A MOBILE CROSS SLOPE MEASUREMENT METHOD USING LIDAR TECHNOLOGY

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ABSTRACT

A properly measured, effective cross slope facilitates drainage on highways and prevents hydroplaning. There is a need for transportation agencies to identify and measure road sections that have improper and non-effective cross slopes so that timely corrective maintenance can be performed. However, the traditional manual methods used by transportation agencies to measure cross slope, i.e. using a digital level, are time-consuming and labor-intensive. They are not feasible for conducting a network-level cross slope measurement. This research project, sponsored by the United States Department of Transportation Research Innovative Technology Administration (USDOT RITA) program, proposes a new mobile cross-slope measurement method using emerging mobile LiDAR technology that can accurately and effectively conduct network-level cross slope measurement at highway speed. The contributions of this paper include the following: 1) proposing a mobile cross slope measurement method using emerging LiDAR technology (LiDAR cloud calibration, data acquisition, ROI extraction, and cross slope computation) ; 2) through a sensitivity study, determining the key parameter (i.e. the ROI interval) for the proposed method; 3) critically validating the accuracy and the repeatability of the proposed method by testing it in a controlled environment; and 4) conducting a case study to demonstrate the capability of the proposed method. Experimental testing at the Georgia Tech Savannah campus is first conducted to critically assess the accuracy and repeatability of measuring cross slopes. When compared to the ground truth established by digital level, the results from 15 cross slopes (ranging between 1.9% and 7.2%) show that the proposed method can achieve desirable accuracy with an average measurement difference of 0.13% (i.e. 0.08 °). Results show that the proposed method can achieve a desirable level of repeatability with a standard deviation of less than 0.05% (i.e. 0.03°) in three different test runs. A case study on Interstate 285 is then conducted to demonstrate the capability of the proposed method for achieving proper, effective, network-level cross slope measurements. Results show that the proposed mobile method can be operated at highway speed and is very promising for a network-level cross slope adequacy assessment. Finally, conclusions and recommendations are presented.

INTRODUCTION

The cross slope is a crucial roadway feature that accelerates water drainage and reduces potential roadway hazards that cause hydroplaning. In addition, roadways are designed to slope in the transverse direction to control lateral vehicle wandering, especially on curves, known as super-elevation. Transportation agencies need to identify the potential for vehicle roadway departure or hydroplaning by analyzing the roadway's cross slope features, along with other factors, e.g. pavement surface friction, vertical grade, etc.

Most transportation agencies currently conduct cross slope measurement manually by using a digital level (1, 2). This method requires field engineers to physically place a 4-foot electronic level on the pavement surface to obtain the measurement. FIGURE 1 shows a field engineer conducting manual measurement. Such manual measurement is time-consuming and dangerous. More importantly, since it is not practical to conduct the manual measurement continuously without traffic control, it is almost impossible for transportation agencies to collect the cross slope data necessary to support a network-level analysis for identifying safety concerns, such as potential hydroplaning locations, inadequate super-elevated locations, etc.

FIGURE 1 Manual cross slope measurement (3).

Light detection and ranging (LiDAR) technology has become popular among transportation agencies for asset data collections (4, 5), traffic data collection (6), safety assessment (7), etc. In recent years, mobile LiDAR has been increasingly used for roadside inventory (8), roadway geometry measurement (9-11), etc. With accurate geo-referenced 3D point cloud data and a high-scanning frequency, the mobile LiDAR technology has the potential to achieve safer and more effective cross slope measurements at highway speed. Such measurements can be extracted from a LiDAR point cloud.

Although some researchers have introduced other sensing technologies to facilitate a mobile cross slope measurement method, such as airborne LiDAR (12), laser profiler and inertial measurement unit (IMU) (13), etc., mobile LiDAR technology has never been practically used for mobile cross slope measurement. This study proposes a new mobile cross slope measurement method using mobile LiDAR; it critically evaluates the accuracy and repeatability of the proposed method by using actual data collected on the Georgia Tech Savannah campus in Savannah, Georgia. A case study is presented to demonstrate the network-level analysis capability of the proposed method by using the actual data collected on Interstate 285 (I-285) in Atlanta, Georgia.

