Long-Term Pavement Performance Automated Faulting Measurement

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Research, Development, and Technology
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LTPP™

FOREWORD

This report documents the development of the Long-Term Pavement Performance (LTPP) automated faulting measurement (AFM) algorithm to identify transverse joint locations on jointed plain concrete pavements and compute faulting at these locations using the profile data collected by LTPP high-speed inertial profilers. The LTPP AFM algorithm is intended to replace traditional manual faulting surveys that entail traffic control and significant survey time from State departments of transportation and highway agencies. The software program developed based on this algorithm will serve as an automated tool for highway engineers to significantly increase their productivity when detecting transverse joint locations with acceptable accuracy.

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16. Abstract

This study focused on identifying transverse joint locations on jointed plain concrete pavements using an automated joint detection algorithm and computing faulting at these locations using Long-Term Pavement Performance (LTPP) Program profile data collected by the program's high-speed inertial profilers (HSIP). This study evaluated two existing American Association of State Highway and Transportation Officials R 36-12 automated faulting measurement (AFM) models: ProVAL (Method-A) and Florida Department of Transportation (FDOT) PaveSuite (Method-B). A new LTPP AFM was developed using LTPP profile data. The LTPP AFM is an automated algorithm to identify joint locations where faulting is also computed for each joint identified to replicate the manually collected faulting data using the Georgia Faultmeter (GFM), which has been used on LTPP test sections since the program's inception.

The study compared the LTPP manual faulting measurements collected using the GFM with the ProVAL AFM and the LTPP AFM using LTPP profile data. Similarly, the FDOT GFM measurements were compared with the FDOT PaveSuite AFM and the LTPP AFM using the same FDOT profile data. The initial results for six LTPP test sections show that the LTPP AFM can identify joint locations with a joint detection rate (JDR) ranging from 95 to 100 percent. ProVAL's JDR range is from 58 to 99 percent for the same six LTPP test sections. Similarly, for the one FDOT test section available, the LTPP AFM's and FDOT PaveSuite's JDRs are approximately 96 percent. This study outlines the LTPP AFM algorithm, discusses the comparison of the three AFM results, and recommends future research needs in this area.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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LIST OF ACRONYMS AND ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AFM	Automated faulting measurement
ANN	Artificial neural network
CEP	Current elevation point
CEPos	Current elevation position
CMaE	Current maximum elevation
CMaEP	Current maximum elevation position
CMiE	Current minimum elevation
CMiEP	Current minimum elevation position
ERD	Engineering Research Division
FDOT	Florida Department of Transportation
GFM	Georgia Faultmeter
HSIP	High-speed inertial profiler
ICC	International Cybernetics Corporation
Inf	Infinity
IRI	International Roughness Index
JDR	Joint detection rate
JPCP	Jointed plain concrete pavements
KDOT	Kansas Department of Transportation
LTPP	Long-Term Pavement Performance
LVDT	Linear Variable Differential Transformer
MFM	Manual faulting measurement
MLR	Multivariate linear regression
NaN	Not a number
PPDB	Pavement performance database
RMS	Root mean square

CHAPTER 1. INTRODUCTION

The performance of jointed concrete pavements depends to a large extent on satisfactory performance of joints. Most jointed concrete pavement failures can be attributed to problems at the joint, as opposed to inadequate structural capacity. The distresses that may result from joint failure include faulting, pumping, spalling, corner breaks, blowups, and mid-panel cracking.(1) This study focuses on faulting on jointed plain concrete pavements (JPCP). Faulting is a common distress type in JPCP and is defined as the difference in elevation across a transverse joint or crack. Faulting can result from a combination of factors such as inefficient load transfer at joints, slab pumping, slab settlements, curling, warping, and inadequate base support conditions. Faulting plays a prominent role in pavement surface roughness over time, affecting ride comfort and driver's safety. Moreover, significant joint faulting has an adverse impact on pavement lifecycle costs for maintenance and rehabilitation as well as vehicle operating costs.(2)

PROBLEM STATEMENT

The Long-Term Pavement Performance (LTPP) Program has been collecting longitudinal profile data using high-speed inertial profilers (HSIP) along the wheelpaths (left and right) on concrete pavements since 1989 and along the center of the lane from 1995. Profile data can be used to evaluate the roughness of the pavement by computing a roughness index such as the International Roughness Index (IRI). The change in longitudinal pavement profile over time, which is directly related to the change in roughness with time, is an important indicator of pavement performance. As previously mentioned, faulting is one of several key pavement performance indicators. The LTPP Program collects joint and crack faulting data on a regular basis at each jointed concrete pavement test site using the Georgia Faultmeter (GFM). Manual faulting measurement (MFM) using the GFM is time consuming and entails traffic control, lane closures, safety measures, personnel cost, etc. To replicate MFMs collected using the GFM, this study uses LTPP longitudinal profile data collected using an International Cybernetics Corporation (ICC) MDR 4086L3 profiler to identify joint locations and determine faulting at each joint on a JPCP.

OBJECTIVES

The first objective was to develop, using the LTPP profile data, a new LTPP automated faulting measurement (AFM) algorithm that could be used in the LTPP Program to reduce the need for lane closure and manual data collection using the GFM (the traditional way of measuring faulting at transverse joints and cracks on JPCP). The second objective was to evaluate two existing American Association of State Highway and Transportation Officials (AASHTO) R 36-12 automated faulting methods: ProVAL (Method-A developed by the Transtec Group, Inc., using LTPP 25-mm interval profiler data as the input) and PaveSuite (Method-B developed by the Florida Department of Transportation (FDOT) using the 20.7-mm interval HSIP data).(3)

DATA COLLECTION

This section introduces LTPP faulting data collection using the manual GFM and longitudinal profile data using the LTPP profiler.

GFM

The GFM was designed, developed, and built by Georgia Department of Transportation Office of Materials and Research personnel to simplify measuring concrete joint faulting and is very light and easy to use. There are two versions of the GFM. The manual GFM uses a dial gage to determine the positive or negative difference at a joint or crack, and the automated GFM uses the Linear Variable Differential Transformer (LVDT) to determine positive or negative faulting at a joint or crack. The unit weighs approximately 3.2 kg and supplies a digital readout with the push of a button located on the carrying handle. It reads out directly in millimeters (e.g., a digital readout of 3 indicates 3 mm of faulting) and shows whether the reading is positive or negative. The legs of the GFM's base are set on the slab in the direction of traffic on the leave side of the joint. The joint must be centered between the guidelines shown on the side of the meter. The measuring probe contacts the slab on the approach side. Vertical movement of this probe is transmitted to an LVDT to measure joint faulting. Any slab that is higher on the approach side of the joint registers a positive faulting number. If the slab on the leave side of the joint is higher, then the meter gives a negative reading.[(4)] MFMs collected using the GFM may have some potential errors caused by, for example, vertical movement of the probe rod. If the measuring rod does not move freely, then the reading will also be in error. In addition, due to non-linearity of the LVDT, cases where approach and departure slabs are not on the same plane (i.e. slabs are at an angle from each other) can cause errors in the readings. In addition, weak batteries and improper calibration of the equipment could cause erroneous readings. Finally, three measurements are taken at each joint or crack, and a representative reading of the three values (average of the three values) is entered into the pavement performance database (PPDB). Thus, data entry errors ± 1 mm reading resolution could occur when recording the three measurements on the data sheet onsite or in the PPDB. Figure 1 shows the MFM using the GFM.

