Feasibility Study of Measuring Concrete Joint Faulting Using 3D Continuous Pavement Profile Data

Yichang (James) Tsai
Associate Professor
School of Civil and Environmental Engineering
Georgia Institute of Technology
210 Technology Cir. Savannah, GA 31407
Phone: (912) 963-6977 Fax: (912)966-7929
Email: james.tsai@ce.gatech.edu

Yiching Wu (corresponding author)
Research Engineer
School of Civil and Environmental Engineering
Georgia Institute of Technology
210 Technology Cir. Savannah, GA 31407
Phone: (912) 965-6264 Fax: (912)966-7929
Email: yw23@mail.gatech.edu

Chengbo Ai
Graduate Student
School of Civil and Environmental Engineering
Georgia Institute of Technology
210 Technology Cir. Savannah, GA 31407
Phone: (912) 965-6264Fax: (912)966-7929
Email: chengbo.ai@gatech.edu

Submission Date: 08/01/2010
Word Count: 3,738
Tables and Figures: 12
Total: 3,738+12 × 250 =6,738

ABSTRACT

Faulting is one of the important performance measurements for jointed concrete pavements, as it has a direct impact on ride quality. Faulting has traditionally been measured manually using hand-held devices, such as the Georgia fault meter. However, manually measuring faulting on the roadways is labor intensive, time-consuming, and hazardous to workers and drivers. There is a need to develop alternative methods for effectively and safely collecting faulting data on each joint at highway speed. This paper proposes a new method to collect faulting data at highway speed using the 3D continuous pavement profile data acquired with emerging 3D laser technology and assesses its feasibility in field tests. While 3D continuous pavement profile data is initially used to detect asphalt pavement cracking and rutting, this paper further explores its use on concrete faulting measurement. Controlled field tests were conducted using artifacts with known elevation differences, and results show the proposed method can achieve desirable accuracy and repeatability with an absolute difference of 0.25 mm (0.02 inches) and a standard deviation less than 0.7 mm (0.003 inches). Field tests were conducted on 15 joints on Interstate 16 (I-16) in Georgia, and preliminary results show that operating the proposed system at highway speeds (e.g. 100 km/hr) is feasible and has reasonable repeatability. Two tests have demonstrated the proposed method is very promising for providing an alternative solution to collect joint faulting data at highway speed. Recommendations for future research are also discussed.

INTRODUCTION

Faulting is the differential vertical displacement of the slab edge across a transverse joint caused by inadequate load transfer, differential deflection at the joint, inadequate base support, and sub-base erosion *(1)*. The difference in elevation affects the ride quality, accelerates vehicle damage, and leads to distresses, such as corner breaks and blowups. Thus, faulting is one of the important performance measurements for jointed concrete pavements and has an impact on pavement life-cycle cost and vehicle operation cost *(2)*. In addition, state highway agencies are now required to collect faulting data under the new Highway Performance Monitoring System (HPMS) reassessment *(3)*. This strongly motivates state DOTs to look for cost-effective means to collect faulting data.

Manual methods have been used to collect joint faulting data. The Georgia fault meter, designed by the Georgia Department of Transportation (GDOT), is one of the most popular hand-held devices used by many state highway agencies, including GDOT *(4)* and the Minnesota Department of Transportation (MnDOT) *(5)*.The surveyor sets the fault meter at a single spot along the joint designated by the agencies (e.g. GDOT sets the meter approximately 15 cm (6 inches) from the pavement edge marking in the outside lane) with the lag on the leave side of the joint and the measuring probe contacting the slab on the approach side, as shown in Figure 1. The surveyor pushes the button to acquire a faulting measurement and records it manually. However, this manual operation is labor-intensive, time-consuming, costly, and dangerous to workers and drivers. Thus, the manual survey is often conducted only on sample joints and does not cover all the joints on jointed concrete pavements.

(a) The Georgia fault meter (b) Manually measure faulting on the roadway

Figure 1 Manually collect faulting data using the Georgia fault meter.

