ALTERNATIVE VALIDATION PRACTICE OF AN AUTOMATED FAULTING MEASUREMENT METHOD

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ABSTRACT

A number of states have adopted profiler based systems to automatically measure faulting, in jointed concrete pavements. However, little published work exists which documents the validation process used for such automated faulting systems. This paper documents an alternative practice for making an initial assessment of a newly developed automated faulting method. Findings from this experiment show that a high speed inertial profiler used in conjunction with a faulting reference device provides a practical validation method under controlled conditions. Furthermore, the algorithm which controls the automated faulting measurement method provides reliable, highly repeatable and reproducible faulting results. This paper also documents the test equipment used in the experiment as well as the data collection efforts, the data analysis and subsequent findings and recommendations.

INTRODUCTION

The AASHTO provisional standard for joint faulting measurement defines faulting as the elevation between two points of measurement (P1 and P2) to the nearest 1mm (0.04 in.), with a difference of 5 mm (0.2 in.) defined as the threshold for faulting [1]. This standard is applicable to both manual as well as automated methods. In the past, automated joint faulting measurement was an area that did not receive great emphasis by many agencies. However, the new Highway Performance Monitoring System (HPMS) reassessment model requires state highway agencies to collect network-level faulting data in accordance with the AAHTO R36-04 protocol, which is intended to measure faulting with a vehicle at highway speed [2]. This requirement in addition to the disadvantages associated with manual data collection methods created a renewed interest in automated technologies that collect data at highway speeds. A number of states have adopted inertial high speed profiler based systems to automatically collect faulting, smoothness, rut depth and other pavement characteristics. However, there is little published work regarding the validation of automated faulting measurement systems.

GOAL AND OBJECTIVE

The objective of this study is to evaluate the accuracy and precision of a HSIP based automated fault measurement system using a two-phase approach. The first phase approach evaluates the high speed inertial profiler's (HSIP) ability to produce reliable faulting measurements under controlled conditions. The second phase tests the validity of the automated method to produce repeatable and reproducible results under normal field conditions. The goal is to use the results from this study to support the implementation of the automated fault measurement system into FDOT's Annual Pavement Condition Survey (PCS) process [3].

SCOPE

A two- phase approach was used to validate the HSIP and the automated faulting method. In the first phase, automated faulting measurements were performed at various speeds using a single HSIP. This approach was selected to test the ability of a HSIP to measure faulting under controlled conditions by virtually eliminating the effects of surface texture and vehicle wander. For this purpose, an aluminum device was manufactured to serve as a reference or ground truth. The device consists of seven C-channel extrusions secured to a support plate, which simulate jointed concrete slabs with different faulting magnitudes. In the second phase of the experiment a rigid pavement section was used to validate the automated faulting method under normal field conditions. Five HSIP operated by different operators, and a manual Faultmeter were used in this phase of the study.

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EQUIPMENT

Georgia Faultmeter

This hand operated device weighs approximately 7 lbs (3.2 kg) and supplies a digital readout with the push of a button located on the carrying handle (Figure 1). The readouts are displayed to the nearest 0.1 mm with a positive or a negative sign, representing positive faulting or negative faulting, respectively. The Faultmeter's support feet are positioned on the leave side of the slab joint, pointing in the direction of traffic while the measuring probe is in contact with the approach side of the slab. The joint is centered between the guide marks visible on the side of the meter. The vertical movement of the 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 [4].

High Speed Inertial Profiler (HSIP)

Five HSIP vehicles operated by five different operators were used in the second phase of this project. The HSIP consisted of a full-size van equipped with various electronic sensors (Figure 2). Three laser height sensors laser sensor were mounted in the front of a specially designed bumper of each host vehicle. Two 32 KHz Selcom 5000 laser sensors to measure longitudinal profiles, and a 16 Khz laser mounted in the middle of the bumper which primarily used for rut depth measurement. The typical single spot height laser footprint measured 0.13 in (3mm) in diameter. The HSIP is also equipped with accelerometers mounted in tandem with each wheel-path height sensor to compensate for the vertical motion of the vehicle body [5]. The HSIP were also equipped with data acquisition systems to collect and store elevation profile data of the traveled surface. One of the HSIP, known as the Multi-Purpose Survey Vehicle (MPSV), was equipped with a forward-view camera, an INO Laser Road Imaging System (LRIS), a Laser Rut Measurement System (LRMS), and a Differential Global Positioning System enabled Position and Orientation System (POS). The LRIS system is comprised 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).

