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A New Rutting Measurement Method Using Emerging 3D Line-Laser-Imaging System

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Abstract: Rut depth is one of the important pavement performance measures. Rut depth has traditionally been measured using a manual rutting measurement, which is time-consuming, labor-intensive, and dangerous. More recently, point-based bar systems (e.g., 3, 5 points) have been used by some agencies. However, studies have shown these systems might not be able to accurately measure rut depth because of limited number of sample points. There is a need to improve the accuracy and reliability of rutting measurement. With the advances of sensing technology, emerging 3D line-laser-imaging system is now capable of acquiring high-resolution transverse profile of more than 4,000 points. This provides a great opportunity for developing a reliably and accurately rut measurement method. However, there is no framework to handle this overwhelming amount of 3D range-based pavement data. A framework is proposed in this paper to acquire, process, analyze, and visualize the high-resolution 3D pavement data collected using emerging 3D line-laser-imaging system. The proposed framework includes 1) data acquisition using the sensing system, 2) data processing, 3) data segmentation, 4) data statistical analysis, 5) data visualization, and 6) decision support. A case study carried on Interstate Highway 95 (I-95) near Savannah, Georgia, at highway speed is used to demonstrate of the applicability of the proposed framework.

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***Key words**: 3D line laser imaging technology; Asphalt pavement; Pavement condition assessment; Rutting measurement.*

Introduction

Rut depth is one of the important pavement performance measures that are required by the Federal Highway Administration (FHWA) under the Highway Performance Monitoring System (HPMS) to provide a consistent performance measure among different states [1]. Manual rutting measurement is still conducted by many state Departments of Transportation (DOTs), like Georgia Department of Transportation (GDOT); however, it is time-consuming, labor-intensive, and dangerous. Although point-based rut bar systems have been developed and utilized by state DOTs to measure rut depth [2], previous studies have shown they often underestimate the rut depths [3-7]. This is because point-based systems only sample a limited number of points in the transverse direction, which may not locate exactly on the peaks and valleys of ruts because of the wandering of the survey vehicle, varying lane widths, and varying rut shapes. Ksaibati evaluated the rut depths measured by 3-sensor and 5-sensor profilometers and found significant differences between the non-contact and direct-contact measurements. A study conducted by HTC Infrastructure Management Inc. [4] compared the rut depths from a 30-sensor ROMDAS profilometer with field measurements using a 1.5-m straightedge method and identified a bias. Mallela and Wang [5] assessed the sampling bias of the profilometers (with 13 to 30 sensors) operated in New Zealand and concluded that rut depth measurement of point-based rut bar systems is underestimated. Simpson [6] determined that the correlation of rut depths measured by a 5-point rut bar and a rod and level method is approximately 0.4. Thus, past studies have consistently shown that point-based rut bar systems cannot provide accurate rut depth measurement. This underestimation negatively impacts the development of a reliable rutting progression model and the determination of timely preventive maintenance to ensure roadway safety. Therefore, there is a need to improve the accuracy and reliability of rutting measurement method. With the advancement of sensing technology, 3D line-laser-imaging systems (termed the 3D line-laser hereafter) are now available and capable of acquiring high-resolution (as high as 1 mm in the transverse direction and 5 mm in the driving direction) 3D range data of the pavement surface at highway speed (100 km/hr), covering the entire pavement width at highway speed. This provides a great opportunity for us not only to reliably and accurately measure traditional rut depth but also to acquire the 3D rutting characteristics (e.g., rut shape) to support roadway safety analysis. However, since these 3D line laser systems only emerged in the past several years, the application of these new systems for pavement condition assessment is still in its infancy. There is an urgent need for a framework to process, analyze, and visualize this overwhelming amount of 3D range-based pavement data to take advantage of the emerging 3D line laser systems to improve pavement condition assessment practices. This paper is organized as follows. The first section identifies the research need and objectives. The second section briefly introduces the line- laser system and a sensing vehicle integrated at the Georgia Institute of Technology for 3D pavement surface data collection. The third section proposes a framework for acquiring, analyzing and visualizing the 3D range-based pavement data. Then, a case study on Interstate highway 95 in Georgia is presented to demonstrate the use of the framework. Finally, conclusions are made.