Some state highway agencies have collected faulting data using point-based laser profilers; however, some of the agencies professed little confidence in the data collected as faulting measurement is reported using vendor's protocol *(6)*. The Florida Department of Transportation (FDOT) uses automated faulting measurement at the network level *(7)*. FDOT has developed an algorithm that uses point-based laser profiler data for identifying the joint locations and for calculating faulting based on AASHTO R 36-04 *(8)*. Note that there is a difference between the footprint used in AASHTO R 36-04 (i.e. 300 mm, approximately 12 inches, between two measurement points) and the one in the Georgia fault meter, which covers only 50 mm (2 inches). FDOT collects a single profile on the right-wheel path with a 15-mm (0.6-inch) laser point spacing at 96 km/hr (60 mph) for faulting measurement. The test result shows 95% of the joints can be identified using a 15-mm (0.6-inch) laser point spacing, with a chance of missing 5% of joints *(7)*. It is noted that the probability of missing joints increases as the laser point spacing increases.

With the advancement in laser technology, 3D continuous pavement profiles with a 1-mm (0.04-inch) resolution can describe pavement surface in detail. The objective of this study is to assess the feasibility of using 3D continuous pavement profiles for collecting faulting data. The 3D continuous pavement profile data is initially used for detecting cracks and rutting on the asphalt pavements. This study further explores its use on concrete faulting measurement. The 3D continuous pavement profile data with a 1-mm resolution in transverse direction, instead of a 15-mm (0.6-inch) point laser spacing using a point-based laser profiler, will not miss a transverse joint. It has the potential to evaluate elevation differences at multiple points across the full lane width rather than just a single point. This paper is organized as follows. The first section briefly reviews existing methods for collecting faulting data and identifies the need for an alternative means to collect faulting data cost effectively. The second section briefly introduces the 3D continuous profile data and the proposed method. The third section presents the controlled field tests and field tests that evaluate the feasibility of the proposed method. Finally, conclusions and recommendations for future research are discussed.

ACQUISITION OF 3D CONTINUOUS PAVEMENT PROFILE DATA

This section presents the 3D continuous pavement profile data acquired using Georgia Tech's sensing system integrated with emerging laser technology that can collect faulting data at highway speed. The integrated sensing system includes a full-size van equipped with a laser crack measurement system (LCMS) and a high resolution distance measurement instrument (DMI), as shown in Figure 2. The LCMS sensors are mounted on the back of the van to acquire 3-D continuous transversal profiles, and the high resolution DMI is mounted on the rear wheel to control the interval between two consecutive transversal profiles. The LCMS sensors are designed to have a tilt angle to the transversal direction, so they can collect the faulting on the transverse joint. This design is to prevent the acquired profiles from aligning with the transverse joints. Designed of a 12-degree clockwise tilt angle and a 1-mm (0.04-inch) resolution, the transverse profiles will always intersect with the joint, as illustrated in Figure 3. With a design of a 12-degree tilt angle and a 4.6-mm (0.18-inch) interval, approximately 165 profiles can be collected from a standard lane width of 3.65 m (12 feet). Both the tilt angel and interval can be adjusted. As the angle increases, the number of profiles intersecting with the joints will decrease. The interval between the transverse profiles is controlled by a high resolution DMI. In our sensing van, the high resolution DMI used can provide an interval of 4.6 mm (0.18-in.) between consecutive profiles.

Figure 2 The sensing van for collecting faulting data.

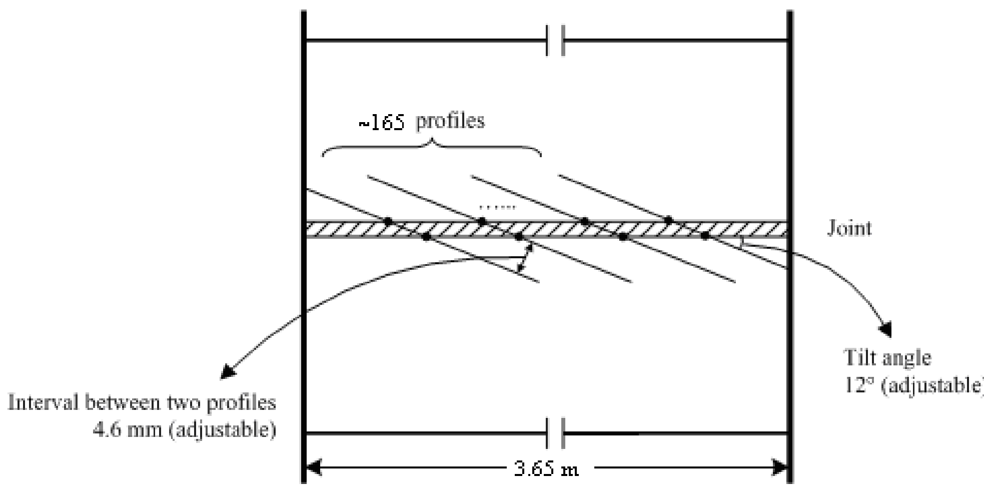


Figure 3 Illustration of the alignment of the 3D continuous laser profiles.

