ASSESSMENT OF RUT DEPTH MEASUREMENT ACCURACY OF POINT-BASED RUT BAR SYSTEMS USING EMERGING 3D LINE LASER IMAGING TECHNOLOGY

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ABSTRACT

Point-based rut bar systems are commonly used by transportation agencies. However, potential measurement errors exist in these systems because of the limited number of sample points (e.g. 3 to 31 points). Now, advanced sensing technology can acquire high-resolution transverse profiles of more than 4,000 points using 3D line laser imaging technology (termed the 3D line laser hereafter). This study, sponsored by the United States Department of Transportation (USDOT) Research and Innovative Technology Administration (RITA) program, is a) to explore the feasibility of using the 3D line laser to accurately and reliably measure rut depth, and b) to quantify the potential rut depth measurement errors using point-based rut bar systems. The rut depth measurement accuracy and repeatability of the 3D line laser were validated in laboratory and field tests. Results show that the absolute rut-depth measurement error is less than 3 mm, and, therefore, the transverse profiles acquired by the 3D line laser can be used to quantitatively evaluate the accuracy and reliability of point-based rut bar systems. Rut bar systems having 3 to 31 sensors were simulated using transverse profiles acquired by the 3D line laser. Test results show that the relative rut-depth measurement error generally decreases with the increasing number of laser sensors. However, the trend is unclear for rut bar systems with fewer sensors because the rut shape affects the rut depth measurement error more than the number of sensors. Thus, a 3-point rut bar system could outperform a 5-point system occasionally. Test results also show that the commonly used 3-point and 5-point rut bar systems can underestimate rut depth by 16% to 51% and 22% to 64%, respectively. The relative rut-depth measurement error is less than 10% only when the number of sensors is greater than 29.

I. INTRODUCTION

Rutting is one of the major asphalt pavement distresses affecting pavement structural integrity and driving safety (Gogoi et al., 2013). Thus, a network-level rutting survey is indispensable in a pavement management system. Rut depth is the indicator used to evaluate the rutting severity. Its measurement accuracy directly impacts the evaluation reliability. As reported by McGhee (McGhee, 2004), point-based rut bar systems are commonly used for rutting surveys in all major transportation agencies in North America. Among 40 state transportation agencies, 16 use 3-point systems, 13 use 5-point systems, and 11 use rut bar systems with sensors varying from 7 to 37. Some agencies that claimed to be using a 37-point system were actually using a 31-point system.

A rut bar system calculates the rut depth based on the 3D range data collected from individual laser sensors. Due to the wandering of a survey vehicle, the rut shape variations, and the limited number of laser sensors, the maximum rut depth will often be underestimated if laser sensors cannot capture the 3D range data where the maximal depth occurs. In addition, a rut bar system cannot cover a full lane because its length is limited to approximately 3 m for safety considerations. The above factors impact the rut depth measurement accuracy of a point-based rut bar system. Studies show that rut depth measurement errors exist in point-based laser systems. For example, Ksaibati (1996) evaluated the rut depths measured by 3-sensor and 5-sensor profilometers and found significant differences between the non-contact and direct-contact
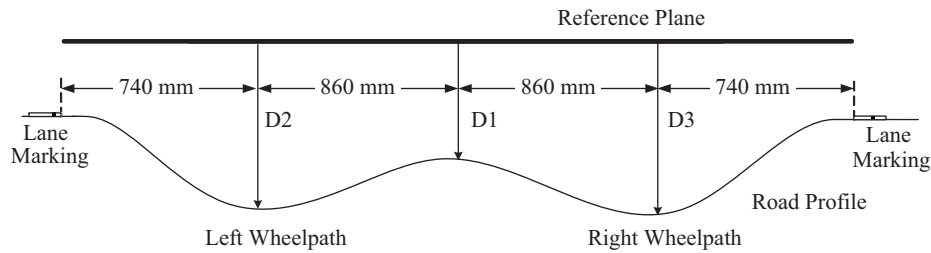
Fig. 1. Sketch of the 3-point rut bar configuration.

measurements. HTC compared the rut depths from a 30-sensor ROMDAS profilometer with field measurements using a 1.5 m straightedge method and identified a bias, which was documented in an internal report of HTC Infrastructure Management Ltd ("validation of ROMDAS transverse profile logger"). Mallela and Wang (2006) assessed the sampling bias of the profilometers operated in New Zealand (with 13 to 30 sensors) and concluded that rut depth measurement of point-based rut bar systems is underestimated. Simpson (2001) determined that the correlation of rut depths measured by a 5-point rut bar and a rod and level elevation survey is approximately 0.4. Thus, the 5-point rut bar system is not reliable with regard to rut depth measurement. In summary, past studies have shown that 3-point and 5-point rut bar systems have poor rut depth measurement accuracy. This underestimation will negatively impact the development of a reliable forecasting model and the determination of timely preventive maintenance to ensure roadway safety.