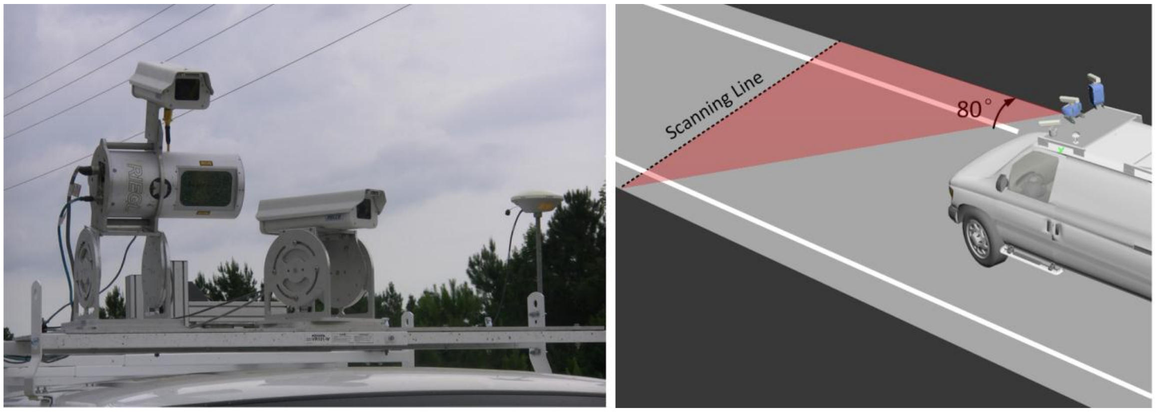
This paper is organized as follows. The first section identifies the research need and objective. The second presents the proposed mobile cross slope measurement method using mobile LiDAR. The third section presents a critical assessment conducted to validate the accuracy and repeatability of the proposed method. The fourth section uses a case study to demonstrate the capability of the proposed method.

PROPOSED CROSS SLOPE MEASUREMENT METHOD USING MOBILE LIDAR

Proposed Method

In this section, a mobile cross slope measurement method is proposed. The method uses Georgia Tech's mobile sensing system, which can collect the data at highway speed. The integrated system includes an emerging mobile LiDAR system (i.e. Riegl LMS-Q120i), high resolution video cameras (i.e. Point Grey Gras-50S5C), and an accurate positioning system (i.e. Applanix LV 210PP) composed of a global positioning system (GPS), an IMU, and a distance measurement instrument (DMI). FIGURE 2(a) shows the mobile LiDAR system and the two corresponding cameras; the rest of the system components are enclosed in the data collection vehicle.

The mobile LiDAR system in this study is a line-scanning laser device that produces 10,000 laser points per second. As the vehicle moves in the longitudinal direction on the road, the scanning line of the LiDAR system is aligned parallel to the transverse direction. The scanning range is 80° in the horizontal direction, which produces an 80 °fan covering the pavement surface. Currently, the frequency of the LiDAR system is configured at 100 Hz with 100 points in each scan. FIGURE 2(b) illustrates data acquisition covering the whole driving lane.



(a) (b)

FIGURE 2 Illustration for data acquisition using LiDAR.

The proposed method for cross slope measurement using mobile LiDAR contains five primary steps, including LiDAR calibration, data acquisition, region of interest (ROI) extraction, cross slope computation, and cross slope spatial analysis. FIGURE 3 shows the flow of the proposed method using mobile LiDAR.