The LCMS, developed by INO, uses laser line projectors, high speed scanning cameras, and customized optics to acquire high resolution 3D profiles and 2D intensities of the pavement surface. The principle of the LCMS sensor is structured light *(9)*. The laser line projector in the LCMS produces a continuous fine laser line, and the laser line is modulated by the pavement surface. The time-delay integration (TDI) camera in the LCMS captures the modulated laser line. Based on the triangulation of the laser and the camera, the range measurements are extracted. The high resolution camera, 4,160 pixels in the transverse direction, used in the LCMS provides the 1-mm (0.04-inch) resolution in the transverse direction (x-axis). It also provides at least 0.5-mm (0.02-inch) resolution in the vertical direction (z-axis), which motivates us to use this data to measure joint faulting. The LCMS can produce as many as 5,600 profiles per second (56 KHz); therefore, triggered by the high resolution DMI, the 3D laser system can acquire profiles with an interval of 4.6 mm (0.18 inches) in longitudinal direction (y-axis) when using a speed of 92 km/hr (57.5 mph). The system can acquire more than 23 million 3D data points per second to describe the pavement surface in detail. Figure 4 shows an example of the acquired faulting data. Figure 4(a) shows a 2D image of the joint, and the corresponding 3D data is shown in Figure

4(b). The joint can be captured in an individual profile as shown in Figure 4(c). This 3D continuous pavement profile can be used to derive the elevation difference between two concrete slabs. The following section presents the preliminary tests conducted to evaluate the feasibility of collecting faulting data using 3D continuous profile data at highway speed.

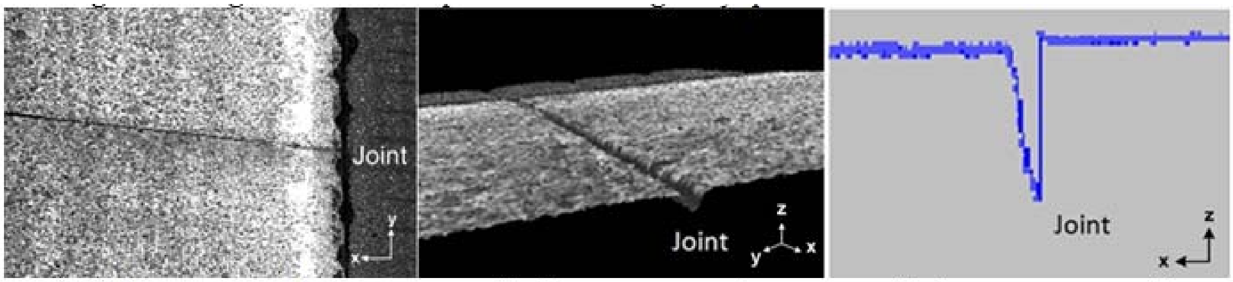


Figure 4 An example of the data collected by the integrated sensing system.