Faulting Reference Device

The device consists of a 0.24 in x 48 in aluminum base plate, which supports seven 0.25 in x 8 in x 6 in C-channel extrusions ranging from 0.036 in (0.96 mm) to 1.96 in (49.92 mm) in height (Figure 3). The different in height between any two adjacent C-channel extrusions are used as reference measurements to simulate faulting. Different "joint" widths can be obtained by adjusting the spacing between the C-channels after being moved along longitudinal grooves cut into longitudinally on the upper side of the base plate. An Allen wrench was used to lock the channel extrusions in place after a 6.4 mm joint spacing was obtained. Multiple measurements of each C-channel extrusion height were performed with a Starrett No. 721A Electronic Digital Caliper calibrated calipers, rated at 0.0005 in. (0.01 mm) resolution and a ± 0.001 in. (± 0.03 mm) accuracy. The difference in height between adjacent C-channels were calculated and recorded and were later used as reference to compare with the HSIP measurements.

Automated Faulting Program

The automated faulting program used in this experiment is an enhancement to the earlier version of the program [6]. The following steps describe the process used by the current program to identify transverse joint locations and to calculate faulting magnitude:

1. The program checks the elevation points along a given profile and removes user-defined exclusion areas such as bridges.
2. The program sets a default sensitivity factor (SF) equal to 0.5 x the HSIP sampling rate, which represents the minimum slope between any two consecutive points along the profile.

3. The program looks for valleys (i.e. negative slope) and peaks (i.e. positive slope) along the profile which meet the minimum slope criterion described in step 2.
4. The program then calculates the distance between the identified peaks and valleys. If the distance is less than 2.5 inches, the program considers a valley to be the location of a joint. The 2.5 inch spacing was selected to ensure at least two elevation points are captured within a joint when using a sampling interval less than 1 inch.
5. Faulting is then calculated based on the AASHTO R36-04 criteria.
6. The program checks whether the computed faulting is greater than 1/64th inch; this is based on the FDOT PCS specification which only considers faulting greater than 1/32 inch [3].
7. If the faulting is greater than 1/64 inch, the corresponding joint location is temporarily saved into a joint location array.
8. The program repeats steps 3 through 7 for all points along the given profile.
9. The program looks up the joint location array to check the distance between any two consecutive joints is less than 14.8 inch. This is to adhere to the AASHTO criteria which require faulting be calculated using elevation points between 3.0 and 8.8 inch away from a joint. It is also to ensure that the elevation point(s) within 3 inches of a joint are not used to calculate faulting at any adjacent joint. If two joint locations are less than 14.8 inches apart, the program will only keep the one with the deepest fault.
10. The program counts the number of joints in the array and then clears the array.
11. The program goes through four more iterations repeating steps 2 through 10 using a binary search each time changing the SF. If the program does not find a number of joints greater than previously found, it uses the number of joints detected in the previous iteration. Otherwise, it continues the process until it cannot find a larger number of joints and keeps the last SF.
12. The program recalculates all the joint locations and magnitudes using the best SF which yields the largest number of joints as determined in step 11 and saves this information into the joint array.

DATA COLLECTION

Phase 1 - Simulated Faulting

This phase of the validation process was to test the HSIP under controlled conditions of variables typically encountered during a typical profile survey such as pavement texture and vehicle lateral wander. This methodology is a practical and a relatively safe method to make a quick assessment of the HSIP's ability to collect accurate and repeatable elevation points at highway speed. The Gainesville Speedway racetrack was used to conduct this part of the experiment. The HSIP's infrared target sensor mounted in the middle of the vehicle's front bumper was adjusted to ensure proper alignment with the faulting reference device. Reflective tape was placed at both ends of the device to trigger the HSIP data acquisition system. An initial run was conducted to test the system's operability, to check for the alignment of the middle laser sensor with the centerline of the reference device, and to check for any obstructive artifacts on the pavement surface. Three replicate passes were conducted by each HSIP at operating speeds of 50, 60 and 70 mph which had slightly different smallest sampling intervals ranging from 0.681in (17.3 mm) to 0.910 in (23.1mm). Since the HSIP middle lasers were not equipped with an accelerometer, the corresponding profile elevations were corrected using the average readings from the left and right accelerometers. All profiles were processed through the vendor software to generate profile elevation files after a 300 ft wavelength filter was applied. The output files were saved as .csv files which were then imported into Microsoft Excel for analysis (Figure 4).

