1 **Feasibility Study of Measuring Concrete Joint Faulting Using 3D Continuous Pavement**
2 **Profile Data**
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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 less than 0.6 mm (0.024 inches) and a standard deviation of less than 0.4 mm (0.016 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

1 Faulting is the differential vertical displacement of the slab edge across a transverse joint caused
2 by inadequate load transfer, differential deflection at the joint, inadequate base support, and sub-
3 base erosion *(1)*. The difference in elevation affects the ride quality, accelerates vehicle damage,
4 and leads to distresses, such as corner breaks and blowups. Thus, faulting is one of the important
5 performance measurements for jointed plain concrete pavements and has an impact on pavement
6 life-cycle cost and vehicle operation cost *(2)*. In addition, state highway agencies are now
7 required to collect faulting data under the new Highway Performance Monitoring System
8 (HPMS) reassessment *(3)*. This strongly motivates state DOTs to look for cost-effective means to
9 collect faulting data.
10
11   Manual methods have been used to collect faulting data. The Georgia fault meter,
12 designed by the Georgia Department of Transportation (GDOT), is one of the most popular
13 hand-held devices used by many state highway agencies, including GDOT *(4)* and the Minnesota
14 Department of Transportation (MnDOT) *(5)*. The surveyor sets the fault meter at a single spot
15 along a designated joint with the lag on the departure slab and the measuring probe contacting
16 the approach slab, as shown in Figure 1. For example, GDOT requires the meter to be set
17 approximately 15 cm (6 inches) from the pavement edge marking in the outside lane. The
18 surveyor pushes the button to acquire a faulting measurement and records it manually. However,
19 this manual operation is labor-intensive, time-consuming, costly, and dangerous to both the
20 surveyors and drivers. Thus, the manual survey is often conducted only on sampled joints and
21 does not cover all the joints.
22
23

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

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

27   Some state highway agencies have collected faulting data using point-based laser
28 profilers; however, some of the agencies professed little confidence in the data collected, as
29 faulting measurement is reported using vendor's protocol *(6)*. The Florida Department of
30 Transportation (FDOT) uses automated faulting measurement at the network level *(7)*. FDOT
31 has developed an algorithm that uses point-based laser profiler data for identifying the joint
32 locations and for calculating faulting based on AASHTO R 36-04 *(8)*. Note that there is a
33 difference between the footprint used in AASHTO R 36-04 (i.e. 300 mm, approximately 12
34 inches, between two measurement points) and the one in the Georgia fault meter, which covers