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3D Line Laser Imaging Technology

The 3D line laser system, also known in available literature as the camera-laser-based 3D scanner, is based on the triangulation principle [8], which is presented in Fig. 1. Typically, a 3D line laser system consists of a laser projector and a digital area scan camera with a charge coupled device (CCD) or complementary metal oxide semiconductor (CMOS) sensor. The camera is placed at a known distance and an oblique angle (ɵ) with respect to the projector. When collecting the 3D range data, the laser projector sheds a structured light, i.e., a laser line in the 3D line laser system, onto an object's surface. And the camera captures the laser line as an image. A sub-pixel peak detection algorithm is then employed to analyze the laser line image, find the sub-pixel location of the laser line, and convert the distortion of the laser line to the unevenness of the object's surface. Meanwhile, corresponding 2D intensity data are obtained. Up to this point, a single range profile and a single intensity profile of the object's surface are obtained. The intensity profiles are used to restore the 2D intensity image of the pavement surface, and the range profiles are used to reconstruct an essentially continuous 3D pavement surface. The measurement range of such a 3D line laser system is determined by the intersection between the emitted laser line and the field of view of the digital camera.

A sensing vehicle, the Georgia Tech Sensing Vehicle (GTSV), has been integrated at the Georgia Institute of Technology for 3D pavement surface data collection in the case study. The GTSV is equipped with the 3D line-laser system by INO, which consists of two high-performance laser profiling units [9]. These two units are mounted on the vehicle 2 m away from each other in the horizontal direction and about 2.25 m above the ground, as shown in Fig. 2 and 3. To prevent the left and right scanning regions from cross-talking with each other, both laser profiling units were installed parallel to each other and with a 15° yaw angle (i.e., 75° to the driving direction) with respect to the vehicle, as shown Fig. 3

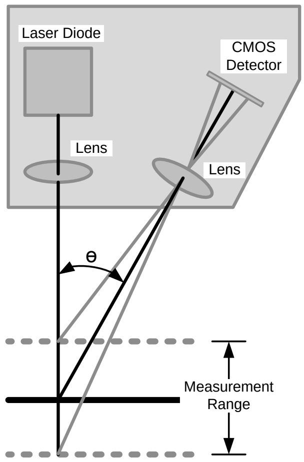


Fig. 1. Illustration of the Optical Triangulation Principle.

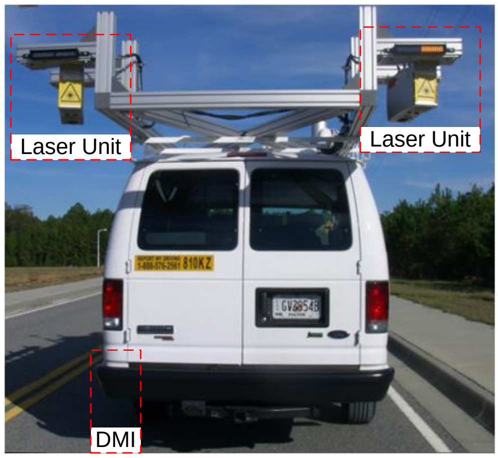
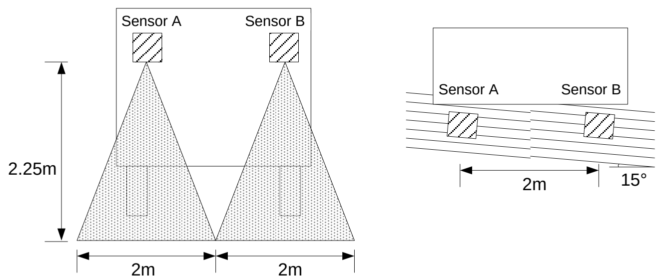


Fig. 2. A Sensing Vehicle Integrated at the Georgia Institute of Technology.



(a) Rear view (b) Birdseye view

Fig. 3. 3D Line Laser System and the GTSV.

Proposed Framework

To address the need of a framework that utilizing emerging 3D line laser technology to measure rut depth, a generalized sensor-based and spatial-enabled pavement rutting condition assessment framework is proposed. The generalized framework takes advantage of the high-resolution and high-speed 3D line laser imaging system, location reference technologies (GPS/IMU/DMI), and roadway images to enhance existing pavement condition assessment. As shown in Fig. 4, the proposed methodology consists of six modules: 1) data acquisition using the sensing system, 2) data processing, 3) data segmentation, 4) data statistical analysis, 5) data visualization, and 6) decision support.