Phase 2 - Field Validation

State Road (SR) 331 is a two-lane joint plain concrete pavement (JPCP) and was selected for its proximity to the FDOT State Materials & Research Office, the relatively low vehicular traffic volume and operating speed, and the relative ease for setting up traffic control. Most rigid pavements in Florida are located on limited access facilities and the logistics involved in conducting a comprehensive field validation operation requires substantial staff and equipment resources, in addition to the potential impact such an operation could have on the safety of project staff and the traveling public. This can add a significant demand on any agency's budget especially when operating with limited resources is the opus operandi.

The southbound inside test lane of SR 331 was closed to traffic during the entire data collection operation which took place in the middle to late afternoon for two consecutive days. This time window was selected to minimize the effects of slab curling and warping. 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 49 concrete slabs. The slabs were 20 ft (6.1m) long by 12 ft (3.7m) wide with a relatively smooth surface finish. Spray paint was applied at nine locations spaced two inches apart across the right wheel-path. Nine faultmeter measurements were taken at these marked locations along each leave slab joint which was identified by a sequential number painted on the approach side of the slab. The four similar HSIP performed three repeat passes each while the MPSV performed five repeat passes, all vehicles operated at a maximum posted speed of 40 mph. The profile sampling interval was slightly different for each HSIP, which ranged between 0.6 and 0.9 in. Only the right HSIP laser and accelerometer data were used to measure faulting with the automated method. The data collection was interrupted on the first day due to rain but resumed on the following day. The weather was mostly fair on both days with partly cloudy skies.

ACCURACY AND PRECISION

HSIP Performance

To evaluate the performance of the HSIP it is important to compare the profiles directly, as index values may compare favorably even though profiles may not. The AASHTO PP-49 protocol sets a minimum profile repeatability and accuracy of 92% and 90%, respectively.

In this experiment, each HSIP's profile repeatability was evaluated in terms of cross-correlation among three unfiltered replicate profiles (Table 1). All HSIP units met the minimum profile repeatability requirement except for HSIP 30781, whose operator was less experienced and had difficulty maintaining a consistent lateral position of the vehicle. Profile accuracy could not be evaluated since a profile reference device was not available during the study.

The repeatability of profile measurement on diamond ground concrete depends heavily on the use of a large foot-print height sensor and consistent lateral tracking of the profiler [7]. However, since faulting measures the difference in elevation between points, the systematic error due to the bias of the relatively small laser sensor footprint is greatly reduced if not eliminated.

Phase 1

For this phase of the study, the faulting measurements by the HSIP at various speeds were compared to the control measurements of the simulated faulting device. Figure 5 shows an example of the insignificant effect of speed gradient on faulting under controlled conditions.

For this phase of the experiment, precision is expressed in terms of accuracy and repeatability. The accuracy is the maximum faulting bias between the five HSIP and the simulated faulting device. Repeatability is the maximum range in faulting within the five HSIP. Table 2 gives an example of assessing the simulated faulting repeatability and accuracy for one HSIP. Table 3 provides a summary of the HSIP automated faulting precision under controlled conditions at test speeds varying from 50 to 70 mph..

Phase 2

The main objective of the second phase was to perform a preliminary accuracy and precision test of the automated faulting measurement method under normal field conditions. The location of HSIP detected joints were compared to the 50 existing joints whose station locations were determined with a measuring wheel. The average joint detection from three repeat passes of each HSIP was expressed in terms of actual existing joints correctly detected (i.e. true positive), existing joints not detected (i.e. true negative), non-existing joints detected (i.e. false positive), and non-existing joints not detected (i.e. false negative). The joint detection rate of each HSIP was measured by the ratio of positively detected joints as shown by the confusion matrix presented in Table 4.