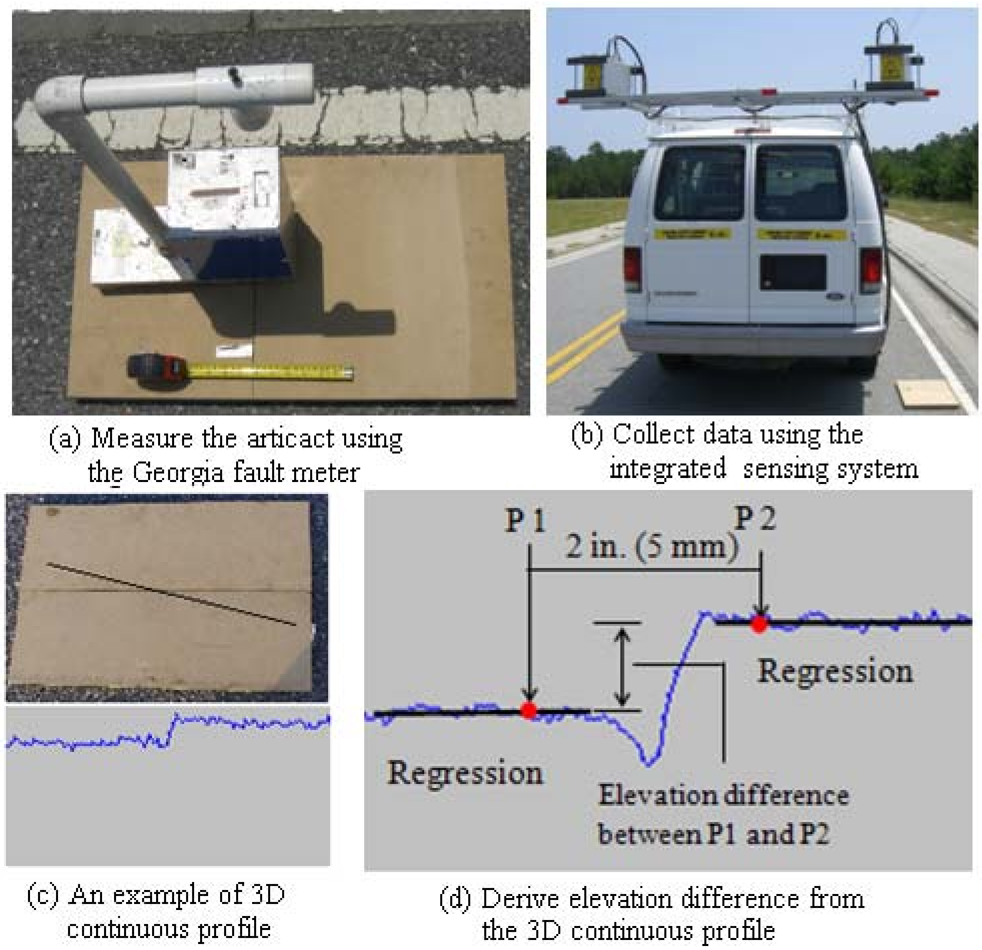
EXPERIMENTAL TESTS

The objective of the experimental tests is to evaluate the feasibility of collecting faulting data using the integrated sensing system. First, controlled field tests were conducted to evaluate the accuracy and repeatability of the elevation difference derived from the 3D continuous profiles using the artifacts made with various known elevation differences as ground truth. Second, field tests were conducted on 15 joints on concrete pavement sections on Interstate (I-16) in Georgia to evaluate the repeatability of the derived faulting and to evaluate the integrated sensing system at highway speed.

Controlled Field Test

Controlled field tests were designed to evaluate the accuracy and repeatability of the elevation difference derived using the proposed method in a well-controlled environment. The artifacts, made of two wood panels creating two flat surfaces with known elevation differences, were used to test the proposed method. The elevation differences range from 1/32 to 19/32 inches, which are the range in the Georgia fault meter. The artifacts were set level on a fairly flat road on the Georgia Tech campus to ensure a consistent elevation difference between any two points on the two panels. The known elevation differences were also confirmed by using the Georgia fault meter on the test site, as shown in Figure 5(a). The integrated sensing system was then used to collect 3D continuous pavement profile data with a 1-mm (0.04-inch) resolution in the transverse direction and a 4.6-mm (1.8-inch) interval (space between two profiles) at low speed, as shown in Figure 5(b). With a 12-degree tilt angle design, approximately 17 profiles were collected along the 38-cm (15-inch) wide wood panel. Figure 5(c) shows one of the 3D continuous pavement profiles that can be used to derive the elevation difference. The elevations of the two flat surfaces can be established by applying regression to the points representing the surface, as shown in Figure 5(d). The elevations of two measurement points (P1 and P2 in Figure 5(d)), separated by 50 mm (2 inches), are estimated using the regression lines, and then the elevation difference can be calculated.

The accuracy and repeatability of the derived elevation differences were then evaluated by comparing the derived and the known elevation differences. Figure 6 shows the derived elevation differences are close to the known elevation differences with small variation. Table 1 summarizes the comparison. The average absolute differences are within 1 mm (0.04 inches), and the variances are fairly small (less than 1 mm) and consistent across various elevation differences. It is noted the derived faulting measurements are slightly higher than the known elevation differences. The 1/32-inch (0.8-mm) elevation difference may not be detected reliably because the resolution. The results of controlled field tests have demonstrated the proposed method can achieve a desirable 1-mm accuracy required in AASHTO R 36-04 and reasonable repeatability for measuring elevation differences.