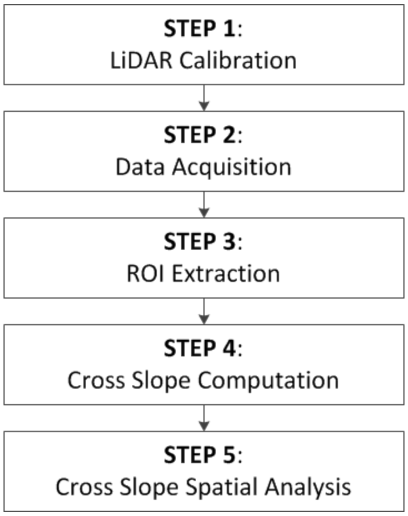


FIGURE 3 Flowchart of the propose cross slope measurement method

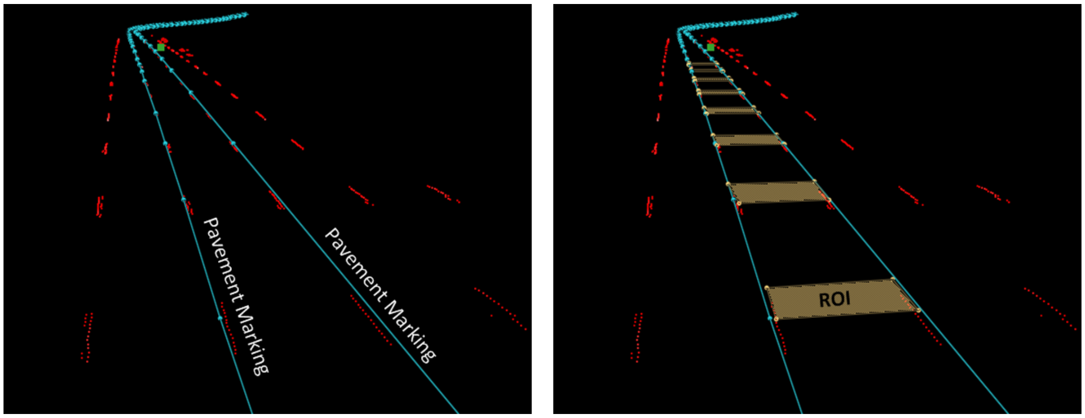
STEP 1: LiDAR calibration. LiDAR calibration is conducted to determine the relative positions (i.e. offsets to the GPS antenna in x, y, and z directions) and the actual orientation (i.e. heading, rolling, and pitching angles) of the data collection system components. The calibration results will be used for point cloud data computation. Sensor calibration needs to be conducted only when the sensor configuration is changed.

STEP 2: Data acquisition. Data acquisition is collected for the testing dataset using the calibrated mobile LiDAR. The raw LiDAR point cloud collected at highway speed contains only the beam distance and beam angle. The raw LiDAR point cloud needs to be post processed using the calibration results and the high accuracy GPS/IMU system (14).

STEP 3: ROI extraction. ROI extraction is performed on the collected LiDAR point cloud to extract the rectangular region within a single lane between the pavement markings. Individual cross slope measurement will be conducted within each ROI. FIGURE 4 shows an example of the ROI for individual cross slope measurement in this study. The ROI can be extracted in two sub-steps, which correspond to the two dimensions of the defined ROI:

<u>STEP 3.1:</u> Pavement marking extraction (ROI width in transverse direction). The width of the ROI is defined by the distance between the pavement markings. The pavement markings can be automatically or semi-automatically extracted from video log images based on the existing pavement marking extraction algorithm (15) or from LiDAR point cloud (16, 11). In this study, the semi-automatic pavement marking extraction method using the LiDAR point cloud is used. FIGURE 4(a) shows the pavement marking extraction result, where the red dots are the extracted pavement marking from the LiDAR point cloud, and the blue line is the connected pavement marking.

<u>STEP 3.2</u>: ROI interval determination (ROI length in longitudinal direction). ROI interval is the key parameter that impacts the accuracy of cross slope computation because it determines the size of the buffer for the regression in the next step. The detailed sensitivity study is presented in the following section. FIGURE 4(b) shows an example of the extracted ROI with an interval of 8ft.



(a) (b)

FIGURE 4 Example of the ROI extraction for individual cross slope measurement.

STEP 4: Cross slope computation. For each extracted ROI, a small group of LiDAR points are extracted for cross slope computation. As each of the LiDAR points incorporates the accuracy of GPS information, including the elevation value in z direction, a linear regression for the association between the extracted elevations and the transverse offset of the lane is conducted. Therefore, the slope of the regression result represents the cross slope within the corresponding ROI. FIGURE 5 shows an illustration of the extracted points from an extracted ROI and the corresponding elevation values for linear regression.