The major issues of the aforementioned studies are 1) the sample size of the transverse profiles is very small and 2) it is labor-intensive and time-consuming to acquire ground truth transverse profiles. Simpson (2001) used the transverse profiles collected by the rod and level method as the benchmark, each of which consists of only 25 points. Also, only 30 transverse profiles were analyzed. Data Collection Ltd. (DCL) used Transverse Profile Beam (TPB) with a transverse resolution of 3 mm to establish the reference profiles (2006). Only 64 reference profiles were collected. There is a need to develop an alternative method to cost-effectively acquire ground truth transverse profiles for quantitatively assessing the rut depth measurement errors of point-based rut bar systems.

With the advance of sensing technology, an emerging 3D line laser is capable of capturing high-resolution pavement transverse profiles at highway speed. For example, the 3D line laser used in this study collects a transverse profile every 5 mm along the driving direction at a speed of 100 km/hr. Each transverse profile contains 4,160 laser points (1 mm resolution in the transverse direction), which covers a full travel lane (Laurent et al., 2008; Tsai et al., 2013). A transverse profile can be used to calculate its rut depth. If the rut depth measurement accuracy is desirable, the transverse profiles can then be used to establish a reference for evaluating the measurement accuracy of a point-based rut bar system by

down-sampling the transverse profile to simulate the point-based system. Because of the dense data along the driving direction and at the transverse direction, sufficient reference data can be cost-effectively acquired. This will overcome the previous challenges of establishing ground truth transverse profiles. Therefore, a more reliable and accurate assessment of the measurement error of point-based rut bar systems can then be achieved. The purposes of this paper are 1) to validate the rut depth measurement accuracy and repeatability of a 3D line laser and 2) to quantitatively assess the accuracy and reliability of point-based rut bar systems.

This paper is organized as follows. The first section identifies the research need and objectives. The second section introduces the rut depth computation methods for the 3D line laser and the point-based rut bar systems. The third section presents the laboratory and field tests to validate the rut depth measurement accuracy and repeatability of the 3D line laser. Then, the rut depth measurement accuracy and reliability of point-based rut bar systems with different sensor configurations under different rut depths is quantitatively analyzed. Finally, conclusions and future recommendations are made.

II. RUT DEPTH CALCULATION METHODS

To calculate the rut depth using 3D transverse profiles collected by the 3D line laser, the simulated straightedge method, as suggested in the ASTM Standard E1703 (ASTM, 2010a) and commonly adopted by researchers (Li et al., 2009; Li et al., 2010), was used in this study. Given that each transverse profile can be considered as a reference profile, a point-based rut bar system can be simulated by down-sampling the ground truth profile. For example, a 3-point laser bar can be simulated by selecting 3 specifically configured points on each transverse profile. The following briefly introduces the configuration of each point-based rut bar system and the corresponding rut depth calculation method.

Fig. 1 illustrates the configuration of a 3-point rut bar system. The 3 sensors are equally spaced at an 860 mm interval with the left and right sensors on top of left and right wheel path. Each sensor measures the distance from the reference plane to the corresponding pavement surface, which are D1, D2 and D3 for the center, left wheel path, and right wheel path sensor. Assuming that the pavement surface in the middle has no rutting, the rut depth in the left and right
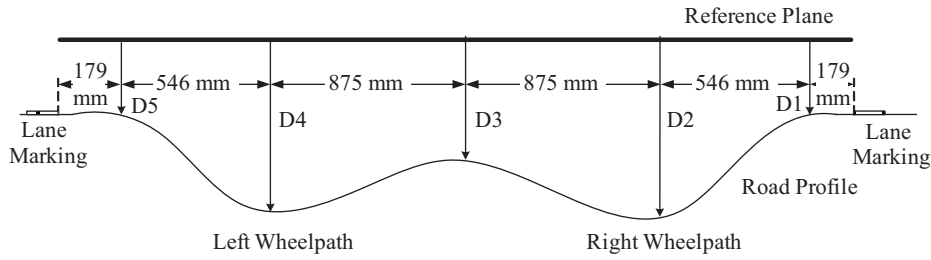
Reference Plane

179 mm | 546 mm | 875 mm | 875 mm | 546 mm | 179 mm

D5 D4 D3 D2 D1

Lane Marking

Left Wheelpath   Right Wheelpath

Road Profile

Lane Marking

Fig. 2. Sketch of the 5-point rut bar configuration.