1   only 50 mm (2 inches). FDOT collects a single profile on the right-wheel path with a 15-mm
2   (0.6-inch) laser point spacing at 96 km/hr (60 mph) for faulting measurement. The test result
3   shows 95% of the joints can be identified using a 15-mm (0.6-inch) laser point spacing, with a
4   chance of missing 5% of joints *(7)*. It is noted that the probability of missing joints increases as
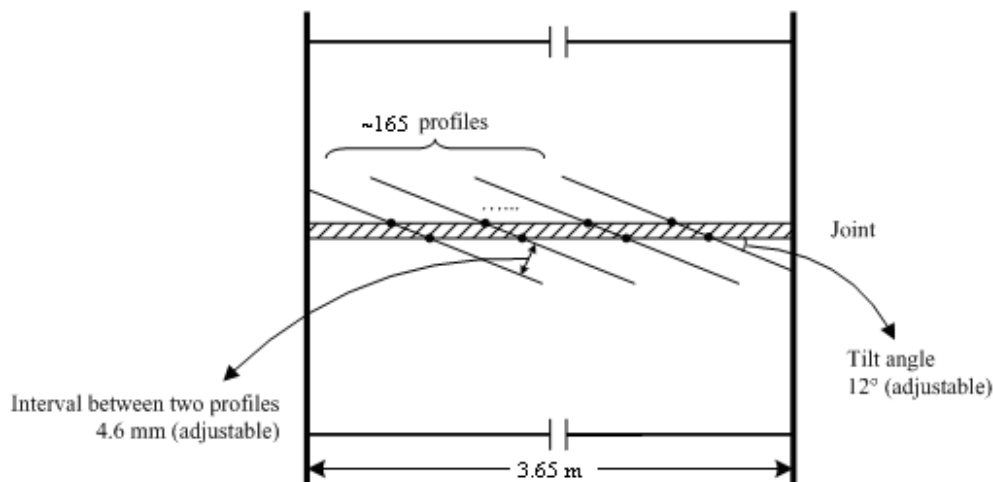5   the laser point spacing increases.
6   With the advancement in laser technology, 3D continuous pavement profiles with a 1-
7   mm (0.04-inch) resolution can describe pavement surface in detail. The objective of this study is
8   to assess the feasibility of using 3D continuous pavement profiles for collecting faulting data.
9   The 3D continuous pavement profile data is initially used for detecting cracks and rutting on the
10   asphalt pavements. This study further explores its use on concrete faulting measurement. The 3D
11   continuous pavement profile data with a 1-mm resolution in transverse direction, instead of a 15-
12   mm (0.6-inch) point laser spacing using a point-based laser profiler, will not miss a transverse
13   joint. It has the potential to evaluate elevation differences at multiple points across the full lane
14   width rather than just a single point. This paper is organized as follows. The first section briefly
15   reviews existing methods for collecting faulting data and identifies the need for an alternative
16   means to collect faulting data cost effectively. The second section briefly introduces the 3D
17   continuous profile data and the proposed method. The third section presents the controlled field
18   tests and field tests that evaluate the feasibility of the proposed method. Finally, conclusions and
19   recommendations for future research are discussed.
20
21   **ACQUISITION OF 3D CONTINUOUS PAVEMENT PROFILE DATA**
22   This section presents the 3D continuous pavement profile data acquired using Georgia Tech's
23   sensing system integrated with emerging laser technology that can collect faulting data at
24   highway speed. The integrated sensing system includes a full-size van equipped with a laser
25   crack measurement system (LCMS) and a high resolution distance measurement instrument
26   (DMI), as shown in Figure 2. The LCMS sensors are mounted on the back of the van to acquire
27   3-D continuous transversal profiles, and the high resolution DMI is mounted on the rear wheel to
28   control the interval between two consecutive transversal profiles. The LCMS sensors are
29   designed to have a tilt angle to the transversal direction, so they can collect the faulting on the
30   transverse joint. This design is to prevent the acquired profiles from aligning with the transverse
31   joints. Designed at a 12-degree clockwise tilt angle and a 1-mm (0.04-inch) resolution, the
32   transverse profiles will always intersect with the joint, as illustrated in Figure 3. With a design of
33   a 12-degree tilt angle and a 4.6-mm (0.18-inch) interval, approximately 165 profiles can be
34   collected from a standard lane width of 3.65 m (12 feet). Both the tilt angle and interval can be
35   adjusted. As the angle increases, the number of profiles intersecting with the joints will decrease.
36   The interval between the transverse profiles is controlled by a high resolution DMI. In our
37   sensing van, the high resolution DMI used can provide an interval of 4.6 mm (0.18-inch.)
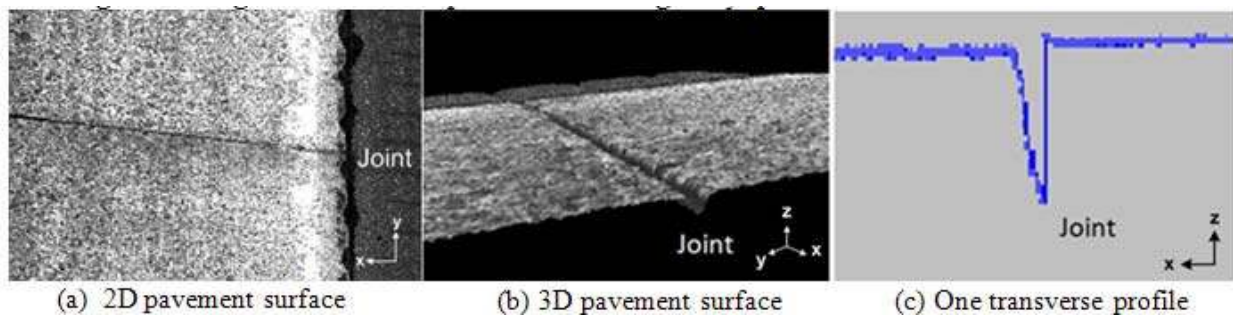38   between consecutive profiles.
39

