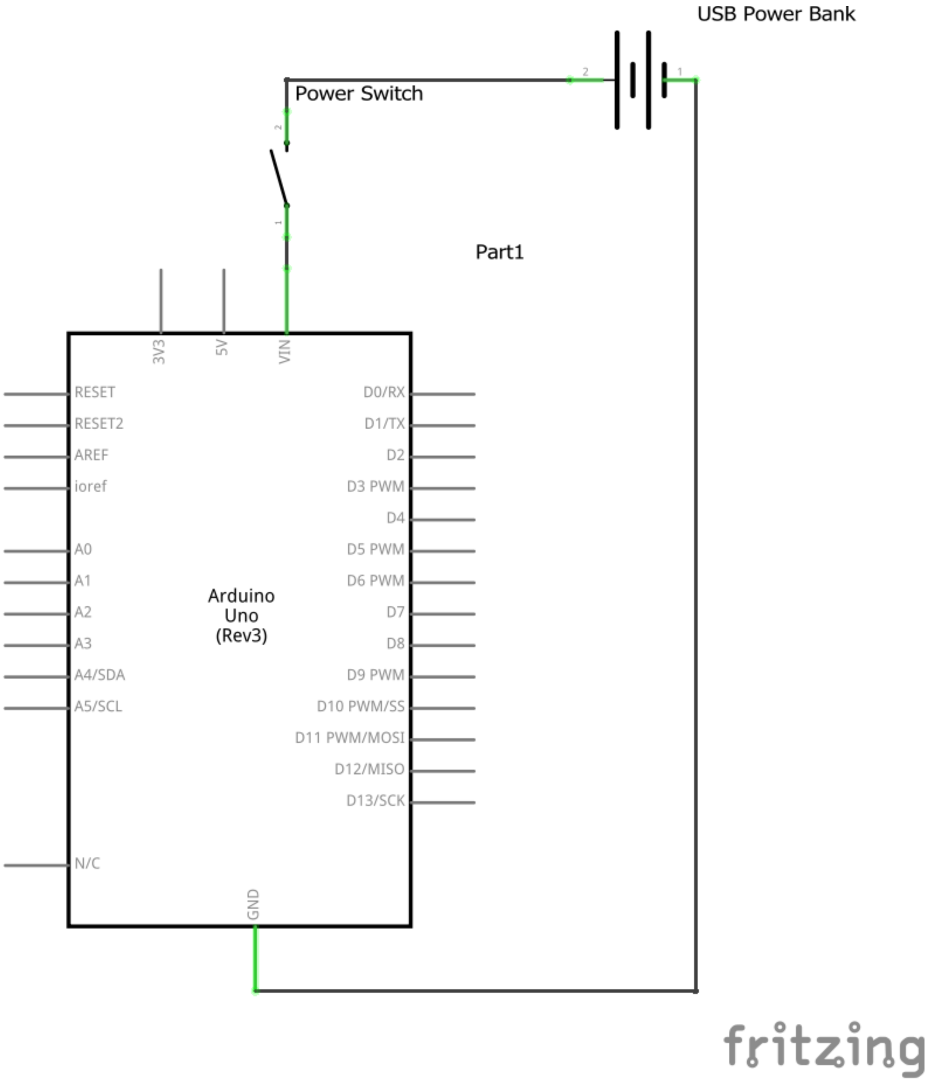


NOTES *1. CALIBRATION STAND MADE FROM SAME 5" ALUMINUM CHANNEL USED FOR FAULTMETER BASE.

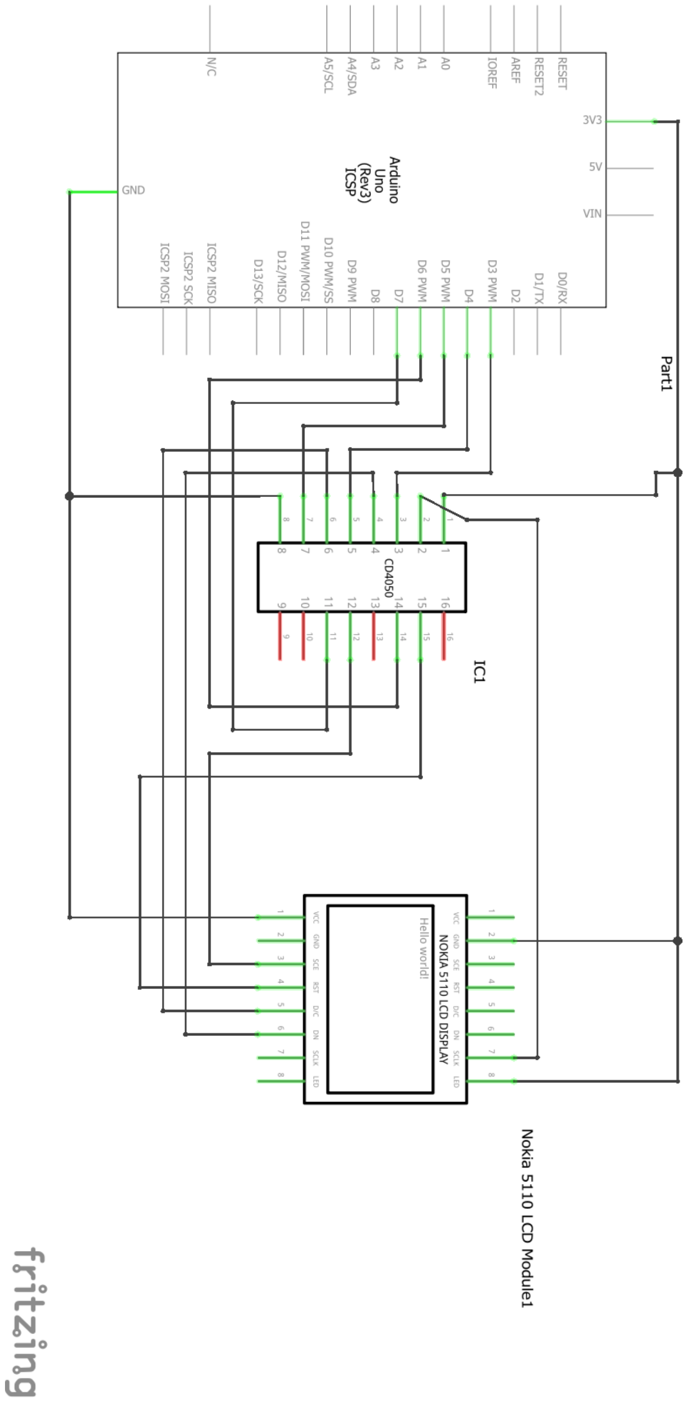
*2. SIDE RAILS MADE FROM 2" X 12" X $\frac{5}{64}$" THICK ALUMINUM BENT OUT SLIGHTLY ALONG THE DOTTED LINE. THE RAILS SERVE AS A GUIDE TO ALIGN FAULTMETER ON CALIBRATION STAND.



- Layer 1 of the control circuit, which includes the Power Bank and the Arduino Uno Microcontroller board



- Layer 2 of the control circuit, which is a proto-board stacked on top of the Arduino. It is used to connect the CD4050 Hex Buffer IC and the Nokia 5110 LCD display



- Layer 3 of the control circuit, which is a proto-board stacked on top layer 2. The layer includes the connections to the Linear Potentiometer, the trigger button and the buzzer.