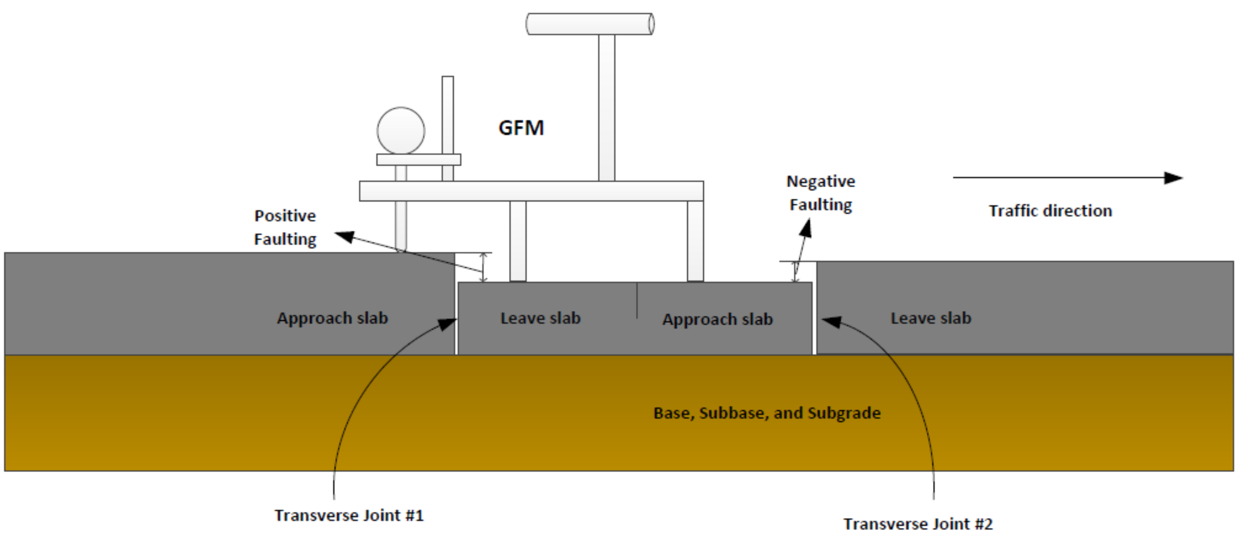

Figure 1. Diagram. MFM using the GFM.

INERTIAL PROFILER

A profiler is an instrument used to produce a series of numbers related in a well-defined way to a true profile. Profile data obtained by a profiler describe a two-dimensional slice of the road surface taken along an imaginary line.[5] The longitudinal profile along the wheelpaths in a pavement can be used to determine ride quality as well as joint/crack faulting on jointed concrete pavement, which are important indicators of pavement performance. Studies have shown that a strong correlation exists between the rate of change in faulting values and the rate of change in IRI values on JPCP. Faulting is a major contributor to the increased roughness of JPCP.[6] The LTPP Program currently uses an Ames Engineering profiler. The profilers previously used by the LTPP Program were ICC MDR 4086L3 and K. J. Law Engineers, Inc., DNC 690 and T-6600. This study uses the 25-mm interval longitudinal profile data collected using the ICC MDR 4086L3 profiler to detect JPCP joint locations and to determine faulting at those locations.

CHALLENGES IN DETECTING JPCP TRANSVERSE JOINTS

This section examines the following challenges in detecting JPCP transverse joints using profile data:

- Varying joint spacing makes it difficult to locate a transverse joint using most joint detection algorithms.
- Cracks that are present on a JPCP section make it difficult for the pattern search routines to detect joints; moreover, false positives may be reported in the detected results.
- Spalled joints in a profile show elevation valleys (dips) similar to those of a true joint. The challenge is to design a joint detection algorithm to find a true joint, eliminating the valleys due to joint spalling.
- Joints filled with sealants or incompressible materials are very difficult to detect.
- Similar to filled joints, closed joints due to slab thermal expansion may be undetectable.
- Pattern search algorithms may have difficulty detecting skewed joints.
- Using a sampling interval of less than 25.4 mm may not identify all the joints in a section. Conversely, a wider sampling interval may miss the joints in an elevation profile.
- An inertial profiler’s difficulty in getting an exact true surface profile could be one of the issues in accurately detecting transverse joints and computing faulting.
- Distance measuring instrument drift (especially for long profiles) may cause inaccuracies in location data.

CHAPTER 2. LITERATURE REVIEW

An extensive literature review was conducted concerning joint detection and faulting computation on jointed concrete pavements. Twelve documents were reviewed, and key findings are listed in the following summaries.

Saghafi et al. researched "Artificial Neural Networks and Regression Analysis for Predicting Faulting in Jointed Concrete Pavements Considering Base Condition."(7) The objective of the research was to predict jointed concrete pavement faulting by considering base layer and other parameters of the LTPP database using artificial neural networks (ANN) and multivariate linear regression (MLR) analysis. Results showed that the ANN approach predicted JPCP faulting more accurately than a MLR analysis, with higher coefficient of multiple determination (R square) values and a very low error level.

Chang et al. studied the "Practical Implementation of Automated Fault Measurement Based on Pavement Profiles."(8) The authors developed an AFM module in the ProVAL to allow practical application of the AFM method for State department of transportation users. The ProVAL AFM method detects transverse joints and cracks on JPCP and computes joint faulting. The ProVAL AFM serves as the basis for AASHTO R36-12, "Standard Practice for Estimating Faulting on Concrete Pavements."(3)

Miller and Bellinger developed the *Distress Identification Manual for LTPP Program (Fourth Revised Edition)*.(4) This manual provides information required for accurate, consistent, and repeatable distress evaluation surveys, including measurement of faulting. It provides graphics illustrating distresses found in three basic pavement types: asphalt concrete-surfaced, jointed (plain and reinforced) Portland cement concrete, and continuously reinforced concrete. These graphics provide a reference to assess distress type, severity, and measurement. Moreover, they provide a method to measure faulting and instructions on how to calibrate and operate fault measurement devices.

Khazanovich et al. worked on *LTPP Data Analysis: FAQs About Joint Faulting with Answers from LTPP*.(9) (This Federal Highway Administration TechBrief was developed from the study "Common Characteristics of Good and Poorly Performing Portland Cement Concrete (PCC) Pavements.") The objective was to examine the LTPP database and identify site conditions and design features that significantly affect transverse joint faulting. The emphasis of the study was to find what works and does not work to control the development of joint faulting. The document provides answers to questions regarding design features and site conditions that lead to "good" (better than expected) and "poor" (worse than expected) performance of jointed concrete pavements with regard to joint faulting. In addition, guidelines are provided to assist highway agencies with what works and what does not work in the design of transverse joints to control joint faulting.

Sayers and Karamihas published *The Little Book of Profiling*.(5) The objective of the book was to provide basic instructions on measuring and interpreting road profiles.

Nazef et al. worked on *A Semi-Automated Faulting Measurement Approach for Rigid Pavements Using High Speed Inertial Profiler Data*.(10) The study objectives were to determine an appropriate profiler sampling interval to accurately locate transverse joints and to determine how well faulting estimated from profile elevations using an AFM algorithm compares with faulting measured with the GFM. The AFM algorithm accurately detects, on average, 95 percent of transverse joints from profile data collected at highway speed using a 17.3-mm sampling interval. This algorithm was also adapted to estimate faulting measured with the GFM in accordance with the AASHTO R36-04 protocol. Although the algorithm results are repeatable, the algorithm over-estimated the faulting at joints by 1.3 mm to 1.5 mm compared with faulting measured with the GFM.

Nazef et al. conducted a validation study, "Alternative Validation Practice of an Automated Faulting Measurement Method."(11) The objective of the study was to evaluate the accuracy and precision of an HSIP-based AFM system using a two-phase approach. The first phase evaluated the HSIP's ability to produce reliable faulting measurements under controlled conditions. The second phase tested the validity of the automated method to produce repeatable and reproducible results under normal field conditions. The goal was to use the results from this study to support the implementation of the AFM system in FDOT's Annual Pavement Condition Survey process. Except for one HSIP, all profilers achieved a minimum profile repeatability cross-correlation of 92 percent. Under controlled conditions, the HSIP has a faulting measurement accuracy and repeatability of 0.60 mm and 0.65 mm, respectively. The HSIP has a positive joint detection rate (JDR) ranging from 80 to 94 percent. Under controlled conditions, the HSIP has accuracy, repeatability, and reproducibility rates of 1.2 mm, 1.1 mm, and 0.5 mm, respectively.

Selezneva et al. worked on *Preliminary Evaluation and Analysis of LTPP Faulting Data—Final Report*."(6) The objective was to evaluate the quality of LTPP faulting data, including identification of missing and questionable data. Faulting data indexes (average joint faulting for each visit) and related statistical parameters were developed. Subsequently, these parameters were used to determine the impact of joint faulting and related data in identifying factors that affect joint faulting. Analysis indicated that doweled joints exhibit very little faulting even after many years of service and that the effects of design features, such as drainage, tied-concrete shoulder use, and joint spacing, are not as significant when doweled joints are used. For non-doweled JPCP, the following design features were found to significantly reduce faulting: widened lanes, an effective drainage system, a stabilized base/subbase, and narrower joint spacing. The effect of faulting on ride quality was also investigated on JPCP sections with three or more faulting and IRI surveys. A strong correlation was found between the rate of change in faulting values and the rate of change in IRI values for JPCP sections. The results indicate that faulting is a major component of increased roughness of JPCP.