1
2   **Figure 2 The sensing van for collecting faulting data.**
3

4
5   **Figure 3 Illustration of the alignment of the 3D continuous laser profiles.**
6
7   The LCMS, developed by INO, uses laser line projectors, high speed scanning cameras,
8   and customized optics to acquire high resolution 3D profiles and 2D intensities of the pavement
9   surface. The principle of the LCMS sensor is structured light *(9)*. The laser line projector in the
10   LCMS produces a continuous fine laser line, and the laser line is modulated by the pavement
11   surface. The time-delay integration (TDI) camera in the LCMS captures the modulated laser line.
12   Based on the triangulation of the laser and the camera, the range measurements are extracted.
13   The high resolution camera, 4,160 pixels in the transverse direction, used in the LCMS provides
14   the 1-mm (0.04-inch) resolution in the transverse direction (x-axis). It also provides at least 0.5-
15   mm (0.02-inch) resolution in the vertical direction (z-axis), which motivates us to use this data to
16   measure joint faulting. The LCMS can produce as many as 5,600 profiles per second (5.6 KHz);
17   that is one transverse profile in179 μs (10^{-6} second). At this high frequency, the effect of vehicle
18   pitching motion, often at a lower frequency (e.g. 40 Hz), will be minimal. Triggered by the high
19   resolution DMI, the 3D laser system can acquire profiles with an interval of 4.6 mm (0.18
20   inches) in longitudinal direction (y-axis) when using a speed of 92 km/hr (57.5 mph). The system
21   can acquire more than 23 million 3D data points per second to describe the pavement surface in

1   detail. Figure 4 shows an example of the acquired faulting data. Figure 4(a) shows a 2D image of
2   the joint, and the corresponding 3D data is shown in Figure 4(b). The joint can be captured in an
3   individual profile, as shown in Figure 4(c). This 3D continuous pavement profile can be used to
4   derive the elevation difference between two concrete slabs. The following section presents the
5   preliminary tests conducted to evaluate the feasibility of collecting faulting data using 3D
6   continuous profile data at highway speed.
7

8   (a) 2D pavement surface   (b) 3D pavement surface   (c) One transverse profile
9   **Figure 4 An example of the data collected by the integrated sensing system.**
10

11 **EXPERIMENTAL TESTS**
12 The objective of the experimental tests is to evaluate the feasibility of collecting faulting data
13 using the integrated sensing system. First, controlled field tests were conducted to evaluate the
14 accuracy and repeatability of the elevation difference derived from the 3D continuous profiles
15 using the artifacts made with various known elevation differences as ground truth. Second, field
16 tests were conducted on 15 joints on concrete pavement sections on Interstate (I-16) in Georgia
17 to evaluate the repeatability of the derived faulting and to evaluate the integrated sensing system
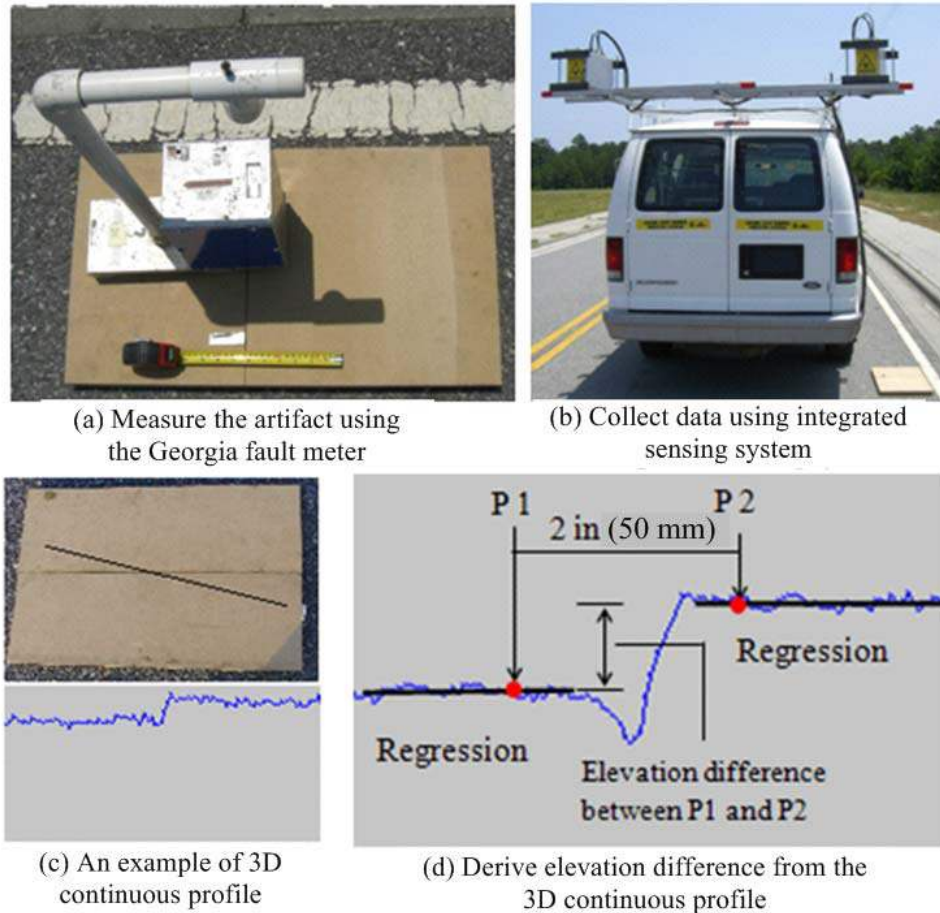18 at highway speed.
19