(a) Measure the articact using the Georgia fault meter

(b) Collect data using the integrated sensing system

(c) An example of 3D continuous profile

(d) Derive elevation difference from the 3D continuous profile

Figure 5 Controlled field test for measuring known elevation differences.

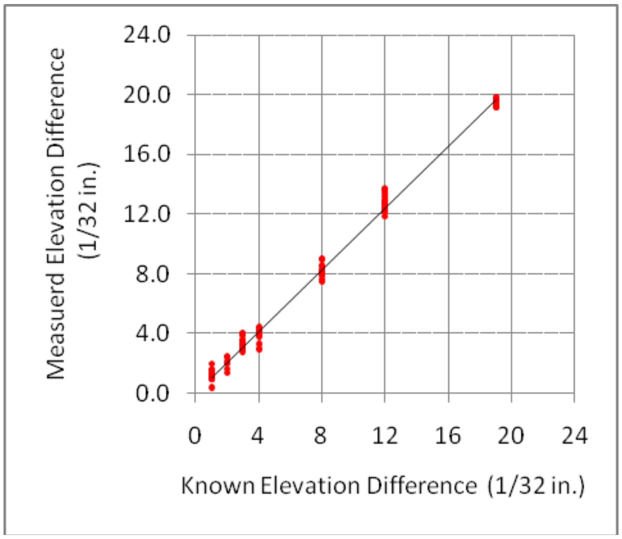


Figure 6 Known elevation differences vs. derived elevation differences.

Table 1 Summary Statistics for the Elevation Differences

Known Elevation Difference		Derived Elevation Difference				
(1/32 in.)	(mm)	Mean (mm)	Difference (mm)	Absolute Difference (mm)	Standard Deviation (mm)	Coefficient of Variance
1/32 in	0.8	1.0	0.2	0.2	0.3	0.27
2/32 in	1.6	1.6	0.0	0.3	0.3	0.21
3/32 in	2.4	2.7	0.3	0.3	0.3	0.12
4/32 in	3.2	3.1	-0.1	0.3	0.4	0.13
8/32 in	6.4	6.5	0.1	0.3	0.4	0.06
12/32 in	9.5	10.1	0.6	0.6	0.4	0.04
19/32 in	15.1	15.5	0.4	0.4	0.2	0.01

Field Test on Interstate I-16

Field tests were conducted on I-16 to evaluate the repeatability of faulting derived from 3D continuous profile data and the feasibility of operating the integrated sensing system at highway speed. After discussing the issues with GDOT's engineer and reviewing 2010 concrete pavement survey report generated by GDOT, a 450-feet test section, covering 15 joints, on the eastbound of I-16 between milepoints 154 and 155, was selected because of the sampled faulting reported on the section. The slabs are 9-m (30-feet) long and 3.65-m (12-feet) wide. Figure 7 illustrates the procedures undertaken during field tests. The 15 slabs were first labeled with a sequential number and a point where the faulting is measured based on GDOT's faulting measurement practice *(4)* is marked, as shown in Figure 7(a). The marked point is approximately 15 cm (6 inches) from the pavement edge marking. The integrated sensing system was then used to collect faulting data at two different highway speeds, 100 km/h and 80 km/h (62.5 mph and 50 mph), as shown in Figure 7(b). Figure 7(c) shows an example of the profiles collected on I-16. It is clear that the joint can be captured by the 1-mm (0.04-inch) resolution profile. Three runs were repeated at each speed to evaluate the repeatability of derived faulting measurements and the feasibility of operating the integrated sensing system at highway speed. The 3D continuous pavement profile at the marked point was retrieved, and faulting was derived using the same method described in the controlled field test section. Again, the faulting is measured as the elevation differences between two measurement points on two sides of the joint separated by 50 mm (2 inches). It is noted that the profile data shows a small slope on the slab. Field tests were conducted on a sunny day, and the data was collected in early morning to minimize the effects of curling and warping.

(a) Label and mark the joint (b) Collect faulting data on I-16 (c) An example of the profiles collected on I-16

Figure 7 Field test conducted on I-16.