Perera et al. worked on *LTPP Manual for Profile Measurements and Processing*.(12) The objective was to provide detailed information on operational procedures for measuring longitudinal pavement profiles for the LTPP Program using the ICC road profiler, Face® Dipstick®, and the rod and level. The manual also explained calibration of equipment, data collection, record keeping, and data processing.

Karamihas and Senn conducted a study, *Curl and Warp Analysis of the LTPP SPS-2 Site in Arizona*.(13) The authors examined the roughness and roughness progression of 21 test sections over the first 16 years of the experiment to analyze slab curl and warp effects on pavement roughness. As part of the study, the authors conducted faulting analysis (detecting joint locations from multiple profiles) using profile data to examine the effect of joint faulting on IRI values. All test sections except 0262 and 0265 produced average faulting of less than 1.27 mm. For sections 0262 and 0265, the severity of faulting grew throughout the experiment, and the increase in IRI with time was primarily due to faulting.

Vedula et al. published "Adaptability of AASHTO Provisional Standards for Condition Surveys for Roughness and Faulting in Kansas."[14] In this study, profile data were collected on about 346 km of Kansas highways following AASHTO provisional standards PP-37-00 for quantifying roughness and PP-39-00 for faulting, and the Kansas Department of Transportation (KDOT) standard for condition surveys. The comparison of statistical analysis results from the algorithms following the KDOT Network Optimization System and the AASHTO provisional standards (PP-37-00) indicated that roughness measurements tended to produce statistically similar results. However, fault values computed from AASHTO PP-39-00 and KDOT automated faulting procedure were significantly different even after some modification to PP 38-00 following current practices in Kansas.

Watkins of the Mississippi Department of Transportation developed a joint/crack-location algorithm based on a brute-force method by determining the elevation difference between adjacent samples greater than 2.03 mm using a profile sampling interval rate of 12.7 mm.[15]

CHAPTER 3. METHODOLOGY

The objective of this chapter is to introduce the methodology adopted to develop the LTPP AFM algorithm to detect JPCP transverse joint locations and to determine faulting at each of the detected joints. The procedure consists of the following five tasks:

- Use the profiler's Engineering Research Division (ERD) file output.
- Import the ERD file into MATLAB®.
- Filter and normalize data.
- Perform joint detection.
- Compute faulting.

USE THE PROFILER'S ERD FILE OUTPUT

The ERD at the University of Michigan Transportation Research Institute developed a file format with an ERD extension to facilitate automated plotting of simulation data, experimentally measured data, and data from various analysis programs. The LTPP profile data are presented in an ERD text file with profile information in two parts, the header and the data. The header portion of the ERD file consists of a series of conventional American Standard Code for Information Interchange text lines. These lines contain information used by post-processing tools to read the numerical data such as start and end locations of the survey, speed of the vehicle, sampling interval, date, and time. The data portion of the ERD file contains numbers organized into columns and rows. There are three columns: the left and right wheelpath profiles, and the center of the lane profile. The LTPP regional support contractors collect a minimum of five profile runs/files on each LTPP test section of 152.4 m in length. If more are needed, then they can collect up to a maximum of nine profile runs/files. Information for the five most representative profile runs/files that pass the ProQual quality check is included in the LTPP PPDB. This study used these five profile runs/files for computing JPCP joint faulting.

IMPORT ERD FILE INTO MATLAB®

This study used MATLAB® software to process and analyze LTPP profile data. The data portion of the profile ERD file was loaded into the MATLAB® program using MATLAB®'s import function. The LTPP test sections are 152.4 m in length. LTPP profile data are collected for the entire length. A new "distance" column was created using the profile sampling interval (25 mm) information from the header portion of the ERD file.

FILTER AND NORMALIZE DATA

Filtering is a process of applying a mathematical transformation to true profile data to remove redundant noise. It is almost always necessary to filter the sequence of numbers that makes up the profile and to view different types of profile features. Many filters exist. A moving average filter was selected, and both smoothing and anti-smoothing filters are applied in this study.

The moving average filter uses the average of several adjacent profile elevation points to replace each profile elevation point. In this study, a 300-mm (12 data points) moving average filter was applied. For a profile p that has been sampled at interval ΔX, a moving average smoothing filter is defined by the summation in figure 2.[5]

$$P_{fl}(i) = \frac{1}{N} \sum_{j=i-\frac{B}{2\Delta X}}^{i+\frac{B}{2\Delta X}} p(j)$$

Figure 2. Equation. Moving average smoothing filter.

Where:

P_{fl} is the smoothed profile (also called a low-pass filtered profile).
B is the base length of the moving average.
N is the number of samples included in the summation.

MATLAB®'s built-in moving average filter function was used to filter the true profile. Anti-smoothing filtering, also called high-pass filtering, is a process of subtracting the smoothed profile from the true/original road profile. The choice of base length for an anti-smoothing filter is important to be able to show either very short-duration bumps or long deviations in the profile elevation. A larger anti-smoothing filter base length eliminates small deviations. To detect transverse joints using profile data, it is important to apply an anti-smoothing filter with a smaller base length. Figure 3 and figure 4 show two anti-smoothed filter profiles with different anti-smoothing base lengths.

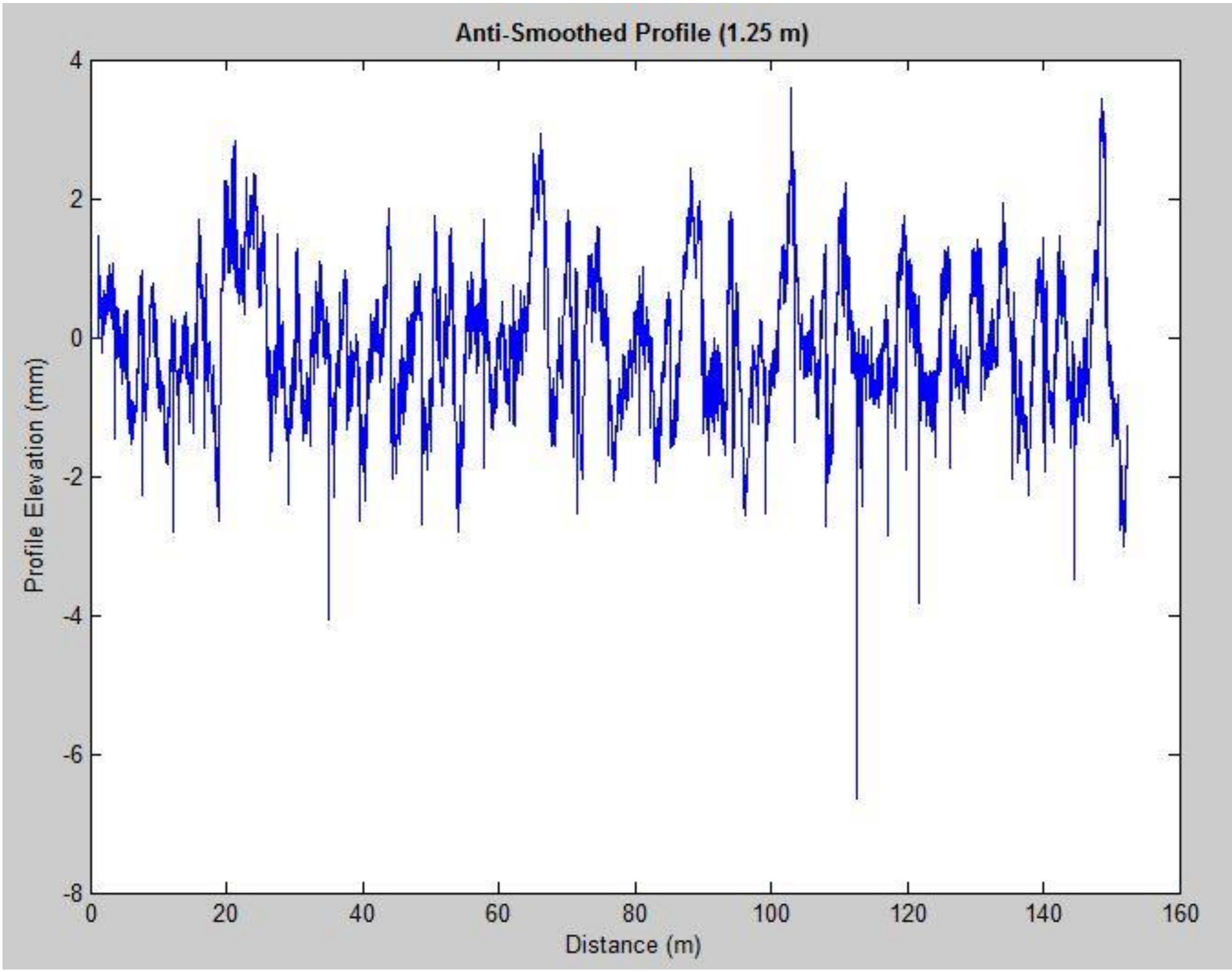

Figure 3. Graph. Anti-smoothed profile with 1.25-m base length.