The average faulting estimated by each HSIP and the average manual faulting at the detected joints are reported in Table 5. The bias is the average difference between the HSIP estimated faulting and the average faulting at the detected joints. The precision for faulting measurement is expressed in terms of accuracy, repeatability, and reproducibility (Table 6). The accuracy is the average difference between the HSIP estimated faulting and the manually measured faulting at all 50 joints; repeatability is expressed by the average standard deviation of all the biases at all 50 joints; reproducibility is expressed as the maximum difference in faulting bias among the five HSIP at any faulted joint.

ANALYSIS

Except for HSIP 30781, all other profilers passed the minimum profile repeatability cross-correlation of 92% in both wheel-paths. Profile accuracy could not be verified since a reference profiler was not available.

The results of Phase 1 show that speed gradient had a minimum effect on estimated faulting under controlled conditions. Faulting measured by the HSIP under controlled conditions shows a high degree of accuracy and repeatability as expressed by the relatively low faulting bias and range of 0.60 mm and 0.65 mm, respectively. This is lower that the 1mm faulting resolution required by the AASHTO R36 protocol.

The results from Phase 2 show that the proposed automated method yields a positive joint detection rate ranging from 80 to 94%. Exception is made for HSIP 30781 with a positive joint detection rate of 74%, which is mostly attributed to the inexperience of the operator. Under field operating conditions, the average difference between faulting estimated by a HSIP and that measured by a manual faultmeter was estimated at 1.2 mm. The average difference in estimated faulting between any two independent runs of a single HSIP, was estimated at 1.1mm. The maximum difference in estimated faulting between two different HSIP was estimated at 0.5 mm. The variability in estimated faulting under field conditions is obviously larger than that estimated under controlled conditions as was to be expected. The increased variability is due to a combination of random factors including equipment, operator and pavement texture and vehicle wander, most of which are greatly reduced under controlled conditions.

CONCLUSIONS

The present study was conducted primarily to assess the accuracy and precision of the enhanced FDOT automated faulting method used in conjunction with a HSIP. A two-phase approach was used for the validation process. The first phase focused on evaluating the accuracy and repeatability of HSIP under controlled conditions. The second phase evaluated the automated faulting method on a rigid pavement using five separate HSIP. The findings indicated the following:

- Except for one HSIP, all profilers passed a minimum profile repeatability cross-correlation of 92%
- 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 ranging from 80 to 94%
- Under filed conditions, the HSIP has an accuracy, repeatability and reproducibility of 1.2 mm. 1.1mm, and 0.5 mm, respectively.

RECOMMENDATIONS

These initial findings suggest that the enhanced automated faulting measurement method offers a safe and reliable alternative method for measuring faulting of jointed concrete pavements. The simulated faulting test approach used in Phase 1 offers a practical method to test a HSIP's ability to measure faulting under controlled conditions and to obtain an estimate of the systematic error. Additional field testing will be required to take into account the variability introduced by other factors such as different joint width, joint condition, slab curling which are typically encountered when testing concrete pavements. This will result in a method with a much wider application.

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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 TABLES AND FIGURES