Faulting measurements of the 15 joints derived using the proposed method was used to evaluate the repeatability of the derived faulting measurements and the feasibility of operating the system at highway speed. Table 2 summarizes the derived faulting measurements on the 15 joints collected on I-16 at different speeds. The derived faulting measurements range from 1.2 mm to 9.4 mm (0.05 inches to 0.37 inches). First, the repeatability of the derived faulting measurements collected in three runs at each speed is evaluated. Figures 8 and 9 show the derived faulting measurements from three runs at 80 km/hr and 100 km/hr, respectively. There is no significant difference observed among different runs. The standard deviations are within 1 mm as shown in Table 2. The maximum differences among three runs are also reviewed. For the data collected at 100 km/hr, 13 out of 15 joints (87%) have a max difference less than 1 mm (0.04 inches). Results indicate the derived faulting measurements can achieve a desirable repeatability among different runs at the same speed. Second, the derived faulting measurements are compared at different speeds. Figure 10 shows the derived faulting measurements are fairly close at different speeds. The differences are within 1 mm (0.04 inches) as shown in Table 2. Based on the analyses, the proposed method can achieve a desirable repeatability among different runs and at different speeds, and it is feasible to operation the integrated sensing system at highway speed (e.g. 100 km/hr) for collecting faulting data.

Based on lab tests and field tests conducted on I-16, the preliminary results have demonstrated that it is feasible to collect faulting data with desirable accuracy at highway speed from a 3D continuous profile acquired using the integrated sensing system. In addition, the integrated sensing system is capable of collecting multiple profiles along a transverse joint; therefore, the faulting measurements on multiple points along the joint can be depicted in detail. The detailed information allows the engineer to identify the locations with abnormal high faulting and/or uneven faulting that require further investigation.

Table 2 Statistics of Derived Faulting Measurement on 15 Slabs by Speeds

Slab		80 km/hr		100 km/hr			80 km/hr – 100 km/hr	
	Mean (mm)	Max. Diff. (mm)	St. Dev. (mm)	Mean (mm)	Max. Diff. (mm)	St. Dev. (mm)	Diff. (mm)	Abs. Diff. (mm)
1	3.9	0.3	0.2	4.6	0.6	0.3	-0.6	0.6
2	1.2	0.6	0.3	1.6	0.4	0.2	-0.5	0.5
3	2.1	0.9	0.5	1.5	0.6	0.3	0.6	0.6
4	6.0	0.6	0.3	6.1	1.8	0.9	-0.1	0.1
5	4.2	0.2	0.1	3.3	0.2	0.1	0.9	0.9
6	4.6	0.2	0.1	4.9	0.6	0.3	-0.3	0.3
7	5.6	0.8	0.4	5.5	0.2	0.1	0.1	0.1
8	2.6	1.1	0.6	2.7	0.4	0.2	-0.1	0.1
9	2.8	1.5	0.8	2.8	0.9	0.4	0.0	0.0
10	3.2	0.9	0.4	2.6	0.6	0.3	0.5	0.5
11	4.7	0.8	0.4	4.9	0.6	0.3	-0.2	0.2
12	2.8	1.1	0.6	3.0	0.6	0.3	-0.2	0.2
13	3.0	1.6	0.9	2.8	0.3	0.1	0.1	0.1
14	2.9	1.1	0.6	3.5	1.5	0.8	-0.5	0.5
15	9.4	1.0	0.5	9.1	0.2	0.1	0.3	0.3

