A SEMI-AUTOMATED FAULTING MEASUREMENT APPROACH FOR RIGID PAVEMENTS USING HIGH SPEED INERTIAL PROFILER DATA

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ABSTRACT

Faulting measurements have traditionally been conducted manually using faultmeters. However, operating any manual device such as a faultmeter close to vehicular traffic is hazardous to the operator and the traveling public. Automated methods like those associated with high-speed profilers, offer a safer, more efficient, and cost effective alternative. Therefore, there is a need to develop an automated method for measuring joint faulting using longitudinal profiles from high-speed profilers.

A study was initiated with a primary objective of determining an appropriate profiler sampling interval to accurately locate transverse joints. A second objective was to determine how well faulting estimated from profile elevation compares with faulting measured with a Georgia Faultmeter.

An algorithm was developed which can accurately detect on average 95% of transverse joints from profile data collected at highway speed using a 0.68 inch (17.3 mm) sampling interval. This algorithm was also adapted to estimate faulting measured with a Georgia Faultmeter in accordance with the AASHTO R36-04 Protocol. Although the algorithm results are repeatable it over-estimated the faulting at joints by 0.05 in (1.3 mm) to 0.06 in (1.5 mm) compared to faulting measured with the Georgia Faultmeter.

INTRODUCTION

Faulting is defined as the difference in elevation across a joint that results from a combination of factors including load transfer at joints, higher corner deflections, and inadequate base support conditions. Faulting of transverse joints and cracks is one of the key distress types for jointed rigid pavements. It is an important indicator of pavement performance as it affects ride quality. In addition, significant joint faulting has a major impact on the life-cycle cost of pavements in terms of rehabilitation and vehicle operating costs [1].

To measure faulting, most agencies use specially designed faultmeters, the most popular of which is the Georgia Faultmeter, from here on referred to as the Faultmeter [2]. The Florida Department of Transportation (FDOT) has been using the Faultmeter as part of the annual network Pavement Condition Survey. Faulting is determined for each rated section by averaging the measurements of five consecutive joints [3]. The ability to measure faulting at each transverse joint is very desirable to obtain a representative faulting value for a rated section. However, operating a Faultmeter close to vehicular traffic is labor intensive and can present a safety hazard to the operator and to the traveling public. Automated data collection methods, like those associated with high speed profilers, offer a better alternative. They are relatively safer, faster, and have the ability to simultaneously measure smoothness and a number of other pavement surface characteristics in an automated and cost effective manner.

In the past, automated joint faulting measurement was an area that did not receive great emphasis by many agencies. This is demonstrated by the relatively few agencies that collect data through automated means. And some of those agencies that did use automated means professed to have little confidence in the data collected [4]. With the recent Highway Performance Monitoring System (HPMS) reassessment effort, there is a renewed interest in automated technologies that collect data at highway speeds. Under the new HPMS data model, state highway agencies are required to collect faulting data in accordance with AASHTO R 36-04 Protocol, which is intended to measure faulting with a vehicle at highway speeds [5].

PROBLEM STATEMENT

High-speed profiler manufacturers typically provide computer application software which allows the user to estimate faulting at a pre-determined distance interval, and by selecting a minimum faulting threshold value. The profiler sampling interval must be adequate to capture the magnitude of faulting and to identify the number of faults and their locations. Even when using a sampling interval less than one inch, there is a probability that a number of joint locations may be missed. Thus an even smaller sampling interval may be needed depending on the degree of accuracy required. Furthermore, most high-speed profilers owned by state agencies use a Distance Measuring Instrument (DMI), which may or may not have the ability to collect data at sampling interval of 1 inch (25.4 mm) or less. One way to mitigate this problem is to make repeat passes to capture any missed joints. However, this process is time consuming and adds to the cost of the data collection effort. Hence, there is a need for an automated method that can accurately detect and measure faulting from profile data collected with one single pass of a high-speed profiler.

OBJECTIVE

The first objective is to develop an algorithm that can detect the presence and location of transverse joints in rigid pavements. The algorithm will use longitudinal profile data to positively identify the presence and location of joints. A second and equally important objective is to estimate the magnitude of faulting using the developed algorithm using two alternative methods. In the first method, the algorithm will be adapted to estimate faulting in accordance with the AASHTO R36-04 standard, from here-on referred to as the AASHTO Method. In the second method, the algorithm will emulate the Faultmeter in measuring faulting at a joint. This method will be from here on referred to as the “In-house” Method. Comparing the results from both method and the results from the manual method will determine how faulting estimated by each alternative method compares to faulting measured directly with the Faultmeter.