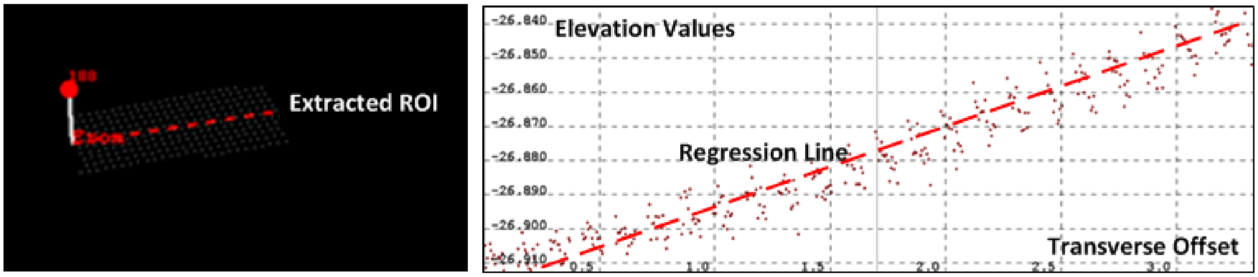


FIGURE 5 Illustration of the extracted point within an ROI for regression.

STEP 5: Cross slope spatial analysis. After all of the cross slope measurements are computed in the tested road section, each measurement from the corresponding ROI is represented by a single geo-referenced point (i.e. the centroids for each ROI). A geo-database can be generated containing the GPS coordinates with all of the cross slope measurements. Such a database can be integrated with other databases with pavement geometry measurements (e.g. curvature, vertical grade, etc.) or pavement surface conditions (e.g. rutting, raveling, etc.) so that a network-level spatial analysis can be conducted to identify potential hydroplaning locations, inadequate super-elevated locations, etc.

CRITICAL ASSESSMENT OF THE PROPOSED METHOD

The objective of the critical assessment is to assess the accuracy and repeatability of the proposed method using mobile LiDAR. Actual data collected on Georgia Tech's Savannah campus and from Jimmy Deloach Parkway and Pooler Parkway in Savannah, Georgia, are used for the accuracy and repeatability assessment.

The dataset collected for the accuracy and repeatability assessment contains 15 distinctive cross slope measurement locations. The benchmarked cross slopes are measured using the digital level with 0.1 ° accuracy, which is typically used by transportation agencies. The benchmarked values range between 1.9% and 7.2%; these cover the most frequent cross slope values and some super-elevated curves. The dataset collected for the case study covers 3 miles of I-285 with three horizontal curves. After the establishment of the ground truth using a digital level, Georgia Tech's mobile sensing system collected the LiDAR data at 30 mph.

Sensitivity Study of the ROI Interval

As presented in previous section, the key parameter used for the cross slope computation is the selection of the ROI interval. Since the cross slope is computed based on the regression result of the LiDAR point's elevation, there is a trade-off in selecting the ROI interval. With a small interval, fewer LiDAR points are included in the ROI, so a single outlier could impact the whole result. With a large interval, more LiDAR points are included in the ROI, but pavement fluctuation could change the elevation within the ROI, which might introduce computation error. In this sub-section, the sensitivity study of the ROI interval is conducted to determine the appropriate ROI interval for the analysis.

Three testing locations are selected for the sensitivity study to determine an adequate interval to compute the cross slope. The testing locations include different cross slope values and vertical grade values. TABLE 1 shows the testing locations' information.

TABLE 1 Testing locations for the ROI interval sensitivity study

	Cross Slope	Vertical Grade	Latitude	Longitude
Georgia Tech Savannah Campus	1.2°	0°	32.170147	-81.209872
Jimmy Deloach Parkway	3.4°	2°	32.168187	-81.219250
Pooler Parkway	4.1°	0°	32.140480	-81.249285

Eleven intervals, 0.5ft., 1ft., 2ft., 3ft., 4ft., 5ft., 6ft., 7ft., 8 ft., 9ft. and 10 ft., were used for each location to assess the sensitivity of the proposed measurement method. No ROI interval smaller than 0.5 ft. was tested because the longitudinal interval of the LiDAR point cloud is about 0.5 ft. when driving at 30mph during the data collection. FIGURE 6 shows the results of the proposed method using different ROI intervals. The result shows several key points for interval selection, including

- When the interval is greater or equal to 2 ft., the cross slope measurement results stabilize, regardless of the actual cross slope value (i.e.1.2° ~ 4.1°) ;
- The cross slope measurement results are not sensitive to the change of the tested ROI interval, regardless of the vertical grade up to 2° (i.e. the data collected on Jimmy Deloach Parkway contains a vertical grade of approximated 2°);
- The cross slope measurement results are sensitive when a small interval is selected because the regression result is sensitive to the outliers when fewer LiDAR points are included in the ROI for regression.
    - The cross slope was underestimated on Pooler Parkway when using 0.5 ft. as the ROI interval (i.e. blue plot in FIGURE 6). A further investigation revealed that the pavement contains several missing stones close to the center, which slightly decreases the computed value.