Reference Plane

400 mm | 400 mm | 400 mm | 400 mm | 400 mm | 400 mm | 400 mm | 400 mm

D5 D4 D3 D2 D1

Lane Marking

Left Wheelpath   Right Wheelpath
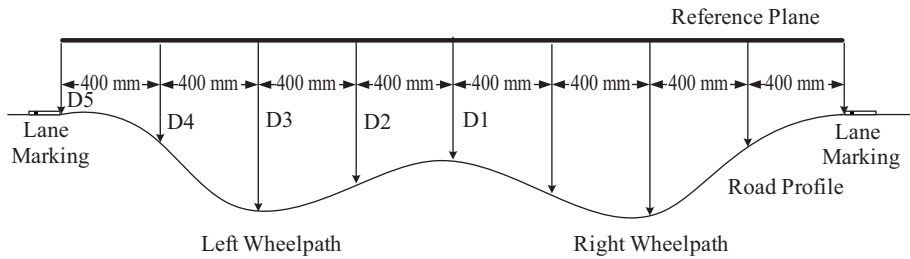
Road Profile

Lane Marking

Fig. 3. Sketch of the 9-point rut bar configuration.

wheel path can be calculated using the distance differences shown in Eqs. (1) and (2).

$$RD_L = D_2 - D_1 \qquad (1)$$

$$RD_R = D_3 - D_1 \qquad (2)$$

Ideally, the centerline of a lane can be used as the reference when configuring a point-based rut bar system on a transverse profile. However, its location is often undecided on a transverse profile as the survey vehicle wanders during the survey. On the other hand, lane marking is visible on the laser intensity images, and, thus, was used as the reference to configure a point-base rut system in this study. The test lane width is 3353 mm (11ft) wide, and the lane marking is about 152 mm (6in) wide. Thus, a 3-point rut bar system can be configured as shown in Fig. 1.

For a 5-point rut bar system, the one used by Hossain et al. (2002), which is shown in Fig. 2, was adopted. The spacing between the sensor on the wheel path and the one on the road centerline is 875 mm. The outer sensor is located 546 mm from the wheel path sensor. Similar to the 3-point system, lane marking was used as the reference when configuring the 5-point system on transverse profiles. The distance between the edge of lane marking and the wheel path sensor is 179 mm. The left and right rut depth can be computed using the left and right three sensor range data, which are shown in Eqs. (3) and (4).

$$R_L = D_4 - (D_3 + D_5)/2 \qquad (3)$$

$$R_R = D_2 - (D_1 + D_3)/2 \qquad (4)$$

For 7- to 31-point systems, it was assumed that such a system can cover the whole lane width. Thus, the distance between the leftmost and rightmost point sensors is 3,200 mm. Also, the spacing between any two neighboring sensors was set to be the same. It is roughly 400 mm for a 9-point rut bar system, as illustrated in Fig. 3. Based on the down-sampled transverse profiles, the rut depth was calculated using the simulated straightedge method.

III. VALIDATION OF RUT DEPTH MEASUREMENT ACCURACY AND REPEATABILITY OF THE 3D LINE LASER

The objective of this section is to validate the accuracy and repeatability of rut depths measured using the 3D line laser before we can confidently use the 3D line laser to assess the rut-depth measurement error of point-based rut bar systems. For this purpose, both laboratory and field tests were conducted. For these tests, 3D transverse profiles were collected and processed using the simulated straightedge method presented previously. The calculated rut depths were then compared to the manually-measured ground truth to quantify the rut depth measurement accuracy.

1. Laboratory Test

Rutting severity levels are commonly determined by different ranges of rut depth. In the Ohio Department of Transportation (ODOT, 2010), rut depth for the low severity rutting is 6.35 mm (1/4in) to 12.7 mm (1/2in). It is 12.7 mm (1/2in) to 19.1 mm (3/4in) for the medium severity rutting and greater than 19.1 mm (3/4in) for the high severity rutting. To simulate rutting of different severity levels in the laboratory, a curved wood board and a curved metal bar were used as shown in

Table 1. Standard deviation of rut depth among 2,000 profiles.

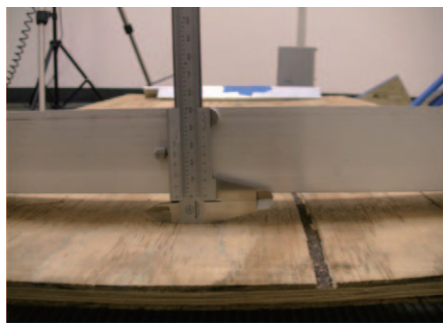| Profile #		1	2	3	4	5	6	7	8	9	10	11
Std. Dev.	1st Run	0.1	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0.1	0.2	0.3
(mm)	2nd Run	0.2	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.2	--

-- Invalid testing data.

(a) Wood board

(b) Metal bar

Fig. 4. Simulated ruts in the laboratory.

(a) Straightedge method

(b) 3D line laser setup in the laboratory

Fig. 5. Laboratory test setup.

Fig. 4(a) and (b). On the wood board, 10 profiles were marked with blue tape. The rut depths of those profiles vary from several millimeters to several centimeters. The curved metal bar was used to simulate a rut of the high severity level. Thus, there were 11 profiles fabricated in the laboratory.

The ground truth was established by using the straightedge method specified in ASTM Standard E1703 (ASTM, 2010a). As shown in Fig. 5(a), a steel angle bar was used as the straight-edge. The rut depth was measured using a vernier caliper with a precision of 0.0 2 mm. During the measurement, the vernier caliper was set perpendicular to the steel bar. To identify the maximal distance between the steel bar and the wood board surface, sufficient measurements were made at different locations along the steel bar. The measurement for each profile was repeated three times. The average rut depth of these three times was used as the ground truth.