Data Acquisition

The data acquisition module (Module 1) uses a 3D line laser system to acquire high-resolution 3D range data consisting of 3D continuous transverse profiles, a Global Position System (GPS), an Inertia Measurement Unit (IMU), a Distance Measurement Instrument (DMI) to provide corresponding location reference, and a camera to take images of the roadway environment. This module includes a) the optimal laser configuration (e.g., the sampling interval between two transverse profiles and the transverse profile tilt angle) to assure the collected 3D range data have the adequate resolution to assess network-level pavement rutting condition as well as other distresses (e.g., transverse cracks) and b) a standard data quality assurance (QA) and quality control (QC) procedure. The QA/QC procedure will include calibration of the equipment and software routines for checking the reasonableness and completeness of the data. Key indicators (e.g., standard deviation and acceptable accuracy) need to be proposed for measuring the deviations of the collected 3D range data from expected patterns and for determining

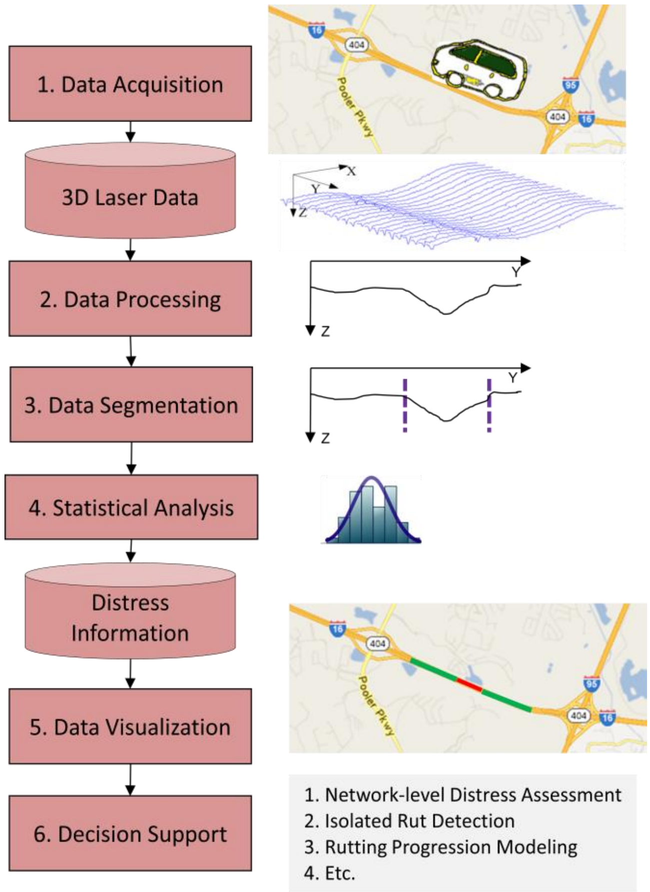


Fig. 4. A Sensor-based and Spatial-enabled Pavement Rutting Condition Assessment Framework.

whether or not the deviations are caused by actual occurrences or false data. The standard QA/QC procedure is the core of the data acquisition module, and it will be studied in the future.

Data Processing

The collected 3D range data will be processed in the data processing module (Module 2), and the rutting measurements, such as the 1D rut depth, rut width, and 2D rut cross-sectional area, will be extracted. The noise created by irregular data and non-rutting features, such as cracking and potholes, needs to be removed in this module. Due to the enormous amount of data points in the 3D range data, methods are needed to extract pavement rutting measurements automatically in a reasonable time period. Various signal processing algorithms and engineering knowledge will be employed to process the 3D range data and obtain accurate rutting measurements. The algorithms developed in this module can be found in [10].

Data Segmentation

In the Data Segmentation Module (Module 3), the continuous pavement rutting measurements obtained from Module 2 need to be partitioned into uniform segments. This module is needed to minimize the data storage requirement and, most importantly, to provide meaningful pavement segments (e.g., reasonably long segments rather than small, 5-mm segments) with uniform rutting condition so that meaningful statistics can be derived for each uniform segment in the next module. A method to determine optimal and engineering-meaningful pavement segments with uniform rutting conditions is presented in [10].

Statistical Analysis

In the Statistical Analysis Module (Module 4), statistics of obtained rutting measurements will be derived in support of network-level pavement management decisions, e.g., statewide pavement rutting condition assessment.

Data Visualization

In the Data Visualization Module (Module 5), 1D rutting statistical information and 2D roadway images will be integrated and presented on a GIS map. The visualization capability allows the overall assessment of the pavement rutting condition, detailed view of rutting (as shown in Fig. 5), and other pavement management decisions in an efficient and intuitive way. For instance, the rutting information can be visualized along with additional data (e.g., the traffic volume, deflection data, and coring results) on a GIS map to assist in diagnosing the causes of rutting, identifying logical treatment projects, and determining adequate treatments. This data visualization module's focus will be on registering the 1D rutting statistics to the linear reference system (LRS) commonly used in GDOT's management practices.

