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Highway Cross Slope Measurement Using Airborne and Mobile LiDAR

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HIGHWAY CROSS SLOPE MEASUREMENT USING AIRBORNE AND MOBILE LIDAR

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Civil Engineering

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by
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ABSTRACT

Ensuring adequate pavement cross slope on highways can improve driver safety by reducing the potential for water sheeting and ponding. Collecting cross slope data is typically only based on small sample because efficient technology and means to collect accurate cross slope data has been evasive. The advent of Light Detection and Ranging (LiDAR) scanning technology has proven to be a valuable tool in the creation of 3D terrain models. Combined with other technologies such as Global Positioning Systems (GPS) and Inertial Measurement Unit devices (IMU) it is now possible to collect accurate 3D coordinate data in the form of a point cloud while the data collection system is moving. This study provides an evaluation of both Airborne LiDAR Scanning (ALS) and Mobile Terrestrial LiDAR Scanning (MTLS) systems regarding the accuracy and precision of collected cross slope data and documentation of procedures needed to calibrate, collect, and process this data.

ALS data was collected by a single vendor on a section of freeway in Spartanburg, South Carolina and MTLS data was collected by six vendors on four roadway sections in South Carolina. The MTLS cross slopes were measured on 23 test stations using conventional surveying methods and compared with the LiDAR-extracted cross slopes. Results indicate that both adjusted and unadjusted MTLS derived cross slopes meets suggested cross slope accuracies (±0.2%). Unadjusted LiDAR data did incorporate corrections from an integrated inertial measurement unit, and high accuracy real-time kinematic GPS, however, was not post-processed adjusted with ground control points.

Similarly, airborne LiDAR-extracted cross slopes was compared with conventional surveying measurement on five test stations along the freeway study section. Whereas, the ALS data accuracy was over the minimum acceptable error when two sides of the travel lanes were used to estimate the cross slope, the use of a fitted line to derive the cross slope provided accuracies similar to the MTLS systems.

The levels of accuracy demonstrate that MTLS and ALS can be reliable methods for cross slope verification. Adoption of LiDAR would enable South Carolina Department of Transportation (SCDOT) or other highway agencies to proactively address cross slope and drainage issues.

When rain falls on a pavement surface, the water depth that accumulates can result in hydroplaning. Previous research has not clearly defined a water depth at which hydroplaning occurs; however, there is considerable agreement that a water depth equal to 0.06 inches as the acceptable upper limit of water depth to minimize the possibility of hydroplaning. This research also explored the potential for hydroplaning with regard to the range of vehicle speed, tire tread depth, tire pressure, and pavement surface texture. Using the results of the sensitivity analysis to provide roadway context combined with MTLS derived cross slope data, SCDOT and other highway agencies can use a data driven approach to evaluate cross slopes and road segments that need corrective measures to minimize hydroplaning potential and enhance safety.

DEDICATION

This dissertation is dedicated to my parents – Col. Fariborz Shams and Mrs. Shekoufeh Shams, my siblings – Farhad and Shahrzad, and my wife – Niloofar.

ACKNOWLEDGMENTS

First, I would like to express my appreciation to Dr. Wayne A. Sarasua, my advisor, for giving me an opportunity to work with him and pursue my Doctorate. Dr. Sarasua showed an indefatigable attitude towards guiding me through my program and sharing his knowledge in all facets of life with me the best he could throughout my stay at Clemson. He is one of my best role models for a professional scholar. I hope that I could be as lively, enthusiastic, and energetic as he is. My appreciation goes to Dr. William J. Davis, Dr. Jennifer H. Ogle, Dr. Christopher Post, and Dr. Bradley J. Putman for being on my advisory committee and for their contributions towards attaining my doctoral degree.

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Alireza Shams

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CHAPTER ONE

INTRODUCTION

Introduction

Roadway Geometry including horizontal and vertical curves, longitudinal grade, super elevation and cross slope are critical elements of designing and planning for all types of roadway projects (*1*). Longitudinal grade and cross slope are used in a number of transportation applications, such as stopping and passing sight distance, roadway capacity, and drainage pattern (*2*). Highway pavement cross slope is a crucially important cross-sectional design element as this provides the means to drain water from the roadway surface laterally (*3*, *4*), so that water will run off the surface to a drainage system such as a street gutter or roadside ditch. Providing adequate pavement cross slopes minimize the occurrence of ponding and improves driver safety by reducing the potential for hydroplaning (*5*). During higher intensity rainfall events, provision of minimum positive drainage through roadway cross slopes becomes an even more critical factor in protecting drivers from hydroplaning (*4*). While it is crucial for roadways to meet minimum pavement cross slope design criteria, it is also important that maximum standards are not exceeded (*6*). When cross slopes are too steep, vehicles may drift to an adjacent lane, skid laterally when braking, and/or become unstable when crossing over the crown to change lanes (*7*). Therefore, problematic pavement cross slope sections should be identified by transportation agencies and corrective maintenance should be performed promptly (*8*).