  - The cross slope was slightly overestimated on the Georgia Tech Savannah campus when using 0.5ft. and 1ft. as the ROI intervals (i.e. red plots in FIGURE 6). A further investigation revealed that the pavement contains small fluctuations near the outside edge of the pavement, which slightly increased the computed value.

It was learned from the sensitivity study that an ROI interval of 2ft. is adequate for the proposed mobile cross slope measurement method at 30 mph. Although other ROI intervals that are greater than 2ft. can still be used for the proposed method with a consistent result, the ROI interval of 2ft. is used in this study to preserve the densest cross slope measurements. In addition, as different LiDAR models or data collection speeds can be used by different transportation agencies, the adequate ROI interval could change. Nevertheless, following the similar sensitivity study procedure, the adequate ROI interval for different transportation agencies can be determined.

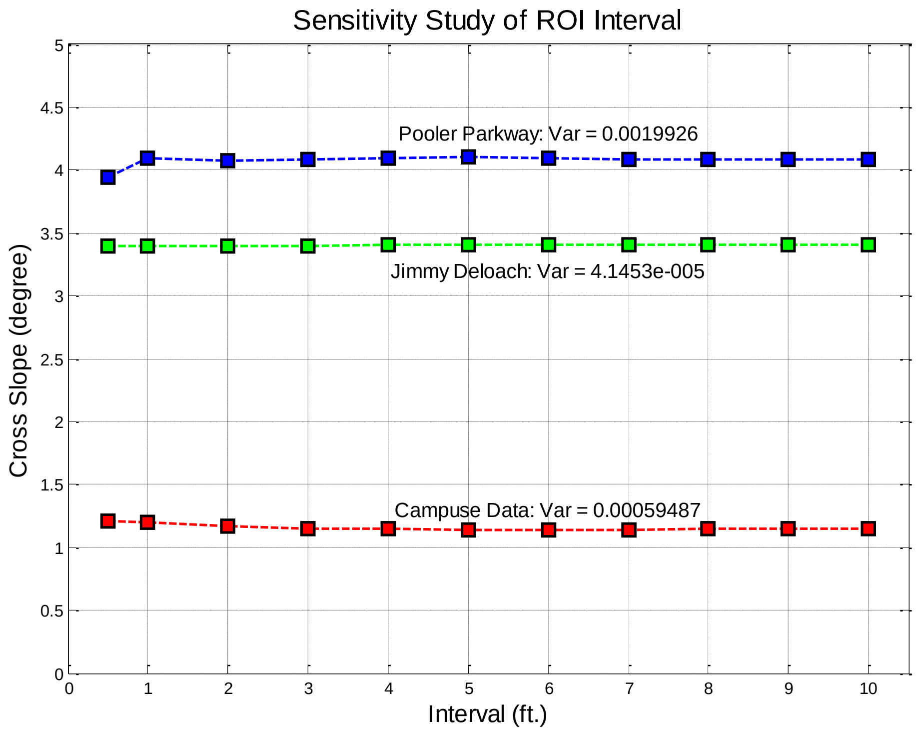


FIGURE 6 Results of the sensitivity study on the ROI interval.

Assessment of the Proposed Method

With the adequate ROI interval, i.e. 2 ft., the datasets collected on the Georgia Tech Savannah campus and from Jimmy Deloach Parkway and Pooler Parkway were tested using the proposed method. TABLE 2 shows the measurement results.