Decision Support

Finally, in the Decision Support Module (Module 6), applications will be developed to report the pavement rutting measurements and the statistical information in support of both network-level and project-level pavement management decisions. For example, the representative rut depth in each management section can be derived and directly stored into a PMS (e.g., GPAM) at the network-level. Integrated with the historical data, road sections with dramatic condition changes will be reported and prioritized for maintenance activities. To support the network-level pavement management decisions, it is important to derive meaningful statistical indicators (e.g., the representative rut depth in one mile) that state DOTs, such as GDOT, can integrate them with the legacy data. To be successful, it is crucial for engineers to be involved in choosing adequate statistical indicators to support existing network-level rutting condition surveys. This network-level rutting condition assessment application's focus will be on gaining involvement from state DOTs and interpreting the derived statistical information, such as whether or not the average rut depth is an adequate indicator to represent the overall pavement rutting condition within a pavement management section and what additional indicators are needed to better support pavement management decisions. In support of the project-level decisions, the rich rutting measurements will be used to identify isolated spots with severe rutting problems to which low-cost, localized treatment could be applied. Ultimately, the high-resolution and high-quality rutting information will improve understanding about the rutting progression behavior and improve the reliability of rutting progression modeling.

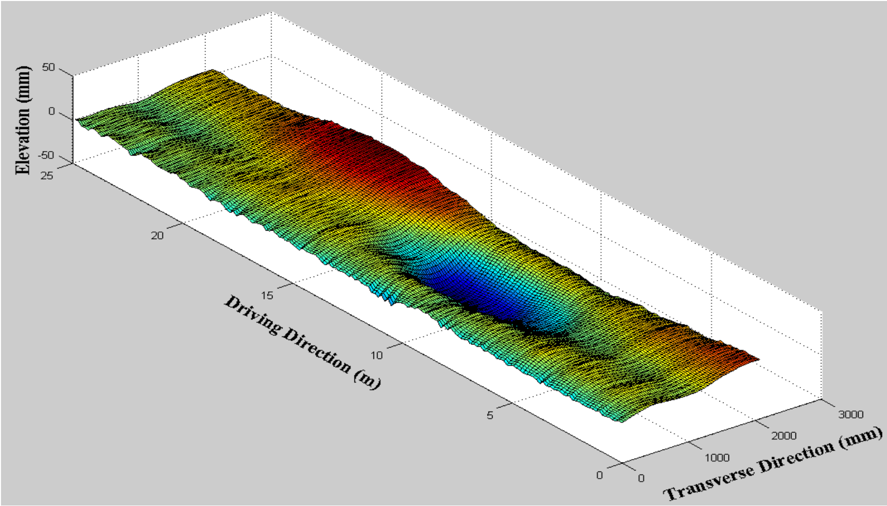


Fig. 5. Visualization of 3D Pavement Data with a Rutting Using 3D Line-laser Imaging Technology.

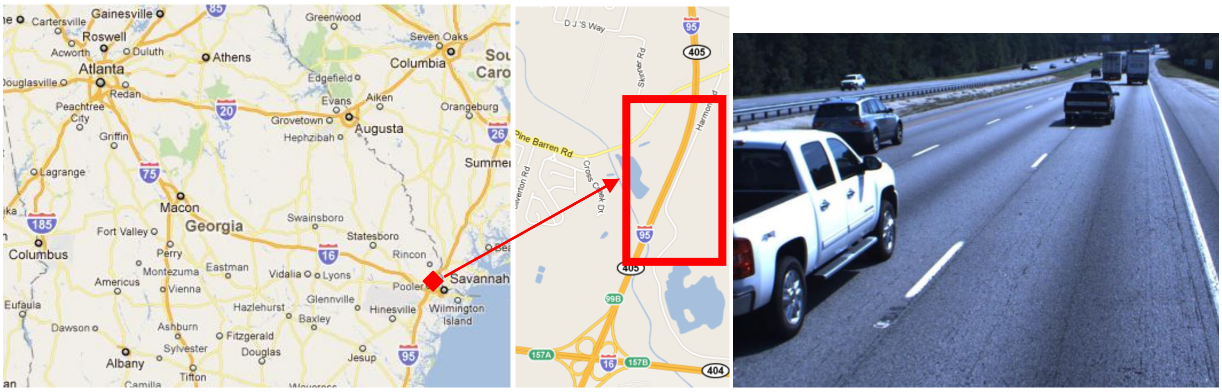


Fig. 6. Location of the Test Section on I-95.