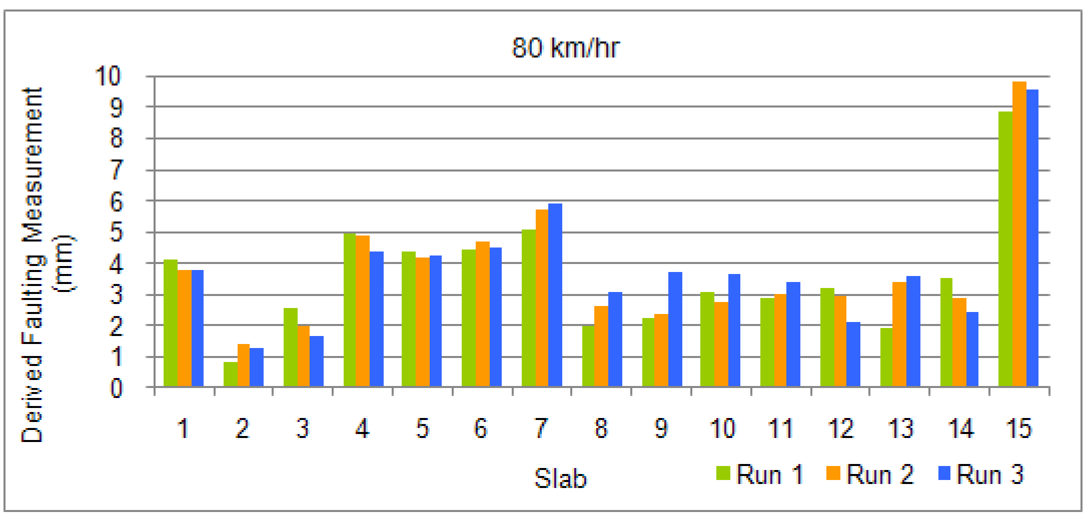


Figure 8 Derived faulting measurements at 80 km/hr.

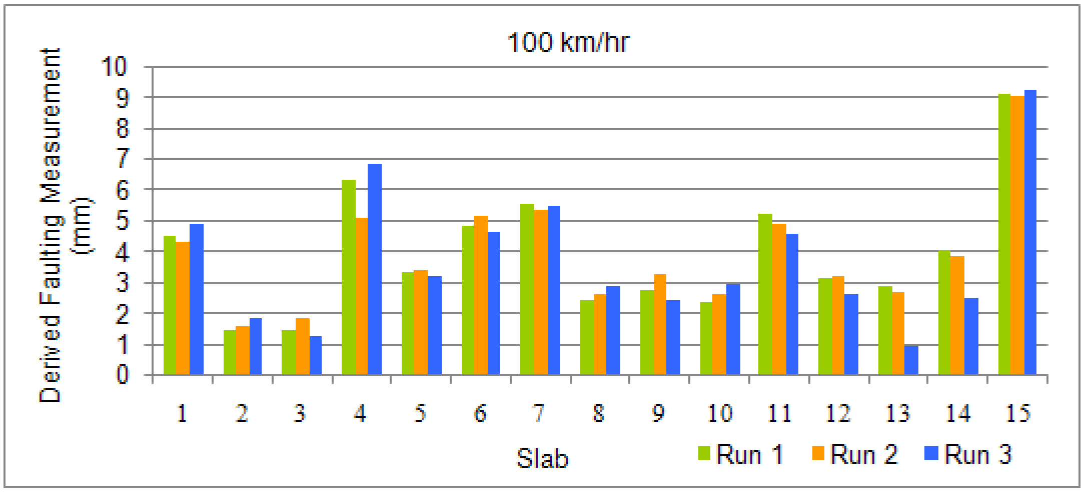


Figure 9 Derived faulting measurements at 100 km/hr.

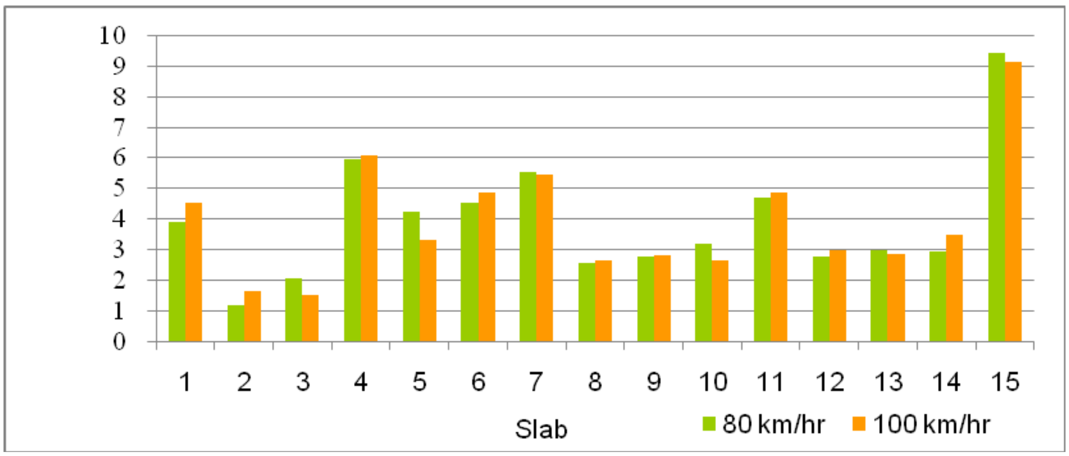


Figure 10 Derived faulting measurements at 100 km/hr.