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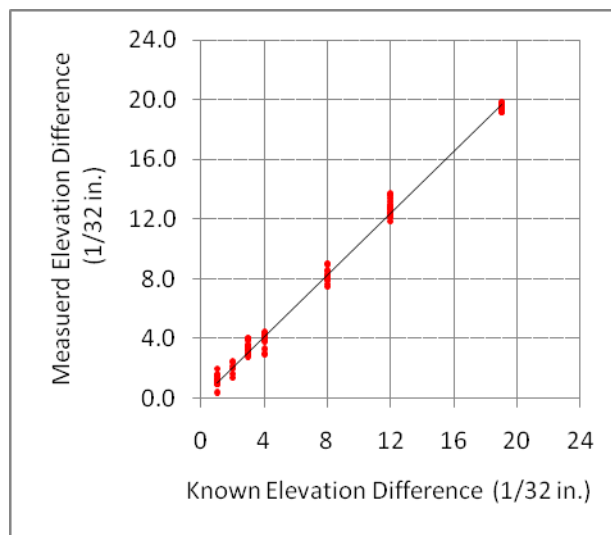37 using the regression lines, and then the elevation difference can be calculated.
38   The accuracy and repeatability of the derived elevation differences were then evaluated

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

(a) Measure the artifact using the Georgia fault meter

(b) Collect data using integrated sensing system

(c) An example of 3D continuous profile

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

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11
12 **Figure 5 Controlled field test for measuring known elevation differences.**
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1
2   **Figure 6 Known elevation differences vs. derived elevation differences.**

3   **Table 1 Summary Statistics for the Elevation Differences**

Known Elevation Difference		Derived Elevation Difference					
(in.)	(mm)	Sample Size	Mean (mm)	Difference (mm)	Absolute Difference (mm)	Standard Deviation (mm)	Coefficient of Variance
1/32	0.8	20	1.0	0.2	0.2	0.3	0.27
2/32	1.6	6	1.6	0.0	0.3	0.3	0.21
3/32	2.4	19	2.7	0.3	0.3	0.3	0.12
4/32	3.2	13	3.1	-0.1	0.3	0.4	0.13
8/32	6.4	15	6.5	0.1	0.3	0.4	0.06
12/32	9.5	20	10.1	0.6	0.6	0.4	0.04
19/32	15.1	20	15.5	0.4	0.4	0.2	0.01

4
5   **Field Test on Interstate I-16**
6   Field tests were conducted on I-16 to evaluate the repeatability of faulting derived from 3D
7   continuous profile data and the feasibility of operating the integrated sensing system at highway
8   speed. After discussing the issues with GDOT's engineer and reviewing 2010 concrete pavement
9   survey report generated by GDOT, a 450-foot test section, covering 15 joints, on the eastbound
10   of I-16 between milepoints 154 and 155, was selected because of the sampled faulting reported
11   on the section. The slabs are 9-m (30-feet) long and 3.65-m (12-feet) wide. Figure 7 illustrates
12   the procedures undertaken during field tests. The 15 slabs were first labeled with a sequential
13   number and a point where the faulting is measured based on GDOT's faulting measurement
14   practice *(4)* is marked, as shown in Figure 7(a). The marked point is approximately 15 cm (6
15   inches) from the pavement edge marking. The integrated sensing system was then used to collect
16   faulting data at two different highway speeds, 100 km/h and 80 km/h (62.5 mph and 50 mph), as
17   shown in Figure 7(b). Figure 7(c) shows an example of the profiles collected on I-16. It is clear
18   that the joint can be captured by the 1-mm (0.04-inch) resolution profile. Three runs were
19   repeated at each speed to evaluate the repeatability of derived faulting measurements and the