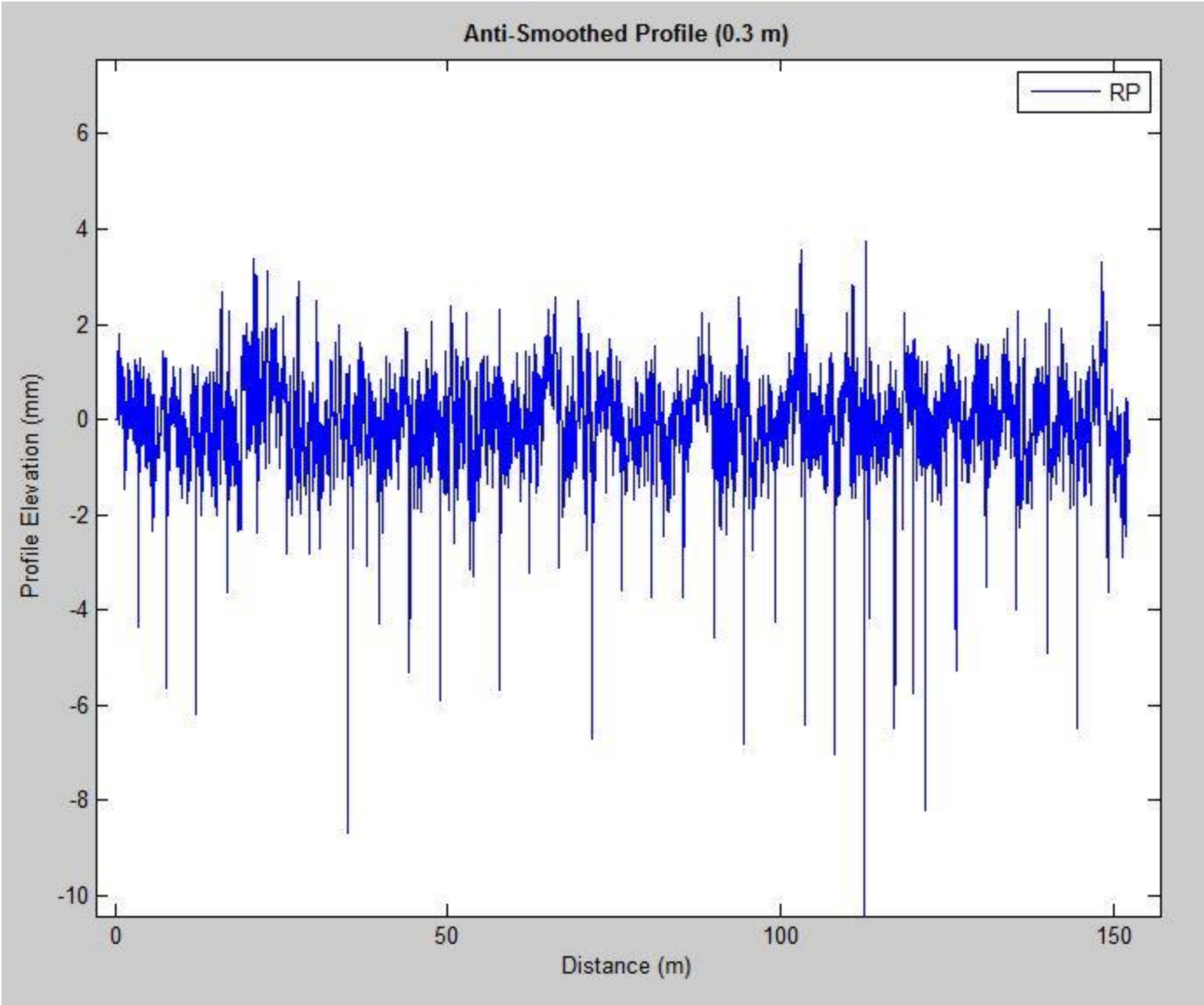

Figure 4. Graph. Anti-smoothed profile with 0.3-m base length.

Figure 3 and figure 4 show that the anti-smoothed profile with a smaller base length (0.3 m) displays profile deviations (joints/cracks) more clearly compared with the anti-smoothed profile with a base length of 1.25 m.

Once smoothing and anti-smoothing filters are applied, the next step is to normalize the anti-smoothed profile with the root-mean-square (RMS) value. The RMS value provides the magnitude of the elevation profile and facilitates an automated search for the deepest dips or valleys.

The RMS value of a vector, *X*, is defined in figure 5 with the summation performed along the specified dimension.

$$X_{RMS} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}|X_n|^2}$$

Figure 5. Equation. RMS.

PERFORM JOINT DETECTION

After filtering a longitudinal profile for two wheelpaths (e.g., left and right wheelpaths) and a center of the lane profile, MATLAB®'s Peakdet algorithm, developed by Eli Billauer, is used, along with the moving window method, to detect the valleys.(16) The algorithm also cross-checks the detected valleys of one wheelpath against the other and against the center lane profile to detect a transverse joint (true joint on JPCP) and eliminate or minimize false positives (other than a true joint on JPCP). A peak is the highest point between valleys. Peakdet looks for the highest point around which there are points lower by Δ (positive value, for example, of 1 or 2) on both sides. A similar peak and valley detection algorithm was reported by Nazef et al.(10) Valleys in longitudinal road profile data collected on JPCP represent either potential joints or cracks. This study focuses on valleys that are transverse joints. Six steps describe how the Peakdet algorithm in MATLAB® detects peaks and valleys in a road elevation profile.

Step 1: Initialize the current elevation point (CEP) at *V(i)* and current elevation position (CEPos) at *X(i)* at the first point (*i* equals 1) in an elevation profile. For illustration, a moving window width of 4 m is used based on the average distance between two JPCP joints for a test section; the window can be adjusted as desired. The CEPos for the first moving window starts at 0 m (*X(i)* at i equals 1), and the last moving window would be the total profile survey distance (152.4 m) minus moving window width (4 m), which is 148.4 m, where *i* equals 5,936 m (148.4/0.025 m).

Step 2: Check the valleys within the moving window (4 m) for the three profiles (left wheelpath, right wheelpath, and center lane). If CEPos is less than or equal to 148.4 m, then CEPos equals 0 for the first point *X(1)* and the moving widow equals (CEPos + 4) m.

Step 3: Initialize current maximum elevation (CMaE) at negative infinity (Inf), current maximum elevation position (CMaEP) at not a number (NaN), current minimum elevation (CMiE) at Inf, and current minimum elevation position (CMiEP) at NaN.

Step 4: Move to the next elevation point *V(i)*. If CEP is greater than CMaE, then make CMaE equal to its elevation and store its position as the new CMaEP. If CEP is less than CMiE, then make CMiE equal to its elevation and store its position as the new CMiEP. If CEP is less than CMaE - Δ, then set Peak (*i*) at CMaE and store the Peak_Loc (*i*) at CMaEP. If CEP is greater than CMiE + Δ, then set Valley (*i*) at CMiE and store the Valley_Loc (*i*) at CMiEP.

The flow chart in figure 6 explains steps 3 and 4.