FIELD TEST

Test Section

The south bound inside lane of State Road 24 in Waldo, Florida, was used as the test section for the study. The more than fifty years old joint plain concrete pavement (JPCP) roadway was selected because of the convenient proximity to the FDOT State Materials & Research Office, the relatively low traffic volume, and the relative ease in setting up traffic control. The 2,000 ft (609.6m) test section included a 500 ft (152.4m) lead- in and lead-out, and a 1,000 ft (304.8m) effective test length spanning over 50 slab joints. The slabs were typically 20 ft (6.1m) long by 12 ft (3.7m) wide with a relatively smooth surface finish. Each transverse joint was identified by a sequential number painted on the approach side of the slab.

Test Equipment

Georgia Faultmeter

The Georgia Faultmeter developed by the Georgia Department of Transportation has served the pavement community well for many years (Figure1). It was considered an improvement over other manual methods such as the ruler, straightedge, calipers, and other type of gauges [6]. The unit weighs approximately 7 lbs (3.2 kg) and supplies a digital readout with the push of a button located on the carrying handle. The readouts are displayed to nearest 0.1 mm with a positive or a negative sign, which represents positive or negative faulting. The Faultmeter‘s support feet are positioned on the leave side of the slab joint, in the direction of traffic. The joint is centered between the guide marks visible on the side of the meter. The measuring probe contacts the slab on the approach side. The vertical movement of this probe is transmitted to a Linear Variable Displacement Transducer (LVDT) to measure joint faulting. A slab which is lower on the leave side of the joint will register a positive faulting value. If the slab leaving the joint is higher, the meter gives a negative reading [2]. The Faultmeter was found to be reliable after conducting several sequences of power on, calibrate, measure, and then power off.

Template

To compare manual faulting measurements to faulting derived from profile elevation data, it is critical to first match the measurement locations of both devices. This presents a challenge as the test vehicle lateral wander can be as much as two feet from the targeted path. To help overcome this problem, the aluminum template shown in Figure 2 was fabricated. It consists of a 46 in (116.8 cm) x 2 in (5.1 cm) x 1 in (2.5 cm) hollow tube riveted to a 19 in (48.3 m) x 13 in (33 cm) x 1/16 in (0.2 cm) rectangular plate. The plate has a 2.75 in (7 cm) diameter circular opening used to mark the right wheel-path and nine 2 in (5.1 cm) center to center slots used to mark the location of the Faultmeter when positioned to measure faulting about a joint. The template has a carrying handle consisting of a 6.5 in (16.5 cm) and a 4 in (10.2 cm) cylindrical aluminum pieces soldered together to form a “T”, and a 14 in (35.6 cm) x 1 in (2.5 cm) x 1 in (2.5 cm) angle soldered to one end of the tube. The template is placed on the approach side of a transverse joint with the angle aligned with the inside edge of the lane-line. Spray paint is then applied over the circular opening to mark the center of the right wheel path, and over the nine oval slots to mark the Faultmeter measurement locations.

High-Speed Profiler

In the present investigation, longitudinal profiles were acquired using a properly calibrated FDOT-owned Multi-Purpose Survey Vehicle (MPSV). This state of the art test vehicle is essentially a high-speed profiler van equipped with a forward-view camera, INO Laser Road Imaging System (LRIS), Laser Rut Measurement System (LRMS), and a DGPS enabled Position and Orientation System (POS). The profiler is fitted with two 32 KHz Selcom 5000 laser height sensors for measuring longitudinal profiles (Figure 3). Both sensors are mounted in the front bumper of the van, one sensor above each wheel-path. A third laser mounted in the middle of the bumper, is used for rut measurement. These height sensors measure the vertical distance from the vehicle body to the pavement surface. The profiler is also equipped with accelerometers at each of the wheel-path sensors to compensate for the vertical motion of the vehicle body [1]. The LRIS system is composed of two high-resolution line-scan cameras and two high-power laser line projectors aligned in the same plane, and configured to image almost 13 ft (4 m) wide pavement sections with a 0.04 in. (1mm) resolution at speeds that can surpass 62 mph (100 km/hr). In this study, the LRIS pavement images were used to identify the Faultmeter measurement marking that best matches the right sensor lateral position.

The Profile Viewing and Analysis Software (ProVAL 2.73) developed by the Transtec Group Inc. for the Federal Highway Department was used to check for profile repeatability, by performing a cross-correlation on the first profile run at Rate 1 (0.6812 in or 1.7 cm). Based on the AASHTO PP-49 provisional standard, the profiler met the minimum threshold requirements test with an average repeatability of 98%. The IRI filter cross-correlation yielded an accuracy of 91% for the left laser, and 93% for the right laser using the Surpro walking profiler as the reference device. The Distance Measuring Instrument (DMI) accuracy was tested on a 1 mile calibration section. The difference between the DMI measured length and the length measured with a digital level was less than 0.15% which meets the PP-49 requirement.