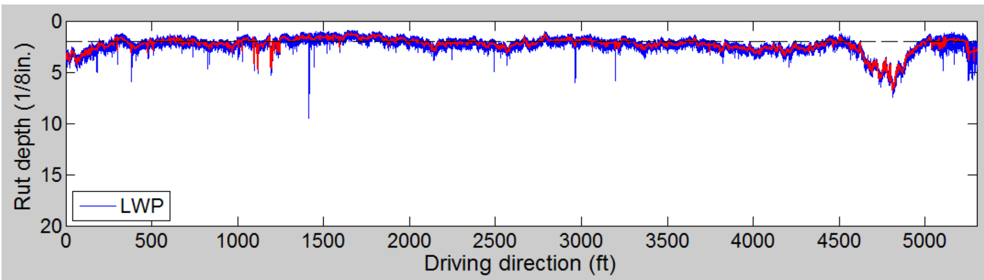


Fig. 7. Raw Longitudinal Rut Depth Profile (Blue) and Filtered Profile (Red).

Case Study

This section presents a case study carried on Interstate highway 95 (I-95) near Savannah, Georgia, to demonstrate the applicability of the proposed framework. The outside lane on southbound of I-95 from MP 101 to MP 100 was selected as a test section. Fig. 6 shows the location of the test section.

GTSV was used to collect 3D range data on I-95 based on the configuration parameters (e.g., 5-mm interval, speed of 55 mi/hr) obtained in previous in-house study. Data was processed and analyzed using the steps and methodologies described in Modules 2 to 6. Test results are presented in this section. The longitudinal rut depth profile, i.e., the distribution of rut depths in the driving direction, for the LWP is the blue line shown in Fig. 7. The total length of this profile is 5,350 ft. A threshold-based outlier removal method was used to remove outliers (i.e., abnormally higher and lower values) in the longitudinal rut depth profile. The red profile is the filtered longitudinal rut depth profile. As shown in Fig. 7, the outliers in the blue profile were successfully filtered out.

Fig. 8 summarizes the homogeneous segmentation results obtained when setting the minimum segment length, i.e., MinLen, as 10 ft, and the minimum mean rut depth difference, MinDiff, as 1/8 in. Each break point on the red profile corresponds to the between two adjacent homogeneous segments. The values of those red line segments are the mean rut depth for each homogeneous segment. As shown in Fig. 8, the homogeneous segmentation method has successfully captured every point at which the pavement rutting condition changes significantly.

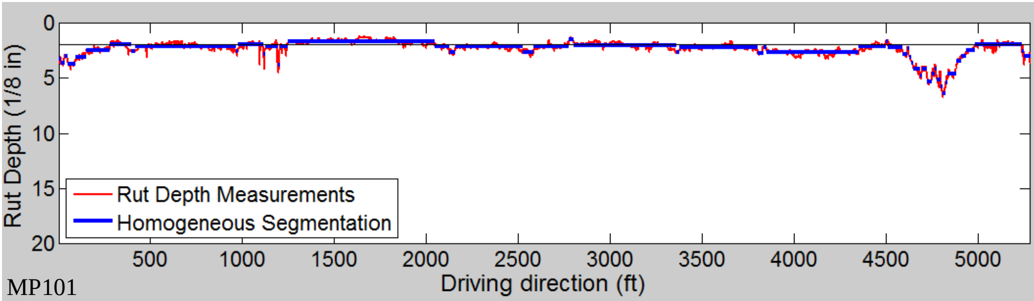


Fig. 8. Homogeneous Segmentation Results (MinLen = 10 ft and MinDiff = 1/8 in).

Table 1. Isolated Rut Detection Results (I-95).