TABLE 2 Assessment results of the cross slope measurement accuracy

	Ground Truth (%)	Proposed Method		Absolute Difference (%)	Relative Difference (%)
		Mean (%)	STDev (%)		
GT Savannah campus	2.18%	2.06%	0.02%	0.13%	5.77%
	2.09%	2.07%	0.02%	0.02%	1.02%
	1.92%	2.04%	0.02%	-0.12%	-6.08%

	2.18%	1.89%	0.02%	0.30%	13.52%
	2.53%	2.39%	0.03%	0.14%	5.48%
Jimmy Deloach Parkway	5.68%	5.92%	0.02%	-0.24%	-4.20%
	5.42%	5.37%	0.03%	0.04%	0.81%
	5.68%	5.44%	0.02%	0.23%	4.14%
	5.33%	5.03%	0.05%	0.29%	5.50%
	5.94%	5.78%	0.03%	0.16%	2.76%
Pooler Parkway	7.17%	7.16%	0.04%	0.01%	0.17%
	6.82%	6.75%	0.02%	0.07%	0.96%
	7.34%	7.46%	0.03%	-0.12%	-1.61%
	6.99%	6.84%	0.02%	0.16%	2.23%
	7.17%	7.24%	0.03%	-0.07%	-1.04%

The cross slope measurements at the 15 benchmarked locations derived from the proposed method were compared to those measured using a digital level with 0.1° accuracy. At each benchmarked location, the ground truth was measured twice, and the measurements were averaged. TABLE 2 shows that the derived measurements are very close to the ones measured using the digital level; there is a maximum difference of 0.28% cross slope (i.e. 0.17°) and an average difference less than 0.13% cross slope (i.e. 0.08°). No bias is observed from the results. From the results, it is identified that the derived cross slope measurements achieve a desirable accuracy, considering the instrumentation accuracy for the digital level is only 0.1°, which is used by many transportation agencies (1, 2).

The repeatability of the measurements at the 15 benchmarked locations was also studied by conducting the data collection in three different runs. FIGURE 7 shows derived cross slope measurement from the three runs. As shown in FIGURE 7 and TABLE 2, there is no significant difference observed among different runs. The standard deviations are within 0.05% (i.e. 0.03°) at all benchmarked locations. The results show that the derived cross slope measurements using the proposed method are consistent and repeatable in different runs.

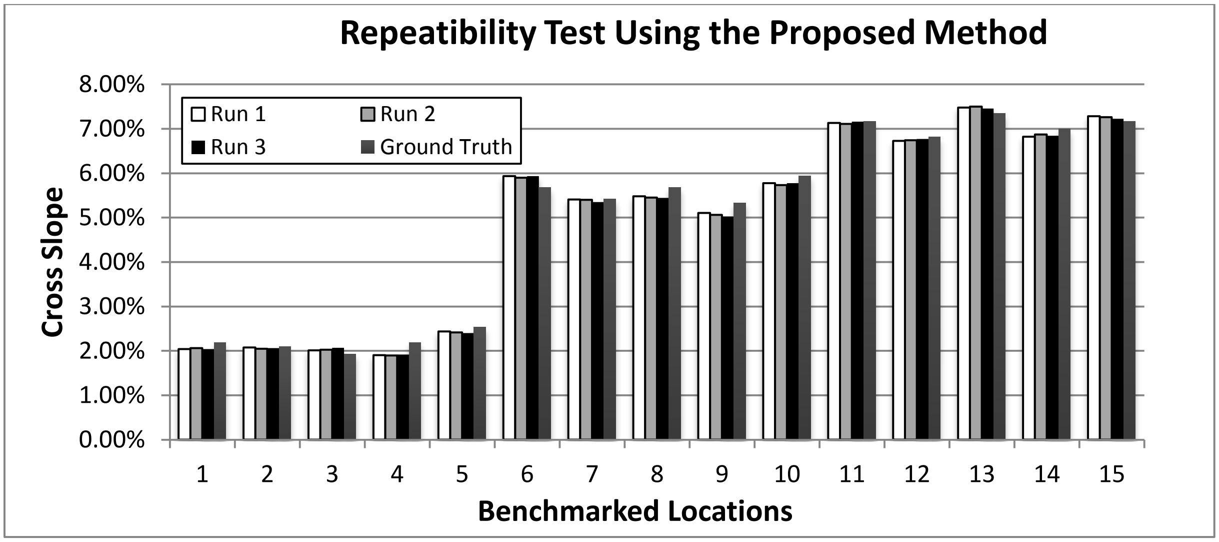


FIGURE 7 Assessment results of the cross slope measurement repeatability.