CONCLUSIONS AND RECOMMENDATIONS

Faulting is one of the important performance measurements for jointed concrete pavements. Based on the new requirement under the HPMS reassessment, state DOTs are required to collect faulting data on jointed concrete pavements. Collecting faulting data using manual methods, such as the Georgia fault meter, is time-consuming, labor intensive, and hazardous to workers and drivers. There is a need to explore alternative means to collect faulting data effectively and safely. This study explores the feasibility of collecting faulting data using 3D continuous profile data, which is initially used to detect asphalt pavement cracking and rutting. A new method is proposed to collect faulting data using 3D continuous profiles acquired using an integrated sensing system equipped with emerging 3D laser technology. Both controlled field tests and field tests on I-16 were conducted to evaluate the feasibility of collecting faulting data using the proposed method. Controlled field tests with known elevation differences conducted under a well-controlled environment show that the proposed method can measure the elevation difference with an error less than 1 mm. The preliminary results of the field tests on I-16 have also demonstrated the proposed method is repeatable with a deviation of 1 mm with three runs at each speed for two different speeds, 100 km/hr and 80 km/hr (62.5 mph and 50 mph). In addition, the tests have demonstrated that it is feasible to operate the integrated sensing system at a highway speed of 100 km/hr (62.5 mph), and the system can be operated at a higher speed with some minor parameter adjustments. Instead of collecting faulting data at a single point on a joint, the proposed method is capable of collecting faulting data at multiple points in a joint to characterize the spatial distribution of elevation difference along a joint. In summary, the preliminary results have demonstrated the proposed method is very promising for collecting faulting data and can provide added value to the 3D continuous pavement profile data. The following are recommended future research to further explore the potential of 3D continuous profiles acquired using the emerging 3D laser technology:

1. A comprehensive validation using a larger set of joints with various faulting depth and surface finishing is needed to critically assess the proposed method and to identify the issues in implementation, such as the impacts of different footprints on the faulting measurement under various conditions (e.g. vertical grade and cross slope).
2. A signal processing algorithm can be developed to automatically detect joint and to measure faulting.
3. Further studies can be conducted to explore the use of the faulting measurements acquired at multiple points along a transverse joint, such as monitoring curling, to improve the understanding of concrete pavement behavior.

ACKNOWLEDGMENTS

Georgia Tech research team would like to acknowledge the assistance of Mr. Eric Pitts, state maintenance engineer and Mr. Curtis Grovner, the liaison of concrete condition evaluation of the Georgia Department of Transportation (GDOT) for collecting the 3D laser profile data on I-16 in Georgia. In addition, the authors would like to thank Mr. Abdenour Nazef from the Florida Department of Transportation (FDOT), Mr. James Watkins from the Mississippi Department of Transportation (MDOT), and Mr. Rick Miller from the Kansas Department of Transportation (KDOT) for their inputs.

REFERENCES

1. *Guidelines for Routine Maintenance of Concrete Pavements*, Texas Transportation Institute, College Station, Texas, 2008.
2. *Integrated Materials and Construction Practices for Concrete Pavement: A State-of-the Practice Manual.* FHWA Publication No. HIF-07-004. FHWA, U.S. Department of Transportation, Dec. 2006.
3. *HPMS Reassessment 2010+ Final report*, Federal Highway Administration, 2008.
4. *Concrete Pavement Condition Survey Instructional Manual*, Georgia Department of Department, Atlanta, GA, 2004.
5. Burnham, T., *PCC Joint Faulting Measurements at the Mn/ROAD Project*, Minnesota Department of Transportation, 2003.
6. McGhee, K.H., *NCHRP SYNTHESIS 334: Automated Pavement Distress Collection Techniques.* Transportation Research Board of the National Academies, Washington, D.C 2004.
7. Nazef, A., Mraz, A., Lyer, S., and Choubane, B., *Semi-Automated Faulting Measurement for Rigid Pavements*, in *Transportation Research Record: Journal of the Transportation*

Research Board, No. 2094, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 121-137.

8. *Standard Practice for Evaluating Faulting of Concrete Pavements AASHTO Designation: R 36-04 (2009)*, AASHTO, 2009.
9. Fofi, D., Sliwa, T., and Voisin, Y. *A comparative survey on invisible structured light*. 2004. San Jose, CA, USA: SPIE.