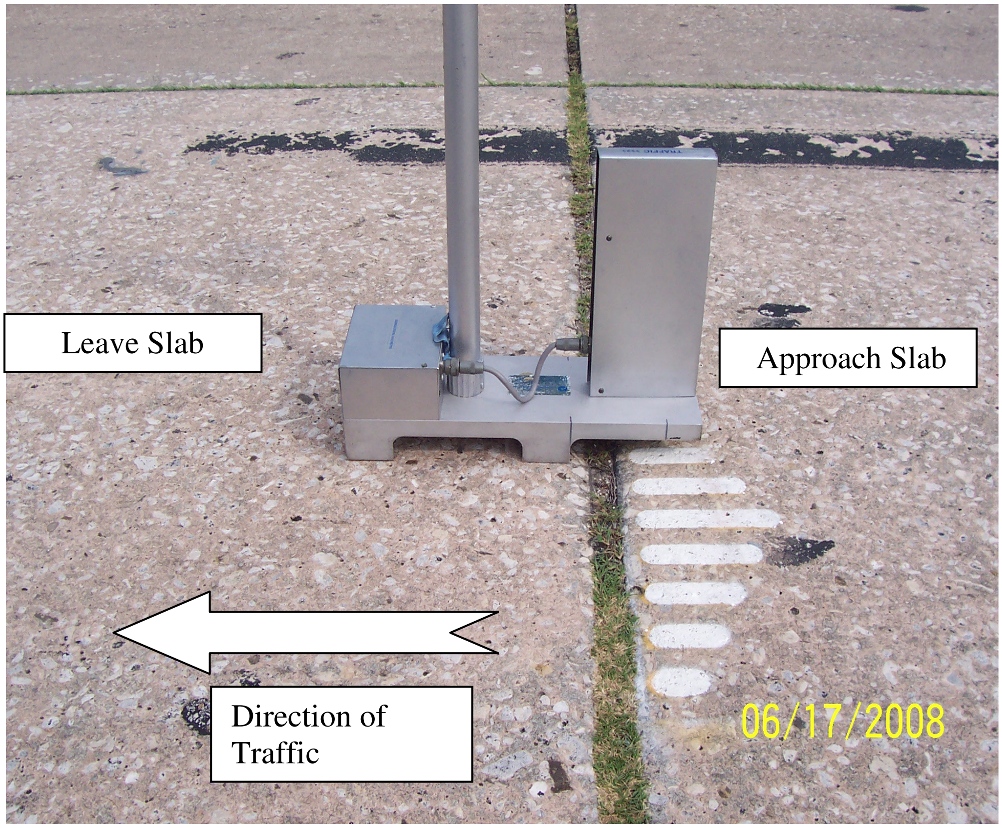

FIGURE 1 Georgia Faultmeter

FIGURE 2   FDOT High Speed Inertial Profiler (HSIP)