Data Collection Procedure

The test lane was closed to traffic during the entire data collection effort which was performed in the mid to late afternoon for two consecutive days. This time window was selected in order to minimize the effects of curling and warping. The Faultmeter was calibrated and tested before the data collection. Spray paint was then applied over the template's circular opening to mark the center of the right wheel-path located 36.5 in (91.4 cm) from edge of lane-line. Spray paint was also applied over the nine slots to mark the locations where the Faultmeter's probe is to be placed. Nine faulting measurements were taken t at the nine marked locations along each transverse joint. The MPSV profiler performed five repeat passes at sampling interval Rate 1 (0.6812 in or 1.73cm), and Rate 2 (1.3624 in or 3.46 cm) at a posted speed limit of 45 mph (72 km/hr). The data collection was interrupted due to rain and resumed the following day when 10 passes were conducted at each of Rate 3 (2.0436 in or 5.2 cm), and Rate 9 (6.1308 in or 15.6 cm). The weather was mostly fair on both days with partly cloudy skies.

Image Evaluation

The effect of test vehicle lateral wander made it necessary to match the lateral position of the right laser spot with one of the nine faultmeter measurements at each joint. An image evaluation technique was improvised and was implemented accordingly. A 6 in (15.2 cm) wide white tape was glued to the floor of the MPSV calibration bay. A black line was drawn in the middle of the tape to mark the trace of the right laser in the center of the right wheel-path (Figure 4). This was done by positioning the vehicle body such that the right laser spot and rear right vehicle wheel were aligned with the black line. The MPSV was set on simulation mode to capture images of the floor surface. The black line was found to have an offset of 2,886 pixels from the left edge of a pavement image (Figure 4).

The pavement images captured with the LRIS were viewed with the Photoshop software application, and only those images showing transverse joints and template markings were evaluated. A lateral offset of 2,886 pixels was measured from the left edge of each image, matching right laser position with corresponding Faultmeter test location (Figure 5). The same process was repeated for the image at each joint. In addition to pavement images, the MPSV simultaneously collected longitudinal profile elevations, which were later used by the developed algorithm to identify joint locations and estimate faulting.

Algorithm Development

The first step in developing the algorithm was to identify maxima (peaks) and minima (valleys) from profile elevations. The valleys (or minimal dips) in a profile are indicators of the presence of joints between the approach and departure slabs. As for example, a profile spanning 50 slabs should theoretically have 49 valleys (minimal dips) representing joints. The objective of the algorithm is to detect the longitudinal location of these minima (joints) and then use this information to compute faulting at these joints. Faulting is calculated as the difference in elevation of points around the valleys. A point is considered a maximum peak or minimum valley if it has the maximal or minimal value and is preceded (to the left) by an elevation change larger than the constant (ζ). This constant is called the sensitivity factor, which is adjusted by the end user based on the desired resolution. The value ζ, which represents the difference in profile elevation between a maxima and minima points, is used to identify joint locations. The smaller the value of ζ, the greater the likelihood of identifying false positives. The value of ζ, selected by the user affects the number of detected joints, and hence the corresponding term "semi-automated" approach of detecting transverse joints' locations.

Algorithm Steps

Step 1: Initialize Current Value (CV), Current Maximum Elevation (CMaE), Current Maximum Elevation Position (CMaEP), Current Minimum Elevation (CMiE), Current Minimum Elevation Position (CMiEP) at the first point (i=1) in the profile elevation vector.

Step 2: Move to the next point (i) and check the following:

- If CV > CMaE, make CMaE its position and store as the new CMaEP
- If CV< CMiE, make CMiE its position and store as the new CMiEP

Step 3: If CV < CMaE – ζ, set Peak (i) = CMaE and store the Peak_Loc (i) = CMaEP

Step 4: If CV > CMiE + ζ, set Valley(i) = CMiE and store the Valley_Loc (i) = CMiEP

Step 5: Toggle between Step 3 and 4 to detect Peaks and Valleys incrementally scanning through the elevation profile.

A simple MATLAB program was developed to implement the above described algorithm steps.

Semi-automated Approach for Joints Detection

The raw profiles were first processed using International Cybernetic Corporation's WinReport Program (version 2.1.2.1) to obtain files in "erd" format. The longitudinal profile, speed, and event files are the necessary input to the WinReport Program. A 300 ft (91.4 m) wavelength filter was initially applied to eliminate long wavelength features. However, this type of filtering was suspected to cause some point averaging and possibly resulting in the removal of certain short wavelength features. Therefore, the raw profile data files were processed a second time without any filtering. The resulting "erd" files from both the filtered and unfiltered profiles were used as inputs into FHWA's ProVal 2.7 software application, and were then exported as comma separated text (csv) files.