Record #	Start MP (mile)	Start DMI (ft)	End DMI (ft)	Rut Length (ft)	Max Rut Depth (1/8 in)	Rut Volume (ft^3)
1	101	1	283	282	3.7	24
2	100.2	4501	4982	481	6.4	51

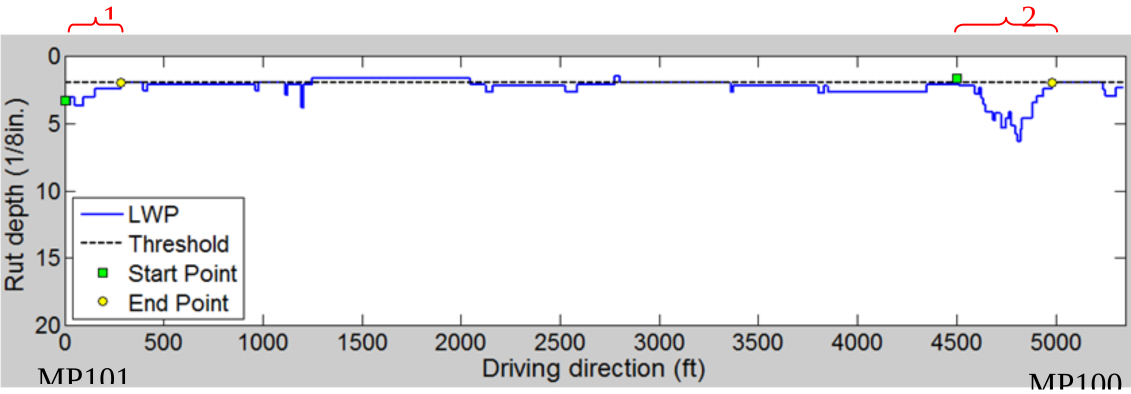
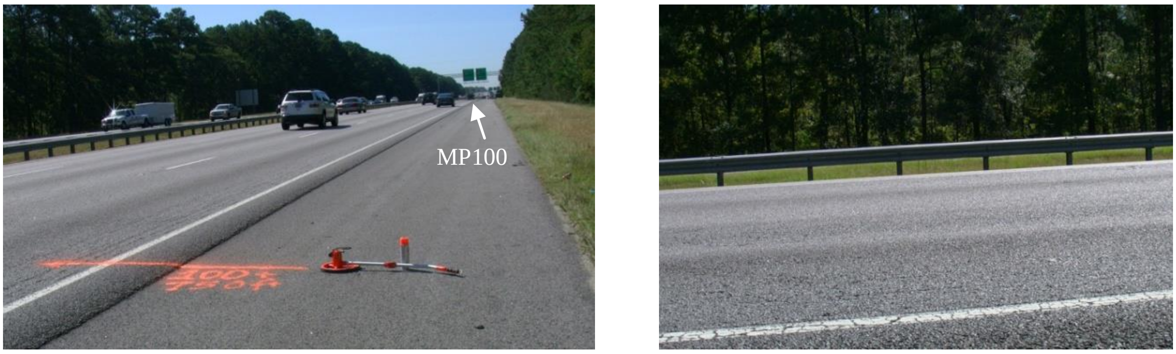


Fig. 9. Detected Isolated Ruts Using the Homogeneous Segments.



(a) Roadway environment (b) Isolated rut

Fig. 10. Isolated Rut Verification in the Field (I-95).

Fig. 9 and Table 1 show the isolated rut detection results. Two isolated ruts are detected (labeled as 1 and 2 in Fig. 9). One is 282 ft long (from 1 ft to 283 ft) and the other one is 481 feet long (from 4,501 ft to 4,982 ft). The maximum rut depth is greater than 1/4 in. for both. The rut volume for these isolated ruts is 24 ft^3 and 51 ft^3, respectively.

Field Verification

A site visit was conducted to confirm that most of this road section exhibited no major rutting problem, and there were only two isolated ruts. The test site is shown in Fig. 10(a), and one of isolated ruts is shown in Fig. 10(b). During the site visit, it was found that the isolated ruts were difficult to locate through the manual survey. In contrast, 3D range data coupled with the isolated rut detection method is capable of automatically locating spots with major rutting problems that could potentially lead to hydroplaning problems for the whole roadway network. Therefore, it is very valuable and may substantially improve existing survey and pavement maintenance practices.

Conclusions

A framework using emerging 3D line-laser-imaging along with GPS/GIS technologies has been proposed to accurately and reliably measure rut depth. The 3D pavement data were collected at highway speed using the vehicle integrated at Georgia Tech and sponsored by the US Department of Transportation Research Innovative Technology Administration Program (RITA) program. The actual 3D data collected from Interstate 95 near Savannah, Georgia, was used to demonstrate the applicability of the proposed framework. Results show the proposed framework is promising for obtaining a more reliable rutting measurement than point-based laser bars. In addition, it also provides a great opportunity in the future to study 3D rutting characteristics and its relationship with roadway safety (e.g. hydroplaning and loss of control). Further testing and refining of the proposed framework is recommended.

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