Based on the accuracy and repeatability test using the actual data collected on the Georgia Tech Savannah campus and Jimmy Deloach Parkway and Pooler Parkway in Savannah, Georgia, the results have demonstrated that the proposed method can measure the cross slope with an average measurement error of less than 0.08 °and a measurement standard deviations of less than 0.05%. Many state DOTs, such as Texas DOT (2), Florida DOT (3), etc., require that the measurement error of the cross slope measurement be 0.1 °, and the measurement standard deviation is 0.2%.

CASE STUDY: INTERSTATE 285

The objective of the case study is to demonstrate the capability of using the proposed method for a network-level cross slope measurement. Georgia Tech's sensing vehicle was used to collect the data at highway speed (i.e. 60mph) on the outside lane of I-285 from MP30 to MP33. The cross slope measurements are aggregated at every 10ft in the longitudinal direction; data was obtained using the proposed method by computing cross slope at every 2ft. FIGURE 8 shows all the measurements from the testing section. Engineers can identify the five sections (i.e. the red sections of A-E in FIGURE 8) with cross slopes less than 1.0% (i.e. sub-standard) that need to have a site visit for close assessment.

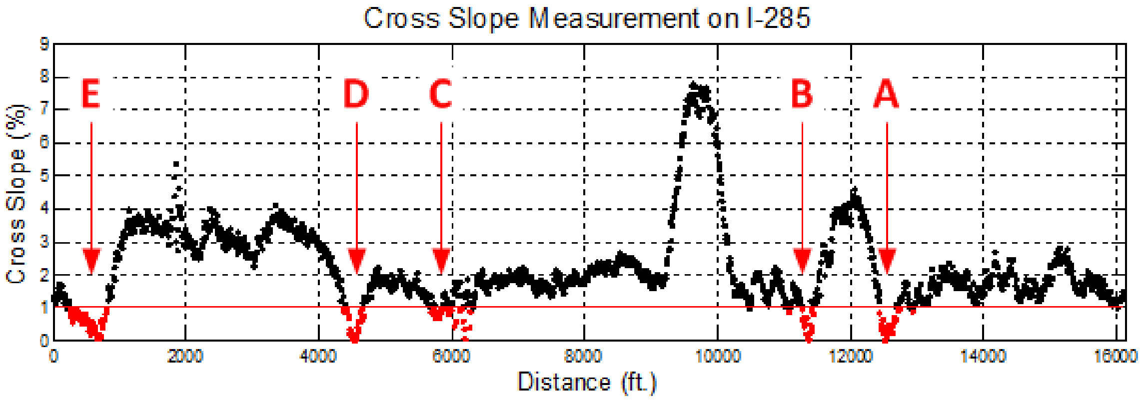


FIGURE 8 Network-level cross slope measurement on I-285.

After the computation, since each cross slope measurement corresponds with a unique GPS coordinate, the cross slope measurement, as shown in FIGURE 8, can be plotted onto a GIS map where the cross slope values can be represented using different colors . FIGURE 9 shows an example of the representation of the results. The red portion displayed in the GIS map corresponds to the locations where cross slope is less than 1%. This information is very useful for transportation agencies. For example, engineers can use this cross slope GIS map to identify the sub-standard cross slope locations (i.e. less than 1.0%) for a focused assessment (e.g. a site visit). In addition, the GIS-based cross slope measurement results can be used to support network-level roadway safety assessment by incorporating them with other measurements, such as vertical grade measurements, curvatures, etc. This case study has demonstrated that the proposed method is very promising because it is capable of conducting a network-level cross slope measurements at highway speed, which will support roadway safety analysis.