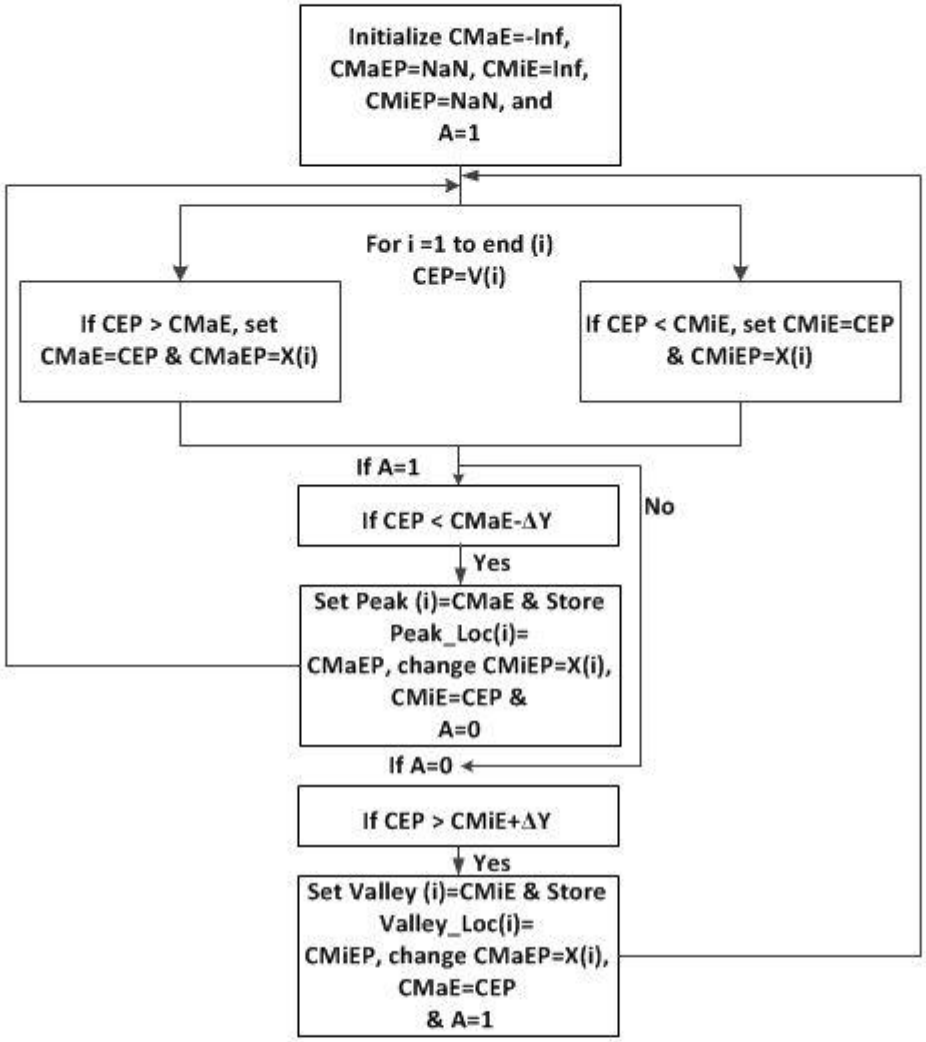

Figure 6. Flowchart. Peakdet algorithm flow chart.

Step 5: Repeat step 4 until the valleys are detected within the moving window. For a profile, more than one valley could be detected in one wheelpath (i.e., CMiEP and its corresponding CMiE) using the Peakdet algorithm within the 4-m moving window. To be certain the valley detected is not a false positive, the difference between the lowest valley positions (i.e., CMiEPs with minimum CMiEs) for at least two profiles (e.g., the left wheelpath and the center lane) should be less than 0.2 m. The transverse joint locations are common for the three profiles along the entire lane width. However, in the case of skewed joints, the transverse joint location varies for the three profiles and is addressed using a 0.2 m criterion. (It allows detection of the skewed joint, if present.)

One of the CMiEPs from two profiles that meet the 0.2 m criterion is taken as the basis to locate true positive joints for the left and right profiles. Once the true positive joint is detected for a profile, the CEPos of the next moving window would start at 2.5 m (which is 0.625 times the moving window width of 4 m) from the detected joint. The transverse joints on JPCP are spaced at least 3 m from the previous joint except in the case of full-depth patching, which causes joint spacing to be less than 3 m. If the first transverse joint detected for the right profile is at 3.525 m from the start point of the profile section (0 m), then the CEPos of the next moving window would not start from 4.025 to 8 m; rather it would start at 6.025 to 10.025 m, (i.e., 3.525 plus 2.5 m) and would detect the next true positive joint. Thus, potential false positives would be eliminated. In addition, the algorithm checks potential true joint locations with two other profiles taken on the same lane to eliminate spalled joint locations.

Figure 7 and figure 8 illustrate the moving window approach to detect transverse joints using the Peakdet algorithm.

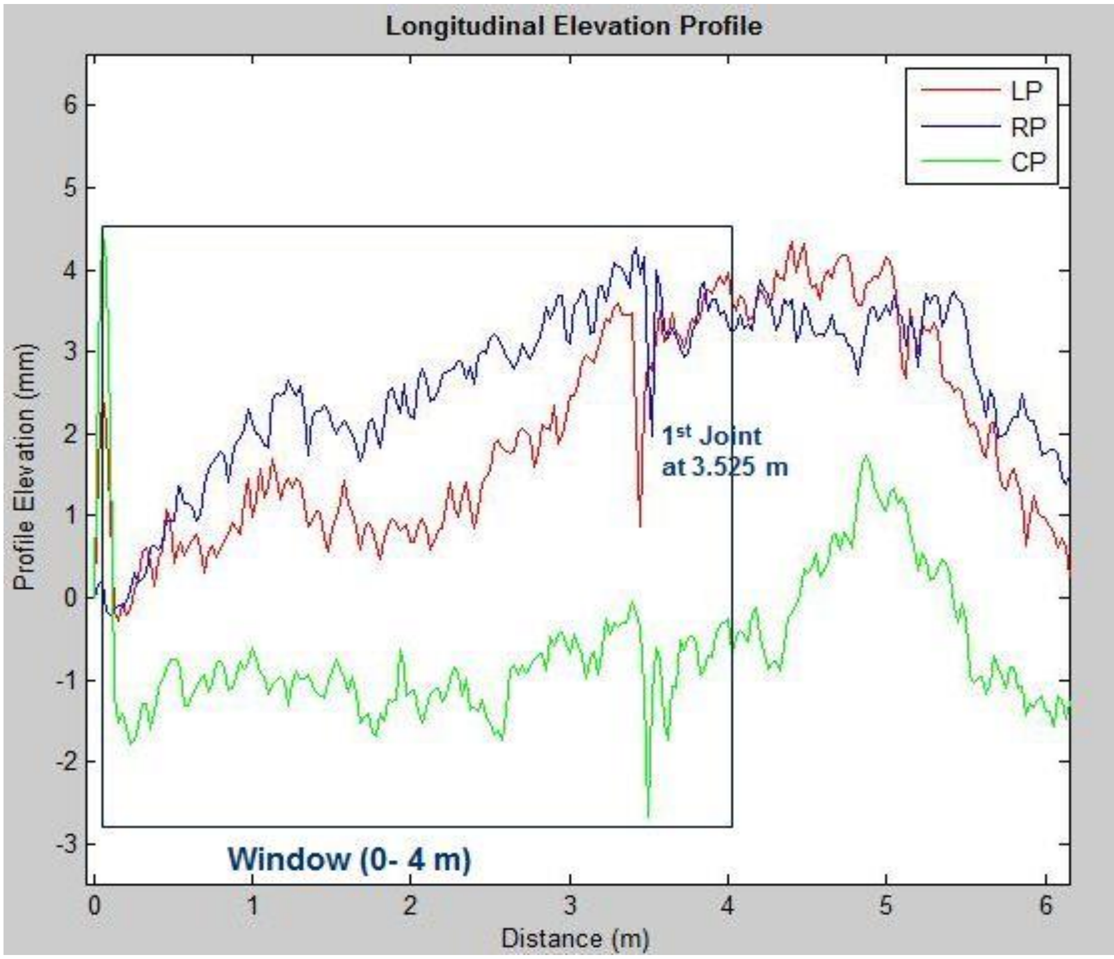

Figure 7. Graph. A 4-m moving window (0–4 m) using the Peakdet algorithm to detect the first transverse joint.