The 3D line laser was set up in the laboratory as shown in Fig. 5(b). Because the length of the simulated pavement profiles was less than half a lane, only one laser profiling unit was installed. The infrared camera shown in Fig. 5(b) was used to observe the invisible laser line. The data collection procedure for each profile was repeated twice. During each procedure, the wood board or the metal bar was placed under the laser profiling unit, and its position was fine-tuned until the laser line was right on the marked profile. Then, 2,000 repetitive data profiles were collected. For testing the 11 simulated ruts, a total of 44,000 (=11*2*2,000) profiles were obtained. Table 1 shows the rut depth standard deviations, ranging from 0.1 mm to 0.3 mm, of 2,000 repetitions for each simulated rut, which indicate very good repeatability of rut depth measurement using the laser profile data. The rut depth for each profile was calculated using a simulated 1.8 m straightedge method.

Table 2 shows the rut depth measurement results of the 11 simulated ruts. The average manual measurements vary from 8.0 mm to 43.4 mm covering the low to high severity levels and were used as the ground truth. Two runs of 3D transverse profile data collection were performed to evaluate the reproducibility of the 3D line laser. The difference between these two runs ranges from 0.1 mm to 1.3 mm, which is comparable to the manual measurement error. The difference between the laser-profile-measured results and the ground truth varies from -0.4 mm to 0.7 mm, which is less than 1 mm. Fig. 6 shows the correlation of rut depth measurements between the two runs. In accordance with the standard ASTM C670-03 (ASTM, 2010b), the average coefficient of variance is about 4.4%, which indicates good measurement repeatability.

2. Field Test

Two local roadway sections were selected in Pooler, Georgia, for the sake of manual survey safety. As shown in Fig. 7(a), a 725 m roadway section was chosen on Benton Blvd., and a 45 m roadway section was selected on Towne Center Ct., as shown in Fig. 7(b). Six test transverse profiles, which are visible on the laser intensity data, were marked on Benton Blvd., the first test section. On the Towne Center Ct., the second test section, 4 test profiles were marked.

Table 2. Laboratory testing results.

Profile #	Severity Level	Rut Depth (mm)					
		Ground Truth	1st Run	2nd Run	Difference between Runs	Average	Difference to Ground Truth
1	Low	8.0	8.3	7.1	1.2	7.7	0.3
2	Low	7.9	8.2	8.0	0.2	8.1	-0.2
3	Low	7.9	6.8	7.6	0.8	7.2	0.7
4	Medium	13.2	13.2	13.1	0.1	13.2	0.0
5	Low	12.3	12.3	11.5	0.8	11.9	0.4
6	Medium	14.2	13.8	14.0	0.2	13.9	0.3
7	Medium	15.5	15.0	14.8	0.2	14.9	0.6
8	Medium	16.2	15.4	16.7	1.3	16.1	0.1
9	Medium	17.5	17.6	17.1	0.5	17.4	0.1
10	Medium	10.0	11.0	9.7	1.3	10.4	-0.4
11	High	43.4	43.2	N/A	N/A	43.2	0.2
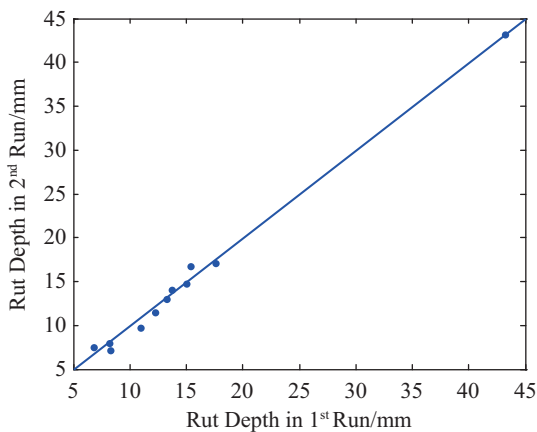
Fig. 6. Correlation of laser-profile-measured rut depths in two runs in the laboratory.

(a) Test section on Benton Blvd.   (b) Test section on Towne Center Ct.

(c) 1.8 m straightedge method   (d) Data collection vehicle
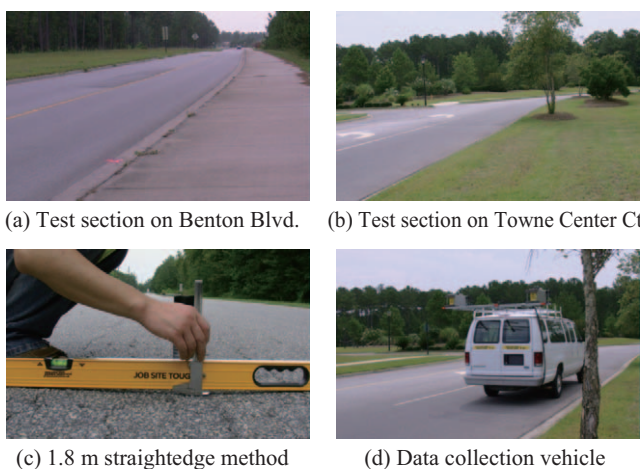
Fig. 7. Field test setup.