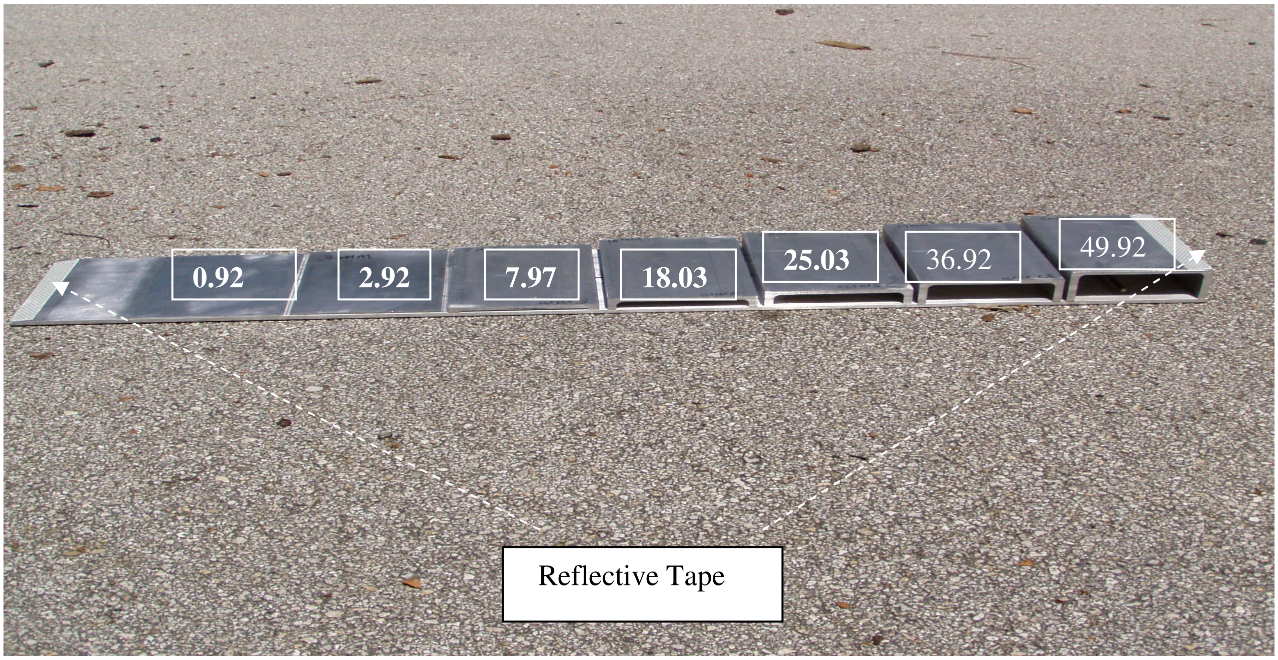

FIGURE 3 Simulated Faulting Device

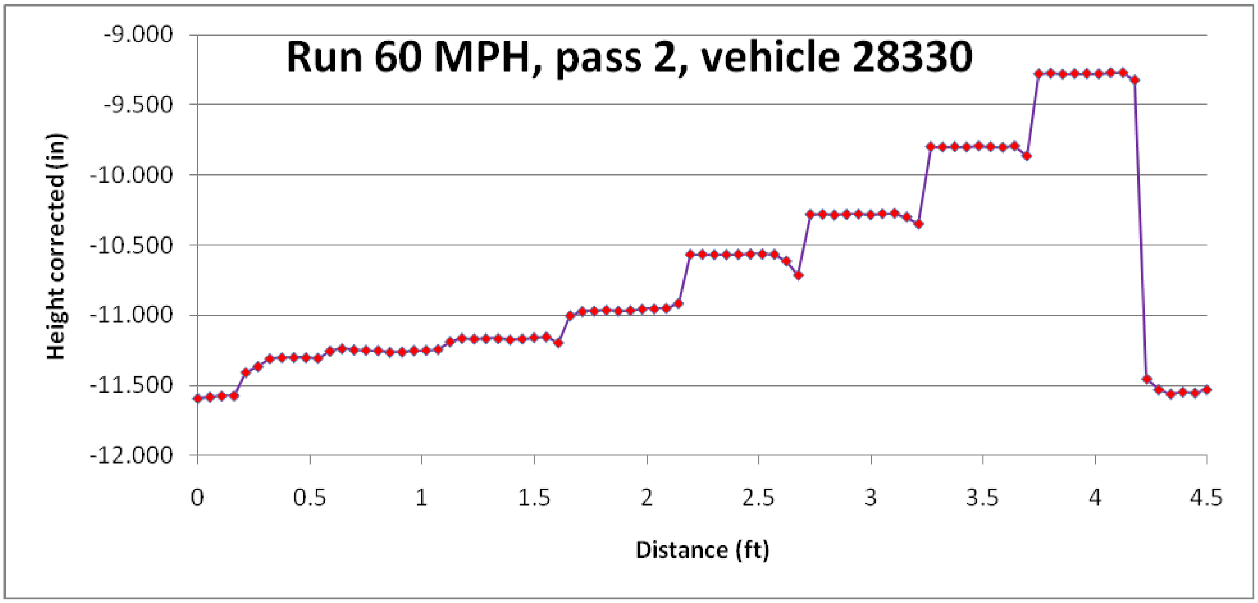

FIGURE 4 Example of HSIP measured simulated faulting

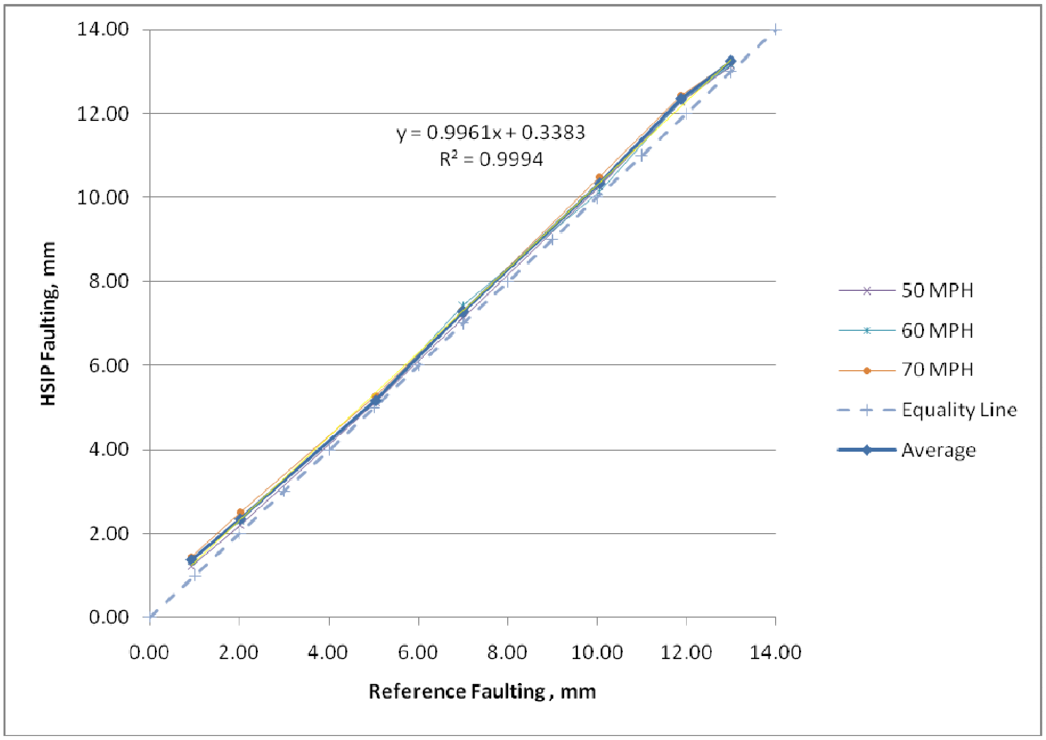

FIGURE 5 Effect of HSIP speed gradient on simulated faulting with eight degrees of freedom

TABLE 1 HSIP Profile Percent Cross-Correlation

HSIP No.	Sampling Interval (in)	Repeatability Left			Repeatability Right		
		Average	Minimum	Maximum	Average	Minimum	Maximum
29748	0.8	93	90	97	94	92	98
30330	0.7	92	90	94	96	95	98
30781	0.9	62	41	78	84	76	88
29863	0.8	94	92	96	97	96	97
30392	0.7	97	95	99	97	96	99

TABLE 2 HSIP vs. Simulated Faulting, mm

HSIP 28330									
Reference Faulting	50 mph		60 mph		70 mph		Average Faulting	Maximum Range	|Bias |
	Mean	Range	Mean	Range	Mean	Range			
13.00	13.13	0.27	13.15	0.19	13.24	0.05	13.17	0.27	0.17
11.89	12.27	0.00	12.29	0.17	12.43	0.04	12.33	0.17	0.44