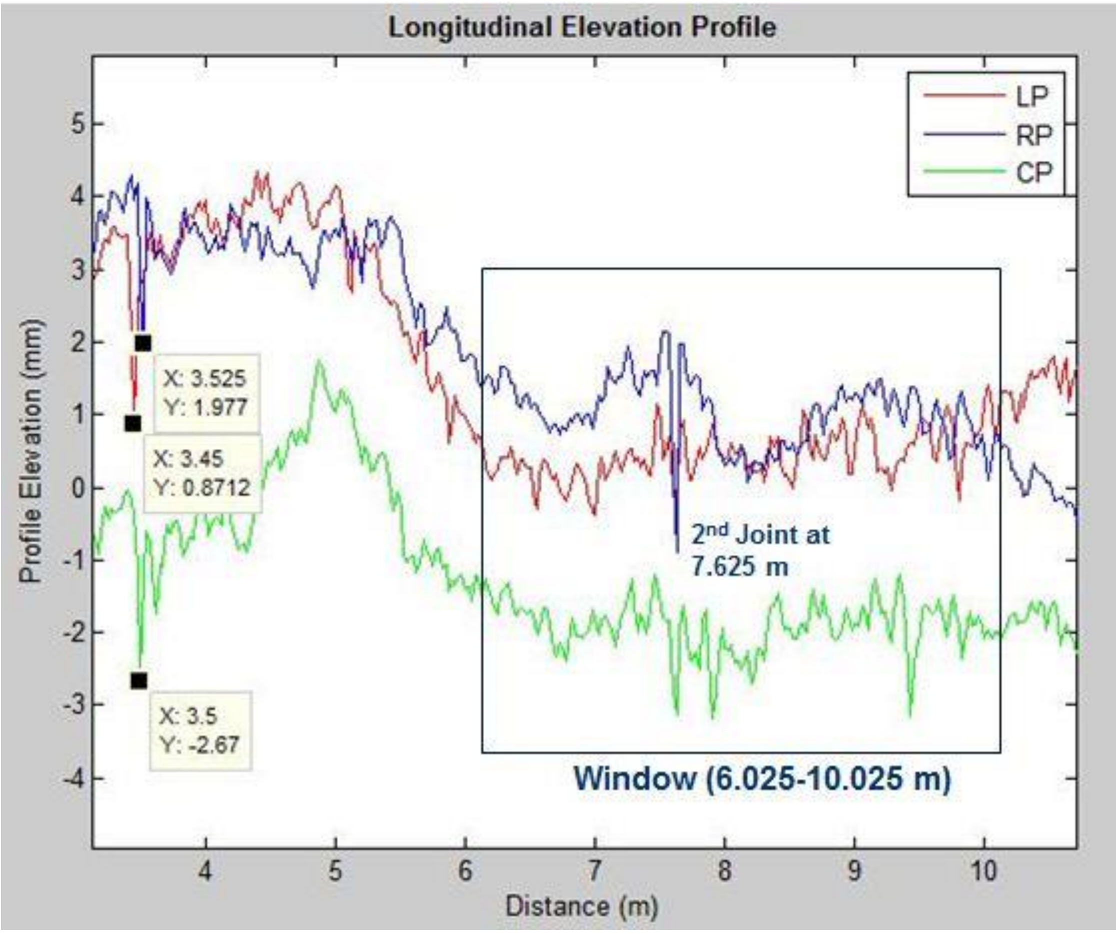

Figure 8. Graph. A 4-m moving window (6.025–10.025 m) using the Peakdet algorithm to detect the second transverse joint.

Step 6: Repeat step 2 through step 5 to detect all true positive transverse joints, incrementally scanning through the elevation profile and sorting the detected joints. Figure 9 shows the detected transverse joints identified by circles on a longitudinal elevation profile.

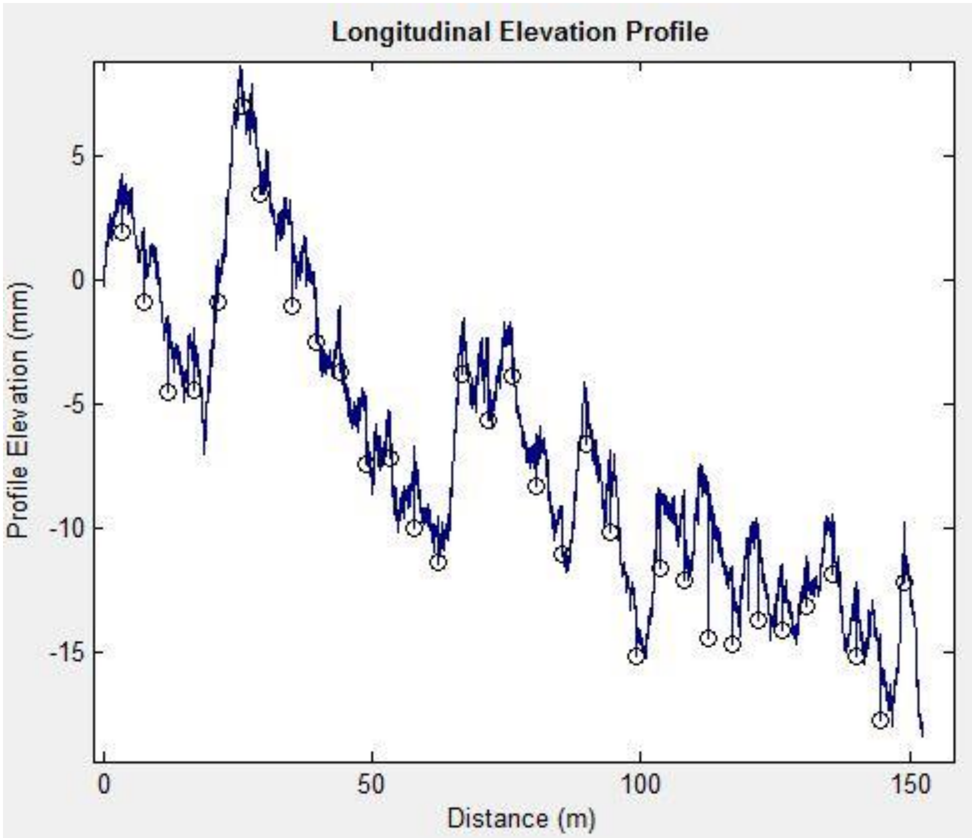

Figure 9. Graph. Detected true positive transverse joints identified by circles.

COMPUTE JOINT FAULTING

The last task is to compute the JPCP transverse joint faulting. Faulting is defined as the difference in elevation across a transverse joint or crack. In this study, faulting is computed using two methods: the slope method (in-house method) and AASHTO R36-12 Method-A. The following steps explain faulting computed using the slope method. For faulting computation using AASHTO R36-12 Method-A, the reader is referred to AASHTO R36-12, "Standard Practice for Estimating Faulting on Concrete Pavements."(3)

The slope method is used to identify the point P1 on the approach slab and point P2 on the leave slab. P1 and P2 are data points on the approach and leave slab. Once P1 and P2 are identified, the faulting can be computed by taking the difference of P1 and P2. If P1 is greater than P2, then the result is called positive faulting. If P1 is less than P2, then the result is called negative faulting. In figure 10, *S* is absolute slope, and (X_1,Y_1) and (X_2, Y_2) are coordinates of points P1 and P2.

$$|S| = \left|\frac{Y_2 - Y_1}{X_2 - X_1}\right|$$

Figure 10. Equation. Two-point slope formula.

To detect P1, the absolute slope is computed using two data points between the detected transverse joint's CMiEP (for example, X2) and CMiE (for example, Y2) and the previous elevation points (for example, X1 and Y1, respectively). If the absolute slope computed is less than 10 (which was selected to make sure the points P1 and P2 are not taken on distressed surface areas such as potholes), then P1 is set equal to Y1. If the absolute slope is not less than 10, then the absolute slope is computed for the closest previous elevation point.

Similarly, to detect P2, the absolute slope is computed using two data points between the detected transverse joint's CMiEP (X2) and CMiE (Y2) and the next location and elevation points (e.g., L1 and E1). If the absolute slope computed is less than 10, then P2 is set equal to E1. If the absolute slope is not less than 10, then the absolute slope is computed for the next elevation point.

Once the joint faulting is computed, the results are exported in Microsoft® Excel format.

Figure 11 illustrates the slope method to compute transverse joint faulting. The traverse joint location is first located, and then points P1 on the approach slab and P2 on the leave slab are established. The transverse joint location was detected at distance 3.525 m (X) and elevation 1.977 mm (Y). The computed absolute slope between the detected transverse joint coordinates (X at 3.525 m and Y at 1.977 mm) and the previous profile data point (X at 3.5 m and Y at 2.759 mm) was more than 10, so the procedure was continued until P1 was reached at X equal to 3.475 m and Y equal to 4.165 mm. Similarly, the computed absolute slope between the detected transverse joint location (X at 3.525 m and Y at 1.977 mm) and the next profile data point (X at 3.55 m and Y at 3.992 mm) was more than 10, so the procedure was continued until P2 was reached at X equal to 3.575 m and Y equal to 3.794 mm. Thus, the elevation (Y) of P1 on the approach slab was 4.165 mm, and the elevation of P2 on the leave slab was 3.794 mm. The faulting computed at the joint location was therefore 0.371 mm (4.165 minus 3.794). This slope method approach was used to compute faulting at all detected transverse joint locations.