To establish the rut depth ground truth of the 10 test profiles, a 1.8 m straightedge method was performed as shown in Fig. 7(c). The same measurement procedure was followed as in the laboratory test, which was repeated three times for each test profile. The average rut depth of those three times was used as the ground truth.

The data collection vehicle is shown in Fig. 7(d). The vehicle collected 3D transverse profile data three runs for each section. The measured profiles were then used to calculate the corresponding rut depth.

The field test results on the local roads are summarized in Table 3. Ten manually marked profiles on the test roadway sections were examined. The manually measured rut depths, which are considered as the ground truth, vary from 6.4 mm to 21.1 mm. They correspond to the low to high severity rutting. The difference between the manual measurements and the average of laser-profile-measured results varies from 0.8 mm to 2.3 mm, which is higher than the one in the well-controlled laboratory test. Several factors could contribute to this. First, for a profile-based comparison, it is very critical to make sure that the location of each extracted profile from 3D line laser data is exactly the same as the manually marked and measured one. In the harsh field testing environment, it is very difficult to make this happen. Second, unlike the well-controlled laboratory test, vehicle wandering is inevitable in a field test, which will impact the rut depth measurement.

From the test results listed in Table 3, the absolute rut depth measurement difference is around 1.6 mm, which is the average of "difference to ground truth." Also, this difference is random and independent of the rut depth, which indicates that the relative error decreases with the increase of rut depth. For example, though the relative error for profile #10 is around 19%, the one for profile #9, which has the largest rut depth, is just 4%. This will assure the accuracy of rut depth measurement for more severe rutting, which is of the most concern in transportation agencies' practices. In addition, for the network level rutting survey, profile-based rutting data is normally aggregated at a fixed interval, such as 1 m, which will further reduce the random measurement error.

Fig. 8 shows the correlation of laser-profile-measured rut

Table 3. Field testing results.

Profile #	Severity Level	Rut Depth (mm)					
		Ground Truth	1st Run	2nd Run	Difference between Runs	Average	Difference to Ground Truth
1	Medium	14.5	12.4	14.4	13.3	13.3	1.2
2	Medium	15.8	13.9	14.8	14.0	14.2	1.6
3	Low	9.6	10.6	10.5	10.2	10.5	-0.9
4	Medium	14.2	12.6	12.4	11.2	12.1	2.1
5	Low	8.5	6.5	7.2	8.4	7.4	1.1
6	Low	9.5	7.8	7.4	7.1	7.5	2.0
7	Low	7.8	6.4	5.9	6.4	6.2	1.6
8	Low	9.4	7.8	7.6	7.6	7.7	1.7
9	High	21.1	20.3	20.4	20.4	20.3	0.8
10	Low	6.4	5.7	4.8	5.5	5.4	1.0
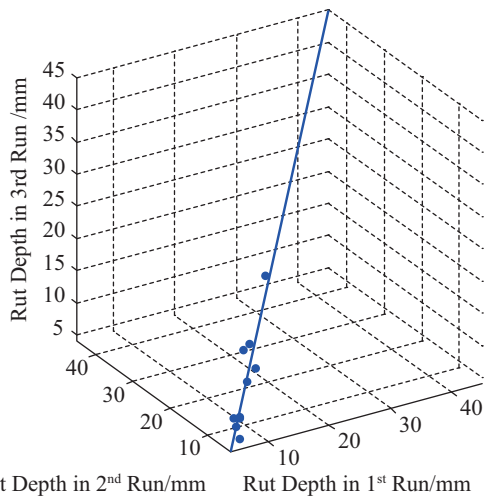
Fig. 8. Correlation of laser-profile-measured rut depths in three runs in the field.

depths for three runs. The average coefficient of variance is about 5.3%, which shows good measurement repeatability.

Both lab and field tested conducted in this chapter validated the rut depth measurement accuracy and repeatability of the 3D line laser, which is sufficient to be used as the reference profiles to further quantify the rut-depth measurement error of point-based rut bar systems.

3. Assessment of Rut-Depth Measurement Error of Point-based Rut Bar Systems

This section presents the quantitative assessment of rut depth measurement error of various point-based rut bar systems using the 3D line laser.

To study the relationship between rut-depth measurement error and the sensor configuration of different point-based rut bar systems, 3-point, 5-pint, and 7- to 31-point rut bar systems were tested in this study. In addition, roadway test sections with various rut shapes were selected because rut shape is an important factor that affects the rut depth measurement accuracy. The test data was collected using the 3D line laser on four asphalt paved roadway test sections; each was 10 m long. For each test section, there are 4,000 transverse profiles. Only half-lane transverse profiles were analyzed in this study.