The "csv" files were read into the MATLAB Computer Program and then processed using the developed algorithm. The location of "peaks" and "valleys" corresponding to maximum (CMaE) and minimum (CMiE) elevations, respectively, were computed with their corresponding distance positions, namely CMaEP, and CMiEP. An iterative process was used to match the known joint locations with the distance positions detected through the algorithm. This was accomplished by adjusting the value of the sensitivity factor "ζ", until the best match or solution with the least number of false positives was attained. Any false positive joint detection was manually removed from the data set. The detected joint locations are identified by the valleys shown in Figure 6, which correspond to the calculated CMiEP values.

Faulting Calculation Methods

Two methods were used by the algorithm to estimate faulting, namely the "In-House" Method and the AASHTO Method.

Method 1: "In-house" Method

In this method, the algorithm estimates faulting as measured by the Faultmeter. The algorithm first identifies the position of two points located 4.5 in (11.4 cm) on either side of a detected joint. The distance between these two points corresponds to the 9 in (22.9 cm) span between the Faultmeter's measuring probe and its resting feet. The algorithm calculates faulting as the absolute difference in elevation between these two points (Figure 7).

Method 2: AASHTO Method

In this method, the algorithm emulates the faulting measurement specified in the AASHTO R36-04 standard practice (Figure 8). The algorithm identifies sets of measurement points P1 and P2 located between 3 and 8.8 in (75 to 225 mm) away from a joint and separated by a constant distance of 11.8 in (300 mm) (Figure 9). The number of sets P1 and P2 is determined by dividing 5.8 in (139.7 mm) by the profile sampling interval plus one. For example, the number of measurement points for a sampling interval of 0.6812 in (Rate 1) is calculated as [(5.8 in/ 0.6812 in) + 1], which results in 10 sets of measurement points P1 and P2. The faulting at a joint is then calculated as the average difference in elevation between the set of points P1 and P2.

Data Analysis

The results of joints detection using the semi-automated approach are shown in Table 1. As expected, Rate 1 sampling interval provided the best positive joints detection for all five runs ranging from 93% to 97%. An even smaller sampling interval may be required for pavements with very narrow joints, and/or for projects requiring more accuracy of joint detection. Rate 2 provided a joint detection rate ranging from 64 to 74%. This sampling interval may be suitable for network level surveys when data collection at Rate 1 is not feasible. If a profiler does not have the capability to collect longitudinal profiles at Rate 1 or smaller, then Rate 2 may be considered. Using Rates 3 and 9 had a positive joint detection range of 58 to 66 % and 34 to 38%, respectively. Using rates 3 and 9 resulted in a large number of false positives, which significantly reduces the efficacy of the semi-automated approach.

The algorithm estimated the magnitude of faulting at each joint by the In-house Method and the AASHTO Method using filtered and unfiltered profile elevation data collected at Rate 1. An average fault value for the test section was calculated by taking the average faulting of all 50 joints for all five passes (Table 2). The faulting for the section estimated by both methods was compared to the faulting measured with the Faultmeter.

The descriptive statistics in Table 2 show the AASHTO Method and the "In-House" Method give very similar faulting estimates regardless whether the 300 ft filter is applied or not. The Average Error represents the average of absolute differences in faulting for all 50 joints estimated by the In-house or AASHTO Method and the manual measurements. Both Methods consistently under-estimated faulting compared to the manual method. The average error between manual faulting and faulting by the two methods were similar, ranging from 0.049 in (1.24 mm) to 0.058 in (1.47 mm), which is slightly higher than 0.04 in (1 mm) accuracy required by the AASHTO R 36-04 standard.

The magnitude of faulting on SR 24 being relatively small magnifies the effect of any small measurement deviation. The investigators suspect that spot grinding of joints may have been performed at some time during the life span of the test section. This is evidenced by field observed isolated patches of exposed aggregates near the joints. This explains the small magnitude of faulting recorded by the faultmeter and the faulting calculated from the profile elevation data. Furthermore, the Faultmeter was arbitrarily selected as the reference device to evaluate the accuracy of each proposed method. However, this may not result in a fair and sound comparison given the fact that the profiler height sensor has a typical range resolution of 0.005 mm compared to the Faultmeter's resolution of 0.1 mm. For further research, the investigators recommend a reference device with resolution similar to that of the profiler and ideally a device with one order of resolution magnitude higher than the profiler.