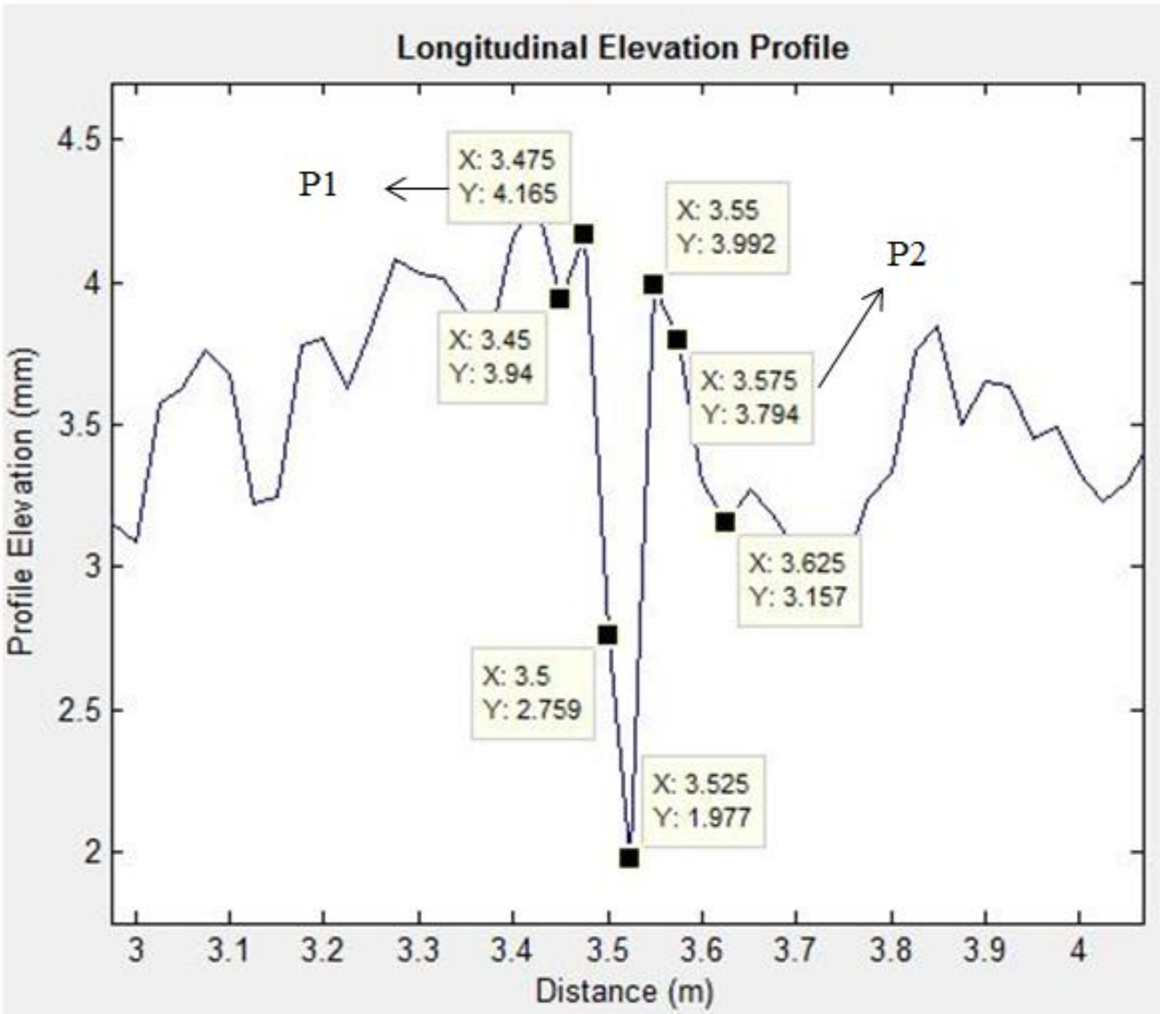

Figure 11. Graph. The slope method to determine P1 on approach slab and P2 on leave slab.

CHAPTER 4. ANALYSIS RESULTS

In this chapter, the analysis and comparison results of the LTPP AFM, the ProVAL AFM, and the FDOT PaveSuite AFM are presented. To evaluate the LTPP AFM, six LTPP JPCP test sections were selected such that the manual distress survey dates matched or were close to the longitudinal profile survey dates. The same six LTPP test sections were also used to evaluate the ProVAL AFM.

Table 1 and table 2 show the evaluation results of the LTPP AFM. In table 1, the fourth column from the left represents the total number of transverse joints present on the 152.4-m test section. The transverse joint locations and faulting measurements were collected using manual distress surveys and were stored in LTPP PPDB table MON_DIS_JPCC_FAULT. Profile runs in ERD format from the MON_PROFILE_MASTER table for the LTPP test section that passed the ProQual quality check were used in the analysis. The column “TP” stands for “true positive,” whereas column “FP” stands for “false positive.” True positive means the true transverse joint was detected, whereas false positive means something other than the true transverse joint, such as a crack or pothole, was detected.

According to the data in table 1, for Georgia test section 133019 (STATE_CODE of 13 and SHRP_ID of 3019), the LTPP AFM detected all of the 25 true transverse joints with 0 false positives using the 5 ERD files collected from that section. For New York test section 364018, the true positive JDR was 95 percent, i.e., the LTPP AFM missed one true positive joint from ERD files 3 and 4. The JDR from the LTPP AFM for the six selected sections ranged from 95 to 100 percent.

Similarly, the same six LTPP test sections and five ERD files were used to evaluate the ProVAL AFM. According to the data in table 2, New York test section 364018 had a JDR of 67.5 percent, whereas the LTPP AFM JDR was 95 percent (table 1). The total number of false positives detected for the New York test section using the ProVAL AFM for the five profile ERD files (i.e., ERD1 to ERD5) was 33 (5 + 7 + 10 + 6 + 5). The total false positives detected using the LTPP AFM (table 1) for the same test section (364018) for five profile files was four. The JDR from ProVAL AFM for the six selected sections ranged from 58 to 99.4 percent.

Table 1. LTPP AFM joint detection results using LTPP profiler data.

State Code	SHRP ID	Survey Date	Total No. of Transverse Joints	ERD File 1		ERD File 2		ERD File 3		ERD File 4		ERD File 5		Average True Positives Detected	JDR (percent)
				TP	FP	TP	FP	TP	FP	TP	FP	TP	FP		
13	3019	11/27/2007	25	25	0	25	0	25	0	25	0	25	0	25	100.0
31	3018	12/18/2003	32	32	0	32	0	32	0	32	0	32	0	32	100.0
36	4018	4/13/2010	8	8	0	8	1	7	1	7	1	8	1	7.6	95.0
37	201	9/19/2002	33	32	0	33	0	33	0	33	0	33	0	32.8	99.4
42	1606	10/15/2003	10	9	2	10	0	10	0	10	1	9	1	9.6	96.0
49	3011	10/9/2007	34	34	0	34	0	34	0	34	0	34	0	34	100.0

ERD = Engineering Research Division
FP = False Positive
JDR = Joint Detection Rate
SHRP = Strategic Highway Research Program
TP = True Positive

Table 2. ProVAL AFM joint detection results using LTPP profiler data.