The four test sections covered four different severity levels of rutting and two main rut shapes, V-shape and U-shape. Fig. 9 shows the typical transverse profiles covering half a lane. The portion of transverse profiles outside the lane marking has been removed. As shown in Fig. 9, the rutting for most profiles is located on wheel paths, except for the profile shown in Fig. 9(b), which is slightly shifted to the left (i.e. the lane marking side). Fig. 9(c) and Fig. 9(d) are two typical pavement profiles with a U shape and a V shape. A U-shape rut has less impact on the rut-depth measurement error brought by a point-based rut bar system because the valley is flat and wide and the possibility of a sensor located on it is high. In contrast, a V-shape rut has a narrow valley, and it is hard for a sensor to be precisely located on the top of the valley. So, a V-shape rut has greater impact on the measurement error when a point-based rut bar system is used.

The configuration of 3-, 5-, 9-, and 31-point rut bar systems on those typical profiles are presented in Fig. 9. As the number of laser sensor increases, a rut bar system can better capture rut shapes. When the number of laser sensor becomes 31 (i.e., when the spacing between two sensors is 105 mm), the rut shape for four transverse profiles can all be captured well. Meanwhile, as the number of laser sensor increases, the rut depth measurement accuracy becomes less sensitive to the spacing configuration of a rut bar system. The sensors in a 31-point system can be set as equally spaced. However, the configuration of a rut bar system with 3, 5, or 9 laser sensors must be designed carefully to assure reliable rut depth measurements.

It is also observed in Fig. 9 that due to the change of rut shape, it is difficult to find an optimal configuration for a rut bar system with fewer sensors. For example, the 3-point and 5-point system configurations shown in Fig. 9(a) and (d) can capture the maximum rut depth, but they cannot capture it for
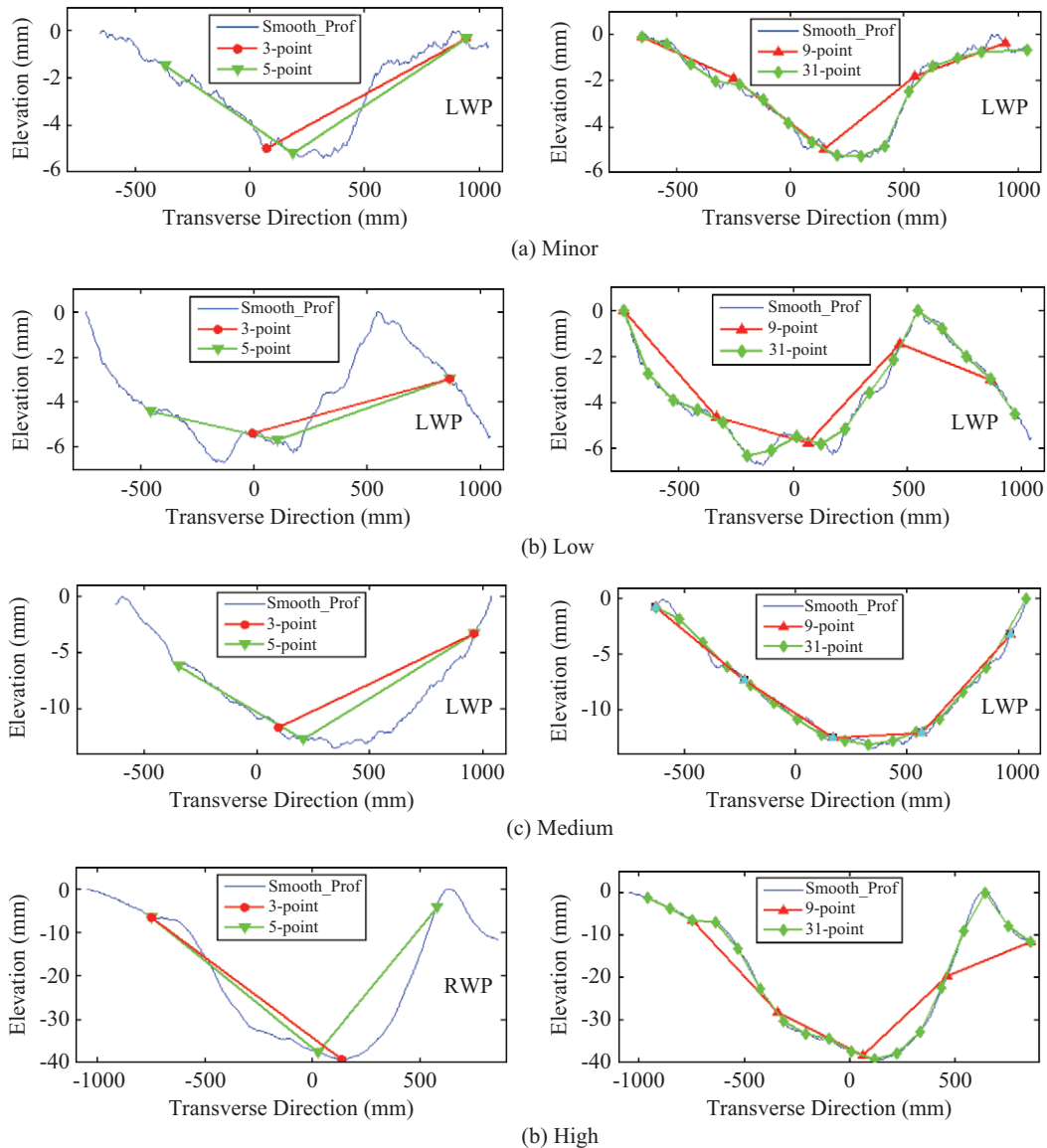
(a) Minor