10.07	10.27	0.33	10.13	0.65	10.49	0.21	10.30	0.65	0.23
7.00	7.13	0.18	7.43	0.52	7.30	0.08	7.29	0.52	0.29
5.05	5.12	0.15	5.18	0.12	5.28	0.17	5.19	0.17	0.15
2.01	2.20	0.23	2.31	0.40	2.51	0.09	2.34	0.40	0.34
0.92	1.21	0.20	1.33	0.07	1.44	0.21	1.33	0.21	0.42

TABLE 3 HSIP Simulated Faulting Precision

Precision, mm	
Accuracy	Repeatability
0.60	0.65

TABLE 4 HSIP Joint Detection Matrix

Existing Joints	Average HSIP Detected Joints									
	29748		29863		30330		30781		30392	
	P	N	P	N	P	N	P	N	P	N
True	41	9	42	8	40	10	37	13	47	3
False	9	0	8	0	8	0	7	0	16	0
True Positive Rate (%)	82		84		80		74		94	

P= Positive; N= Negative

TABLE 5 SR 331 Faulting Summary, mm

HSIP	Manual Faulting	Automated Faulting	Bias	St Dev
29748	2.1	2.0	0.9	0.18
29863	2.2	1.7	0.9	0.33
30330	2.2	1.9	1.0	0.34
30781	2.0	1.9	1.0	0.37
30392	2.2	1.6	1.0	0.25

TABLE 6 HSIP Automated Faulting Precision

Precision (mm)		
Accuracy	Repeatability	Reproducibility
1.2	1.1	0.5