1 feasibility of operating the integrated sensing system at highway speed. The 3D continuous
2 pavement profile at the marked point was retrieved manually location measured by the Georgia
3 fault meter, and faulting was derived using the same method described in the controlled field test
4 section. Again, the faulting is measured as the elevation differences between two measurement
5 points on two sides of the joint separated by 50 mm (2 inches), which is consistent with the
6 footprint of the Georgia fault meter. Field tests were conducted on a Sunday morning for safety
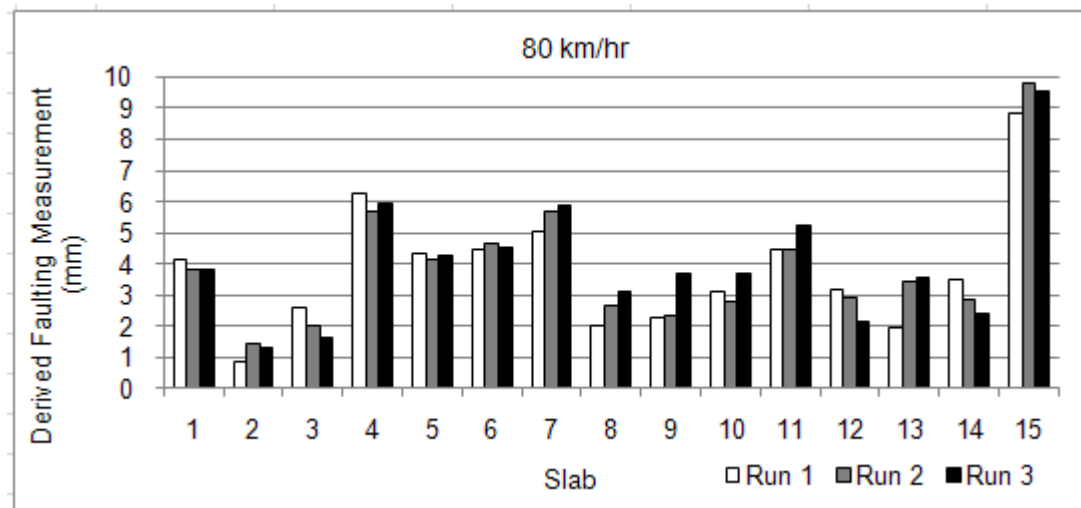7 concern, and the effects of curling and warping was not considered in this study.
8

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

9
10   **Figure 7 Field test conducted on I-16.**
11

12   Faulting measurements of the 15 joints derived using the proposed method was used to
13 evaluate the repeatability of the derived faulting measurements and the feasibility of operating
14 the system at highway speed. Table 2 summarizes the derived faulting measurements on the 15
15 joints collected on I-16 at different speeds. The derived faulting measurements range from 1.2
16 mm to 9.4 mm (0.05 inches to 0.37 inches). First, the repeatability of the derived faulting
17 measurements collected in three runs at each speed is evaluated. Figures 8 and 9 show the
18 derived faulting measurements from three runs at 80 km/hr and 100 km/hr, respectively. There is
19 no significant difference observed among different runs. The standard deviations are within 1
20 mm, as shown in Table 2. The maximum differences among three runs are also reviewed. For the
21 data collected at 100 km/hr, 13 out of 15 joints (87%) have a max difference less than 1 mm
22 (0.04 inches). Results indicate the derived faulting measurements can achieve a desirable
23 repeatability among different runs at the same speed. Second, the derived faulting measurements
24 are compared at different speeds. Figure 10 shows the derived faulting measurements are fairly
25 close at different speeds. The differences are within 1 mm (0.04 inches), as shown in Table 2.
26 Based on the analyses, the proposed method can achieve a desirable repeatability among
27 different runs and at different speeds, and it is feasible to operate the integrated sensing system at
28 highway speed (e.g. 100 km/hr) for collecting faulting data.
29   Based on lab tests and field tests conducted on I-16, the preliminary results have
30 demonstrated that it is feasible to collect faulting data with desirable accuracy at highway speed
31 from a 3D continuous profile acquired using the integrated sensing system. In addition, the
32 integrated sensing system is capable of collecting multiple profiles along a transverse joint;
33 therefore, the faulting measurements on multiple points along the joint can be depicted in detail.
34 The detailed information allows the engineer to identify the locations with abnormally high
35 faulting and/or uneven faulting that require further investigation.
36