CONCLUSION

The summary results in Table 1 show that the semi-automated approach yields an average of 95% joints detection using longitudinal profiles collected at Rate 1 (0.6812 in (17.3 mm). At Rate 2 (1.3624 in or 34.6 mm) 69% of the joints were detected. This sampling may be acceptable for network surveys when data collection at Rate 1 or less is not feasible. At Rate 9 (6.1308 in or 15.6 cm) only 36% of joints were detected. This sampling interval results in missing most of the joints and is too large to meet the 300 mm distance between fault measurement points P1 and P2 required by AASHTO R 36-04.

The results presented in Table 2 show the "In-house" Method and the AASHTO Method give similar results when estimating faulting. When compared to the Faultmeter, both methods under-estimated the faulting for the test section.

Another outcome of this study was the manufacturing of a practical template, which allows the user to mark the center of a wheel-path and the locations for manual faulting measurement. This simple tool provides for a more efficient and expeditious data collection process. In addition, an innovative method was improvised as a result of this study. It allows the user to identify the lateral position of the profiler's right laser using a simple image analysis technique. This technique made it possible to match profiler profile measurement with Faultmeter measurements along the transverse joints.

This study was a first effort to pilot test the developed algorithm. However, additional data from other JPCP test sections of various slab lengths, surface finish and range of faulting are needed for a comprehensive validation the proposed approach.

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DISCLAIMER

The content of this paper reflects the views of the authors who are solely responsible for the facts and accuracy of the data as well as for the opinions, findings and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Florida DOT. This paper does not constitute a standard, specification, or regulation. In addition, the above listed agency assumes no liability for its contents or use thereof.