(b) Low

(c) Medium

(b) High

Fig. 9. Road transverse profiles and point-based system configurations.

ruts shown in Fig. 9(b) and (c), for which the rut depth will be significantly underestimated.

Fig. 10 shows the calculated rut depths along the driving direction. The blue line indicates the distribution of the ground truth rut depth along the driving direction. In comparison, the distributions of rut depth measured by different point-based rut bar systems are also drawn in Fig. 10 with different colors. For better reading of the chart, only the results from 3-, 5-, 9- and 31-point rut bar systems are presented. Generally, the rut depth measurement accuracy increases with the increasing number of sensors. However, for those rut bar systems with fewer sensors, the rut depth measurement error is largely affected by the rut shape. For example, based on the experimental test results shown in Fig. 10, it is difficult to tell if the 3- or 5- rut bar system is better. In some cases, for example in

Fig. 10(d), a 3-point rut bar system could outperform a 9-point one.

The corresponding means of absolute and relative measurement errors for all point-based rut bar systems are shown in Fig. 11. As shown in Fig. 11(a), for those rut bar systems with fewer sensors, the absolute measurement error increases with the increasing rut depth. However, this trend doesn't apply to a rut bar system with more sensors. For the 31-point rut bar system, the mean absolute rut-depth measurement error is about 0.4 mm, which is very close to the ground truth.

The relative measurement error varies among different ruts and different rut bar systems, as shown in Fig. 11(b). The relative rut-depth measurement error for a 3-point and a 5-point rut bar system varies from 16% to 51% and from 22% to 64%, respectively. When the sensor number increases to 9,
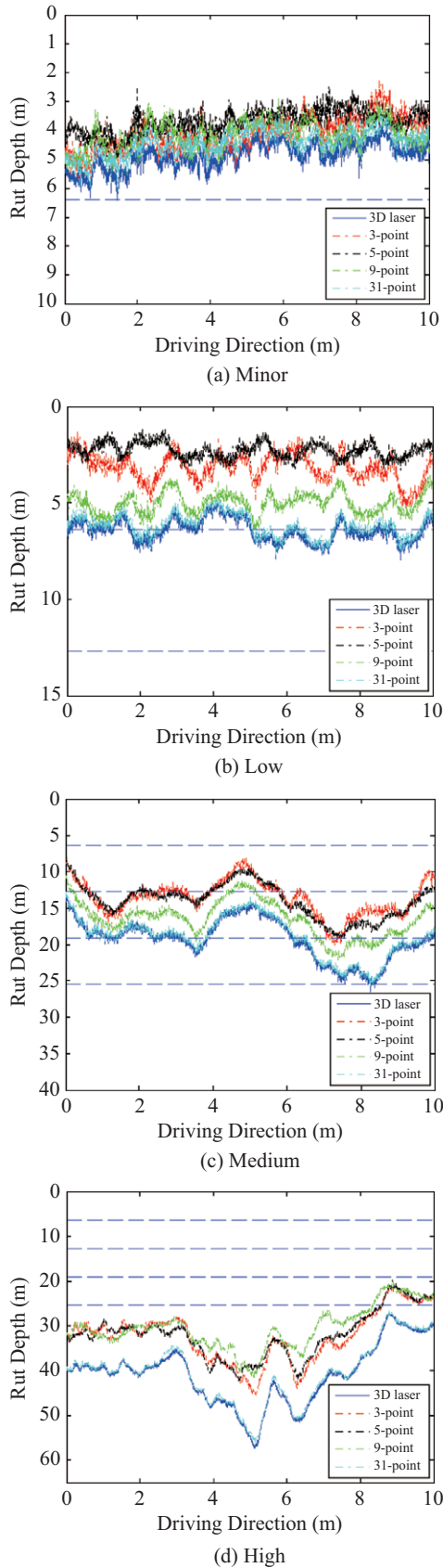
(a) Minor

(b) Low

(c) Medium

(d) High

Fig. 10. Measurement errors of point-based rut bar systems along the driving direction.