1   **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

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4   **Figure 8 Derived faulting measurements at 80 km/hr.**
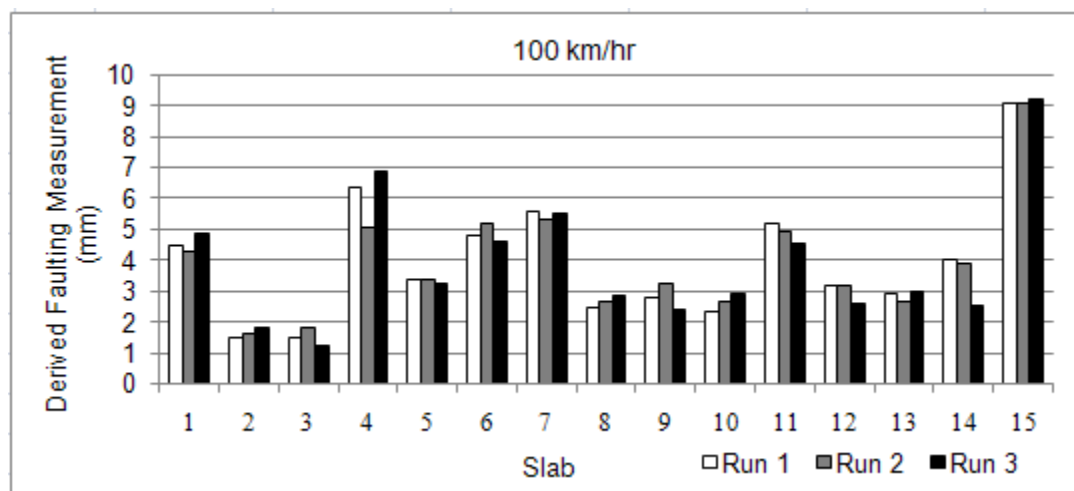
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6

Figure 9 Derived faulting measurements at 100 km/hr.
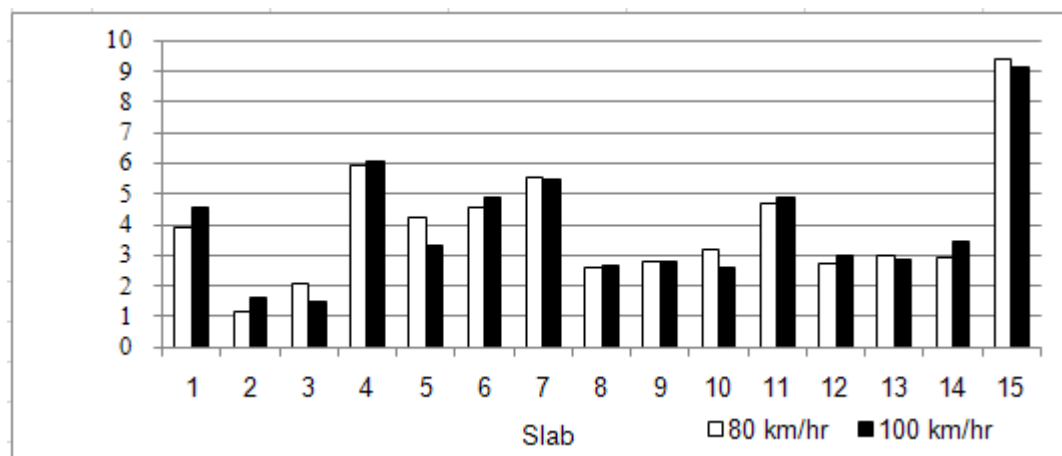

Figure 10 Comparison of faulting measurements at different speeds.

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 for 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 joints 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

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