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LIST OF FIGURES AND TABLES

FIGURE 1 Georgia Faultmeter

FIGURE 2 Manufactured template

FIGURE 3 FDOT Multi- Purpose Survey Vehicle

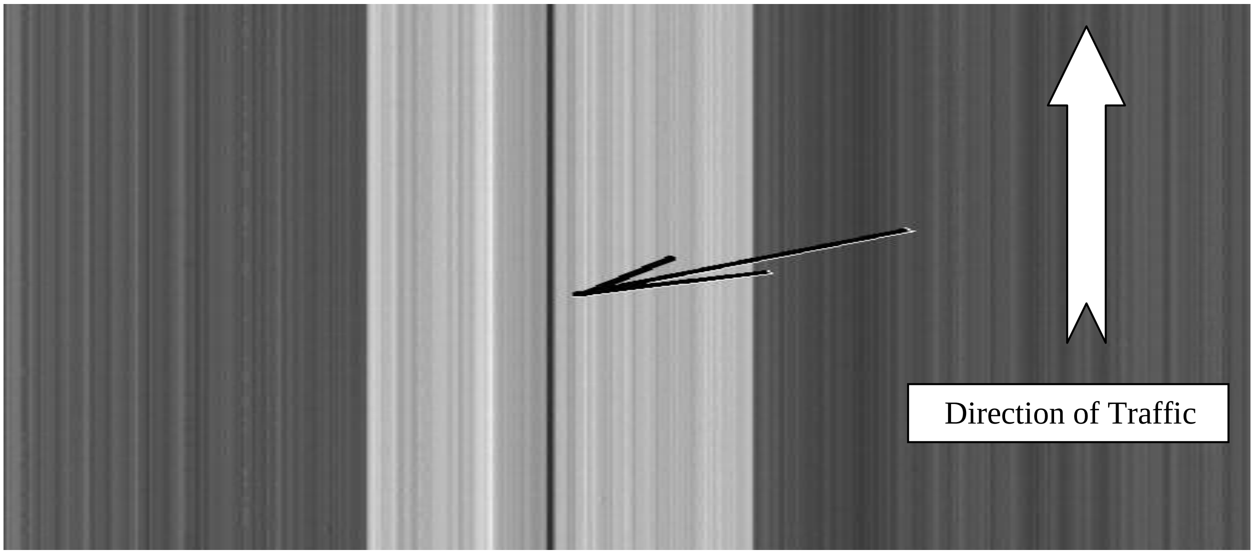


FIGURE 4 Lateral offset of MPSV's right laser