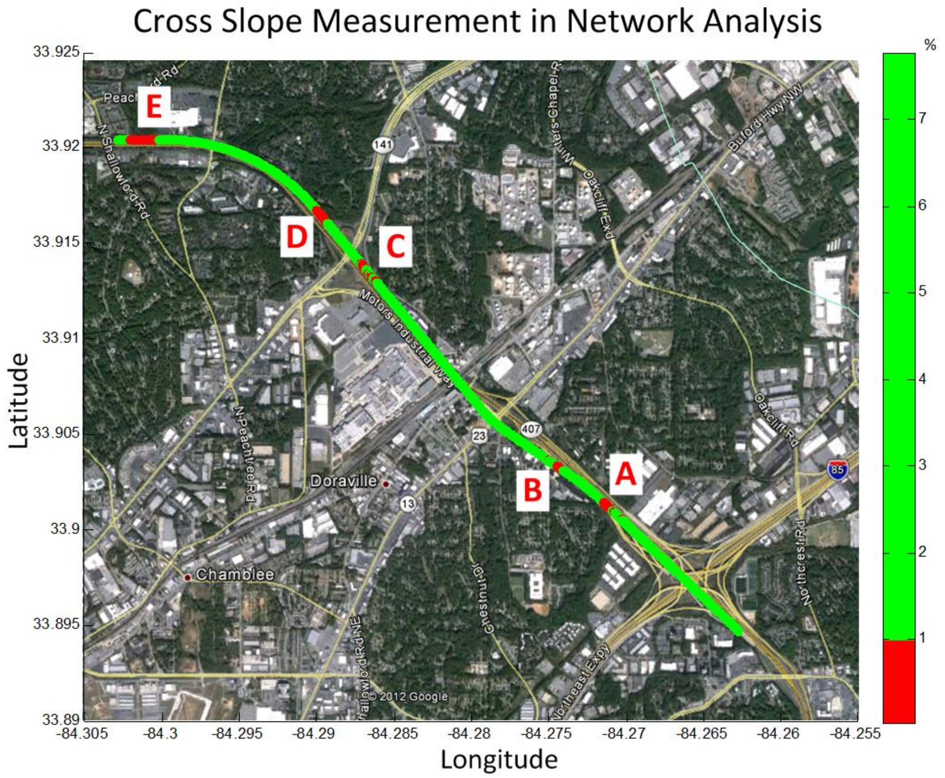


FIGURE 9 GIS-based cross slope measurement analysis on I-285.

CONCLUSIONS AND RECOMMEDNATIONS

The cross slope is a critical roadway feature that facilitates water drainage and reduces the potential of hydroplaning. It is important for transportation agencies to identify road sections with poor, ineffective, and sub-standard cross slopes that require correction. However, the current practice for cross slope measurement is conducted manually, which is time-consuming, labor-intensive, and ineffective. Some automated technologies have been proposed for cross slope measurement using airborne LiDAR (12), laser profiler and inertial measurement unit (IMU) (13), etc. However, none of these technologies have been practically used, and their accuracy and repeatability have not been quantitatively assessed. In this study, a new mobile cross slope measurement method using the emerging mobile LiDAR technology is proposed to address the need of transportation agencies for a mobile, cost-effective network-level cross slope measurement method. The accuracy and repeatability of the proposed methods are quantitatively assessed and compared with the current cross slope measurement methods that are commonly used in state DOTs. The proposed method provides a better measurement accuracy and repeatability. The following points summarize the major findings of this study:

- Based on critical assessment, results show that the proposed method is very promising; it can achieve a desirable measurement accuracy with a maximum difference of 0.28% cross slope (i.e. 0.17°) and an average difference less than 0.13% cross slope (i.e. 0.08°) on the tested sections with cross slopes ranging between 1.9% and 7.2%. The acceptable accuracy is typically 0.2% (or 0.1°) during the construction quality control (3).
- Repeatability assessment results show the proposed method can achieve a good repeatability with the standard deviations within 0.05% (i.e. 0.03°) at 15 different benchmarked locations

in three different runs. The acceptable repeatability is typically 0.2% during the construction quality control (3).

- The case study on I-285 has demonstrated that the proposed method has the capability to conduct network-level analysis efficiently. The GIS-based cross slope measurement map of the 3-mile section of roadway that was studied can be derived in less than 2 man hours using the collected raw LiDAR data.

The following are the recommendations for future research:

- Additional datasets with different roadway environments should be used for further assessment of the performance of the proposed method. Using the proposed method to study of the impacts of a non-uniform cross slope (e.g. ruttings, drop-offs, parabolic cross slopes, etc.) on the measurement results is recommended.
- Further study should be undertaken to establish the relationship between the ROI interval and the data collection speed, the LiDAR model, the pavement condition, etc., to provide a reliable guideline for transportation agencies.
- A fully automatic pavement marking extraction algorithm is recommended to improve the performance of the ROI extraction in the proposed method.
- Further comparison study of cost-effectiveness between the existing technologies and the proposed method is recommended.

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