(a) Absolute measurement errors
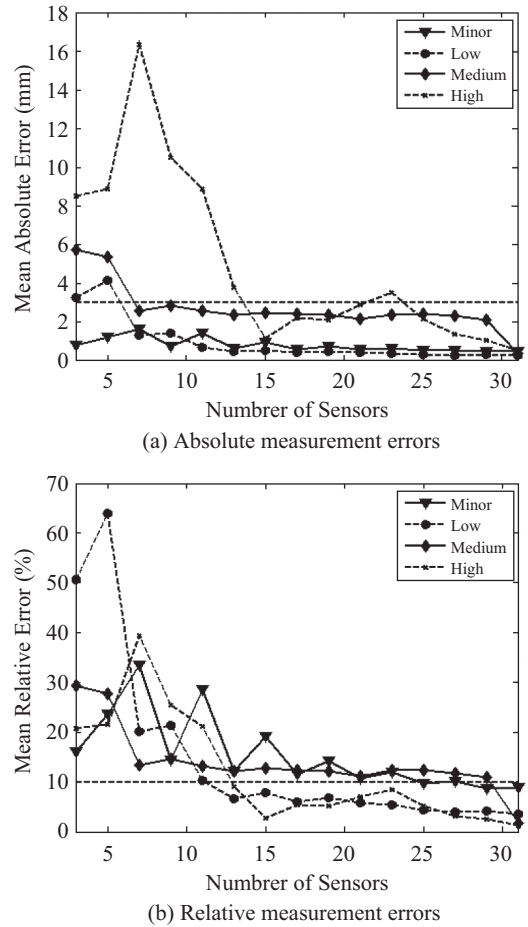

(b) Relative measurement errors

Fig. 11. Relationship between the number of laser sensors and the measurement error.

the mean error varies from 14% to 25%. If the number of sensors increases to 31, the average measurement error is lowered to between 1% and 9%. For those rut bar systems with fewer sensors, rut shape plays a more important role in affecting measurement error. For example, when the location of maximum rut depth is close to the lane marking, the side sensor for a 5-point rut bar system often fails to capture the outmost highest point, which will perform worse than a 3-point system. Thus, based on the test results shown in Fig. 11(b), it is difficult to tell whether a 3-point or a 5-point rut bar system is better. Even a 9-point system could perform worse than a 3-point or 5-point in some cases. Thus, a rut bar system with fewer sensors performs less consistently among various rut shapes. Nevertheless, the overall trend is clear: the measurement error decreases with the increasing number of sensors. If the number of sensors is greater than 29, the mean error for all four sites drops below 10%. In other words, when the spacing between adjacent sensors is 112 mm or less, the rut-depth measurement error becomes 10% or less. This is close to the 100 mm spacing, which gives an average of 5% error, recommended for use for routine data collection by Chen et al. (2001).

IV. CONCLUSIONS AND RECOMMENDATIONS

The high-resolution 3D transverse profiles acquired by the emerging 3D line laser were first used in this study to assess the rut-depth measurement error of point-based rut bar systems. The 3D line laser can readily provide a large volume of high-resolution transverse profiles to characterize and quantify the rut depth measurement accuracy of different point-based rut bar systems. The quantitative assessment results can be used by transportation agencies to determine the potential error of the point-based rut bar systems they are using and to provide a guideline for choosing a rut bar system that will provide an acceptable accuracy for their network-level rutting survey.

This paper also presented the validation results of the 3D line laser technology through both laboratory and field tests. The rut depth measurement accuracy of the 3D line laser was validated by testing 11 laboratory-fabricated profiles and 10 field-selected profiles. The ground truth of the rut depth for each test profile was established by using the manual straight-edge method. Laboratory test results show that the difference between the laser-profile-measured rut depths and the ground truth varies from 0.1 mm to 0.7 mm. In the field test, the absolute difference ranges from 0.8 mm to 2.3 mm. This measurement accuracy satisfies the rut depth measurement requirement, which is +/- 3 mm, for multiple transportation agencies (McGhee, 2004).

In this study, the commonly used 3-point and 5-point rut bar systems and equally-spaced rut bar systems with 7 to 31 laser sensors were tested with the simulated data sampled from the data acquired by a 3D line laser. The test data was collected on four 10 m road sections that cover various rut depths and rut shapes. Test results show that generally the relative rut-depth measurement error decreases with the increasing number of laser sensors. However, the trend is unclear for rut bar systems with fewer sensors because, in these cases, the rut shape plays a more important role in affecting the rut depth measurement error. A 3-point rut bar system could outperform a 5-point system occasionally. The test results also show that the commonly used 3-point and 5-point rut bar systems can underestimate the rut depth significantly. The relative rut-depth measurement error for a 3-point and a 5-point rut bar system varies from 16% to 51% and from 22% to 64%, respectively. The relative measurement error consistently drops under 10% only when the number of sensors is greater than 29. In conclusion, to achieve desirable accuracy, the number of sensors on a point-based rut bar system should be sufficient to capture various rut shapes. Besides using the 3D line laser technology as a reference to assess the rut depth measurement accuracy of point-based rut bar systems, it is recommended to use the 3D line laser for more reliable and accurate rut depth measurements.

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