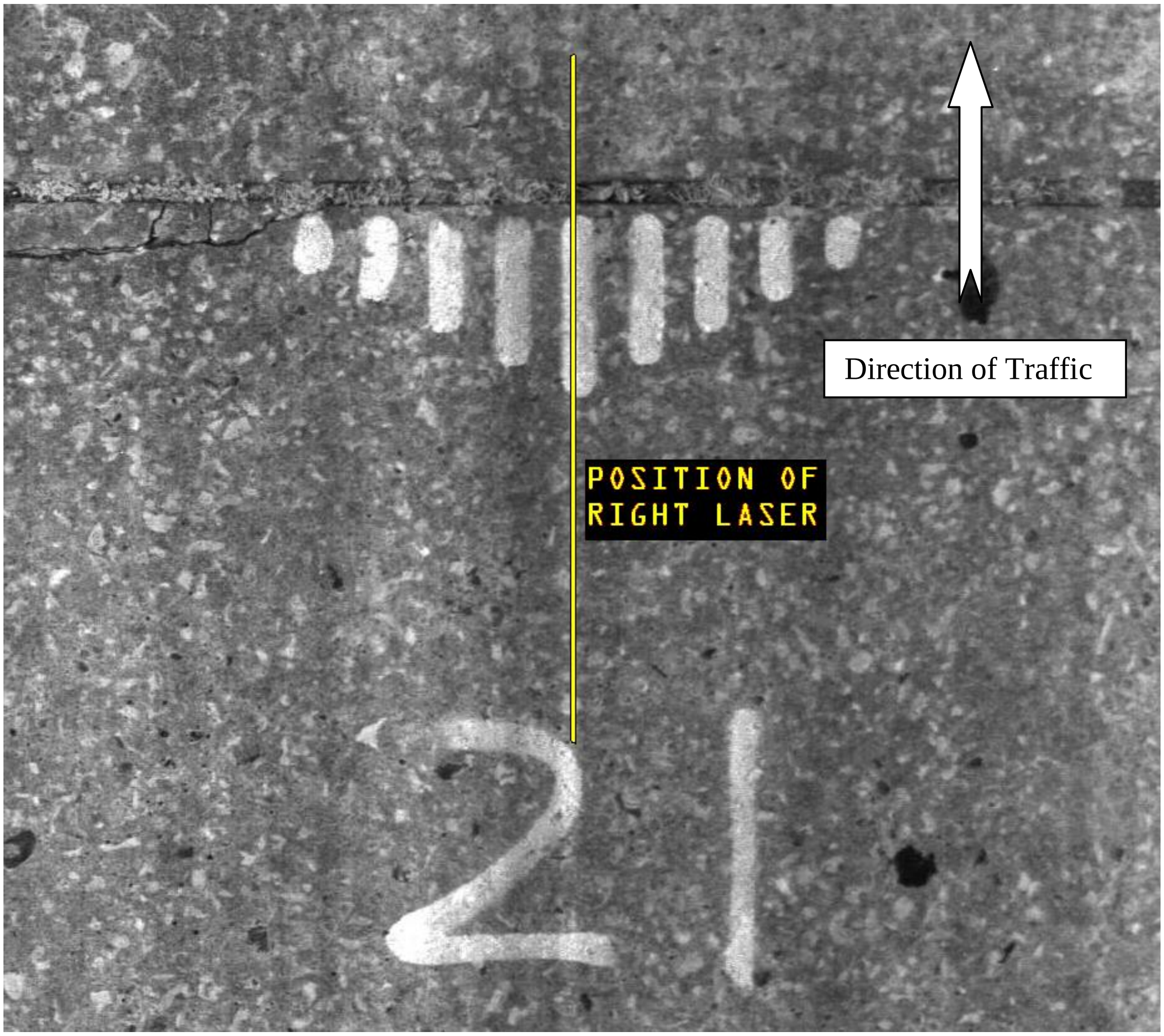


FIGURE 5 Matching of right laser lateral position with Faultmeter test location

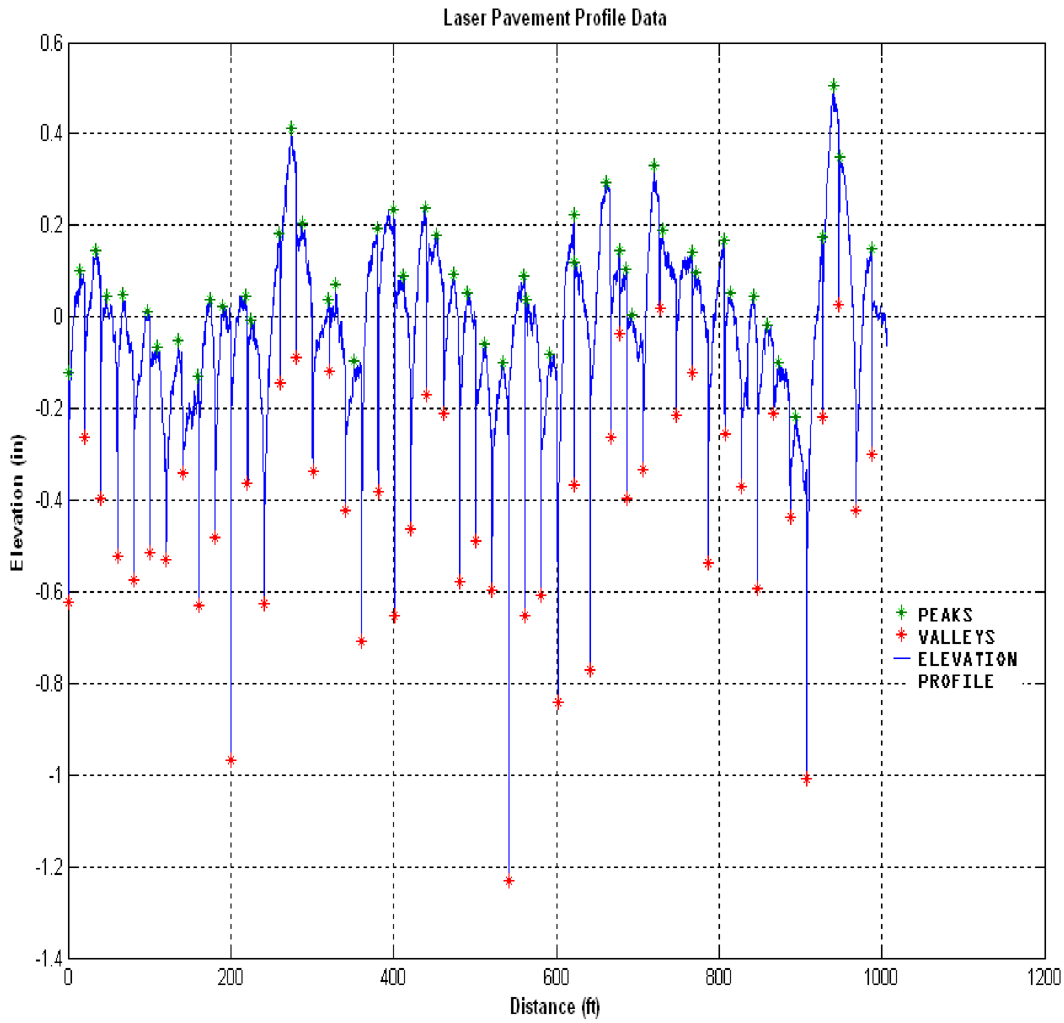


FIGURE 6 Peaks and valleys (joints) detected by the algorithm

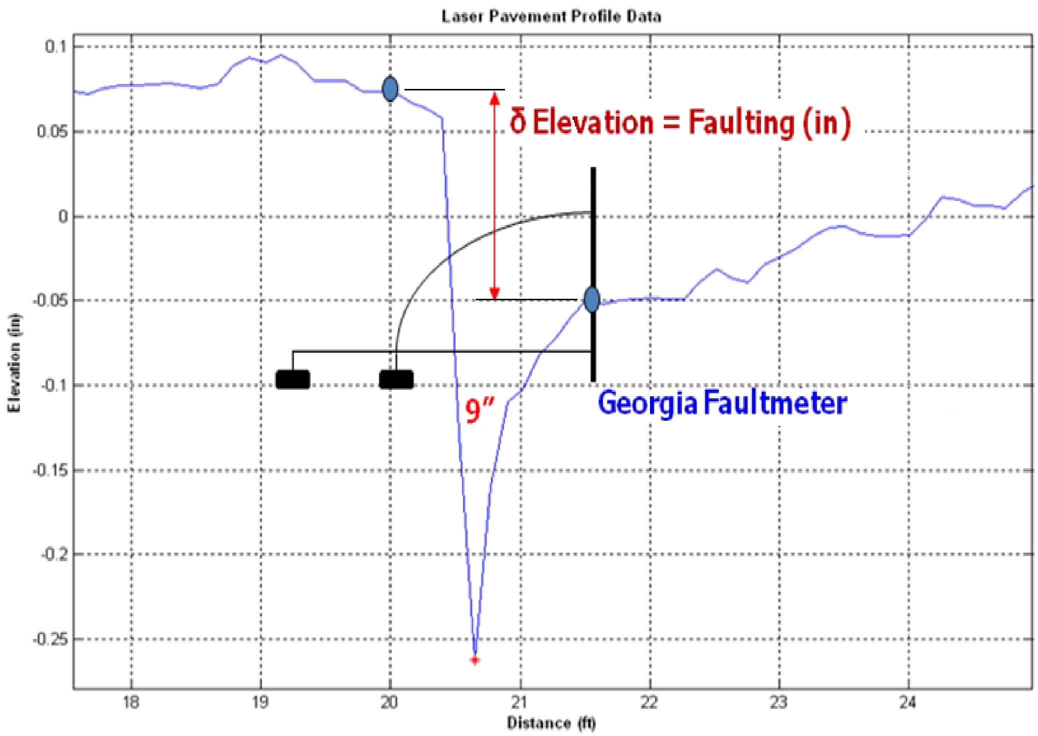
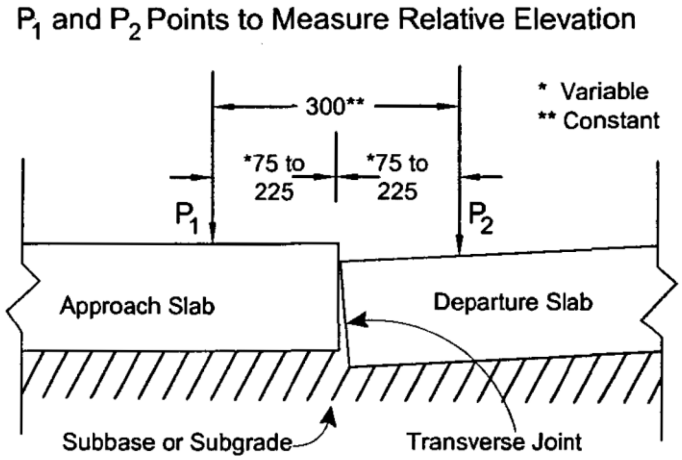