State Code	SHRP ID	Survey Date	Total No. of Transverse Joints	ERD File 1		ERD File 2		ERD File 3		ERD File 4		ERD File 5		Average True Positives Detected	JDR (percent)
				TP	FP	TP	FP	TP	FP	TP	FP	TP	FP		
13	3019	11/27/2007	25	22	1	21	1	23	0	22	1	23	0	22.2	88.8
31	3018	12/18/2003	32	28	0	29	0	29	0	29	0	30	0	29	90.6
36	4018	4/13/2010	8	7	5	4	7	3	10	7	6	6	5	5.4	67.5
37	201	9/19/2002	33	31	0	31	0	30	0	31	0	30	0	30.6	92.7
42	1606	10/15/2003	10	6	5	6	4	6	7	5	9	6	8	5.8	58.0
49	3011	10/9/2007	34	34	0	33	1	34	0	34	0	34	0	33.8	99.4

ERD = Engineering Research Division
FP = False Positive
JDR = Joint Detection Rate
SHRP = Strategic Highway Research Program
TP = True Positive

Table 3 shows the joint detection comparison results between the LTPP AFM and the FDOT PaveSuite AFM methods, using FDOT HSIP data collected on State Road 24 in Waldo, FL. FDOT's 609.6-m test section included a 152.4-m lead-in and lead-out, and a 304.8-m effective test length spanning 50 slab joints. The slabs were typically 6.1 m long by 3.66 m wide with a relatively smooth surface finish. Both AFM methods detected 48 true positives with a JDR of 96 percent. However, according to the data in table 3, the FDOT PaveSuite AFM detected eight false positives, whereas the LTPP AFM detected zero false positives.

Table 3. FDOT and LTPP AFM joint detection results using FDOT HSIP.

AFM Method	Total No. of Transverse Joints	FDOT HSIP Profiler		JDR (percent)
		TP	FP	
FDOT AFM	50	48	8	96
LTPP AFM		48	0	96

AFM = Automated faulting measurement
FDOT = Florida Department of Transportation
HSIP = High-speed intertial profiler
JDR = Joint detection rate
LTPP = Long-Term Pavement Performance

Table 4 through table 7 show the analysis results for AFMs computed using both the ProVAL and the LTPP AFM methods. As discussed in the methodology, the LTPP AFM uses two methods, the slope method (in-house method) and the AASHTO R 36-12 Method-A, to compute faulting measurements. The ProVAL AFM uses AASHTO R 36-12 Method-A. Table 4 shows the average faulting for the entire test section (152.4 m) for all five profile runs computed using the LTPP AFM slope method. The average of absolute differences in faulting estimated by the LTPP AFM and faulting measured by the manual GFM on the six LTPP JPCP test sections are shown in the "Average section |Bias|" column. Test sections 133019, 370201, and 493011 have less than 1-mm bias/error as required by the AASHTO R 36-04 standard. However, test sections 313018, 364018, and 421606 have a bias/error greater than 1 mm.

Table 4. LTPP AFM faulting results (slope method) using LTPP profiler data.

State Code	SHRP ID	Survey Date	GFM Average Section Faulting (mm)	Average Section Faulting for All Five Runs (mm)	Average Section |Bias| for All Five Runs (mm)
13	3019	11/27/2007	0.84	0.56	0.80
31	3018	12/18/2003	4.41	3.28	3.72
36	4018	4/13/2010	1.75	-3.05	5.07
37	201	9/19/2002	0.15	0.37	0.44
42	1606	10/15/2003	3.30	0.39	2.98
49	3011	10/9/2007	3.32	3.48	0.95

GFM = Georgia Faultmeter
SHRP = Strategic Highway Research Program

The average faultings for the entire test section (152.4 m) for all five runs computed using the ProVAL AFM are shown in table 5. Also, the average of the absolute difference in faulting estimated by the ProVAL AFM and faulting measured by the manual GFM on the six LTPP

JPCP test sections are shown in the "Average section |Bias|" column of table 5. Sections 133019 and 313018 have less than 1-mm bias/error as required by the AASHTO R 36-04 standard. However, test sections 364018, 370201, 421606, and 493011 have a bias/error greater than 1 mm.

Table 5. ProVAL AFM faulting results using LTPP profiler data.

State Code	SHRP ID	Survey Date	GFM Average Section Faulting (mm)	Average Section Faulting for All Five Runs (mm)	Average Section |Bias| for All Five Runs (mm)
31	3018	12/18/2003	4.41	5.04	0.88
36	4018	4/13/2010	1.75	-6.58	8.75
37	201	9/19/2002	0.15	1.08	1.02
42	1606	10/15/2003	3.30	1.35	2.46
49	3011	10/9/2007	3.32	4.71	1.46

GFM = Georgia Faultmeter
SHRP = Strategic Highway Research Program

Table 6 shows the LTPP AFM joint faulting using AASHTO R 36-12 Method-A. Only four test sections were analyzed using AASHTO R 36-12 Method-A. Test sections 133019 and 370201 have less than a 2-mm bias/error. However, sections 364018 and 421606 have a bias/error of 13.81 and 3.68 mm, respectively.

Table 6. LTPP AFM faulting results (AASHTO Method-A) using LTPP profiler data.

State Code	SHRP ID	Survey Date	GFM Average Section Faulting (mm)	Average Section Faulting for all Five Runs (mm)	Average Section |Bias| for All Five Runs (mm)
36	4018	4/13/2010	1.75	-12.06	13.81
37	201	9/19/2002	0.15	1.66	1.59
42	1606	10/15/2003	3.30	-0.38	3.68

GFM = Georgia Faultmeter
SHRP = Strategic Highway Research Program

Comparison results of the FDOT PaveSuite AFM and the LTPP AFM using the FDOT HSIP data are shown in table 7. The average faulting measured from the FDOT PaveSuite AFM was 1.69 mm, while the LTPP AFM, using the slope method for the same data, was 1.62 mm. (For FDOT HSIP data, only the in-house method, i.e., the slope method, was used to compute joint faulting; AASHTO R 36-12 Method-A was not used.) Also, the average of absolute differences in faulting estimated by the FDOT PaveSuite AFM and the LTPP AFM slope method with the measured manual GFM were 1.05 and 1.14 mm, respectively. Both AFM results using the FDOT data were similar.

Table 7. Joint faulting results using FDOT HSIP data.

Method	GFM Average Section Faulting (mm)	Average Section Faulting (mm)	Average Section |Bias| (mm)
FDOT AFM	1.81	1.69	1.05
LTPP AFM (Slope Method)		1.62	1.14

AFM = Automated faulting measurement
FDOT = Florida Department of Transportation
GFM = Georgia Faultmeter
LTPP = Long-Term Pavement Performance

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

This study was conducted to develop a new LTPP AFM algorithm to detect transverse joint locations and compute joint faulting and to compare the new method with the existing AASHTO R 36-12 AFM methods (including the ProVAL AFM (AASHTO Method-A) and the FDOT PaveSuite AFM (AASHTO Method-B)). LTPP profiler longitudinal elevation profiles at 25-mm sampling intervals and the FDOT profiler at 20.7-mm sampling intervals were used. The joint detection results from the six selected LTPP sections show that the LTPP AFM algorithm was more effective than the ProVAL AFM routine. The JDRs from the ProVAL AFM for the six selected sections ranged from 58 to 99.4 percent, whereas the JDRs for the same six LTPP test sections using the LTPP AFM ranged from 95 to 100 percent. The average section biases computed for the ProVAL AFM and the manual GFM for test sections 364018, 370201, 421606, and 493011 were greater than 1 mm, as were the average section biases for the LTPP AFM and the manual GFM for test sections 313018, 364018, and 421606. These results could be because the joint faulting measurement surveys using the GFM and the LTPP profilers were not conducted on the same wheelpaths, at the same time of the day, or under the same temperature conditions.

The average of absolute differences between faulting estimated by the LTPP AFM and the manual GFM (average section bias) for the six LTPP sections ranged from 0.44 to 5.07 mm. Similarly, the average of absolute differences between faulting estimated by the ProVAL AFM and the manual GFM (average section bias) for the same six LTPP sections ranged from 0.88 to 8.75 mm. FDOT used an HSIP profiler to collect elevation profile data with a 20.7-mm sampling interval on the same wheelpaths (left and right) where manual GFM measurements were collected, at same time of the day, and under the same temperature conditions. The JDR for the one FDOT test section using both the LTPP AFM and the FDOT AFM was 96 percent. The averages of absolute differences in faulting estimated by the FDOT PaveSuite AFM and the LTPP AFM with the measured manual GFM were 1.05 and 1.14 mm, respectively. From this study, it appears that the newly developed LTPP AFM is relatively reliable in detecting transverse joints and computing joint faulting.

RECOMMENDATIONS

- A profiler sampling interval of less than 25.4 mm may yield better results for both transverse joint detection and faulting measurements.

- Faulting measurements surveys conducted using the manual GFM and the LTPP profiler on the same wheelpaths, at the same time of the day, and under the same temperature conditions may generate better AFM results.

- Further research is needed to understand the bias of the AFMs and manual GFM measurements.

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