FIGURE 7 Faulting estimated by the "In-house" Method



Note: All dimensions shown in millimeters unless otherwise noted.

FIGURE 8 Joint-faulting measurement per AASHTO R36-04

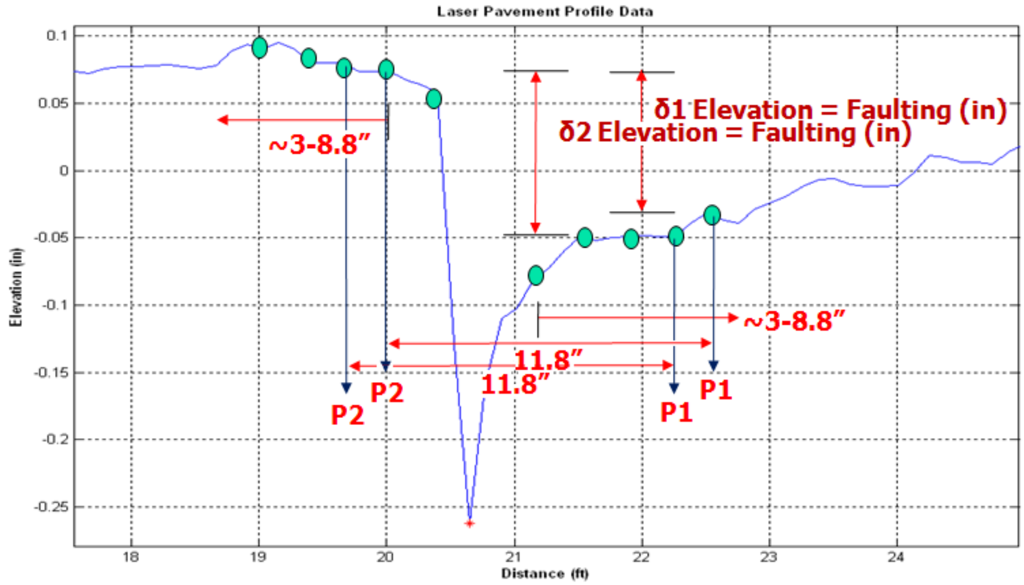


FIGURE 9 Faulting estimated by the AASHTO Method

Table 1 Joints Detected Using the Semi-automated Method

Run #	Number of Matching Joints				Matching Joints [%]			
	Rate 1	Rate 2	Rate 3	Rate 9	Rate1	Rate 2	Rate 3	Rate 9
1	46	37	33	16	92	74	66	32
2	47	31	33	19	94	62	66	38
3	47	33	28	19	94	66	56	38
4	49	38	30	17	98	76	60	34
5	48	34	31	19	96	68	62	38
Mean					95	69	62	36
Std. Dev.					2.28	5.76	4.24	2.83
95% C.I.					93-97	64-74	58-66	34-38

Table 2 Summary Statistics for In-house and AASHTO Methods

Method Used		Average Error (in.)	St. Dev.	Var.	Covar.	Faulting @95% Confidence (in)
No Filter	"In-house"	0.058	0.046	0.002	80.052	0.052 ± 0.0036
	AASHTO	0.058	0.047	0.002	80.381	0.053 ± 0.0036
300 ft Filter	"In-house"	0.049	0.048	0.002	98.990	0.053 ± 0.0049
	AASHTO	0.058	0.048	0.002	82.490	0.049 ± 0.0033