Problem Statement

Clemson researchers recently conducted a survey of state highway agencies across the U.S. that focused on cross slope evaluation practices. Of the 18 respondents, 70% indicated that they collect some type of cross slope data, however almost none did so on a system-wide basis. The majority of respondents indicated using mobile techniques to some extent with the most popular method being Mobile Terrestrial LiDAR Scanning (MTLS) for collecting cross slope data. Nearly 40% of the respondents reported using traditional surveying techniques. Other techniques include using smart levels or other leveling methods. Also, most of the states only performed cross slope verification on Interstate and primary routes and only on a very limited basis as a response to crash data or drainage issues (*7*). The “reactive” rather than “preventive” approach to the collection of cross slope data suggests that system-wide cross slope evaluation is desirable but not a priority based on available resources.

Conventional roadway cross-section survey methods are time-consuming, labor intensive, require surveying crew to work in close proximity to vehicular traffic (*2*, *5*), and/or may require short-term lane closures disrupting traffic flow that results in congestion (*7*). Cross section data collected using conventional survey methods are done and specified intervals and are not continuous.

Knowing the limits and extents of existing cross slope problems prior to obtaining contractor construction bids for a project is crucial for accurate material quantity estimates, and cost-effective repaving projects, with minimal change orders (*7*). Currently, the location of problematic cross slope sections are identified for improvement using a number of approaches including identifying roadway locations where ponding is apparent, cross slope verification (particularly after rehabilitation projects) using conventional surveying techniques, crash analysis, and tort litigation. In cases of bodily injury and/or fatalities related to hydroplaning crashes, when site investigations determined prevailing pavement cross slope did not meet minimum design criteria, South Carolina Department of Transportation (SCDOT) has been found at-fault in tort claims brought against the department (*7*).

This dissertation research provides a basis for evaluating the effectiveness of Light Detection and Ranging (LiDAR) technology and equipment for addressing maintenance, safety and reconstruction issues in attaining proper pavement cross slope data for use in network-based roadway improvement purposes and programs. MTLS may provide an efficient, high resolution, and reliable cross slope measurement method along the roadway at highway speed (*8*). Similarly, the Airborne LiDAR Scanning (ALS) platform is capable to measuring and monitoring large areas (*8*) and provide continuous and comprehensive 3D point cloud which is use for various applications (*9*). Both MTLS and ALS are evaluated in this research.

Research Objectives

The SCDOT's emphasis on ensuring that adequate pavement cross slopes are maintained through verification is predicated upon two principles: 1) Deployment of a safe and efficient method for collecting cross slope data, and 2) Adoption occurs system-wide so an accurate and comprehensive network-based cross slope database can be maintained. Therefore, the primary goal for conducting this research is to investigate if MTLS and ALS can be efficient, effective, and safe methods for collecting a system-wide, reliable, continuous, and comprehensive cross slope dataset which can serve multiple users in SCDOT and other state highway agencies across the country. The objectives towards achieving the research goal are as follows:

- Develop an efficient work flow for extracting cross slope data from MTLS and ALS point clouds
- Evaluating the accuracy of MTLS and ALS technologies for system-wide verification of highway cross slope.
- Include both mapping grade and survey grade MTLS in the accuracy evaluation.
- Defined the critical water depth at which hydroplaning occurs with regard to the range of vehicle speed, tire tread depth, tire pressure, pavement surface texture, pavement width, and highway cross slope.

In order to achieve the research objectives, LiDAR data was collected on four different roadway test sections, including representative urban and rural restricted roadway locations, and rural parkways in Anderson, SC, Easley, SC, and Spartanburg, SC. The collected data from a single ALS vendor and from six MTLS vendors were used in conducting this evaluation in terms of the accuracy of the collected cross slope data, as well as procedures to calibrate, collect, and process the data. Conventional surveying measurement on 23 selected test stations were used for comparison purposes.

Organization of Dissertation

This dissertation document consists of three research papers on highway cross slope measurement using LiDAR techniques, and each paper accounts for one chapter of the dissertation. The data acquisition sections of the three papers reflect the fact that the same point clouds were used. Consequently, there are tasks which are common through all three papers. The objectives and tasks performed towards achieving the research goal were divided among the three papers and are as follows:

- Task A: Knowledge acquisition
    a. Survey of various state DOTs to Identify current practices related to cross slope data collection
- Task B: Select rodeo section(s)
    a. Non-interstate 4-lane divided section
    b. Lower speed limit than interstates and low vehicle volumes road
    c. The average cross slope should be 2.08%. With some variability
    d. Relatively new pavement - It can be used as a test section over the time
    e. Super elevated horizontal curve section
- Task C: Establish validation sites using conventional survey methods
    a. Requested as-built plans and survey data for rodeo sites
    b. Conducted field surveying under the supervision of an SC Registered Land Surveyor
    c. Primary Survey Control (PSC) points and secoundary control poins were collected and marked throughout the roadway
    d. All control points met SCDOT minimum accuracy.
        i. Horizontal coordinate system: NAD 83 South Carolina State Plane
        ii. Elevations are on NAVD 88 and tied to at least one National Geodetic benchmark.

- Task D: Developed data collection plan including the location of cross section station(s)
- Task E: Conducted vendor rodeo to validate MTLS and ALS
    a. Vendors were asked to provide a point cloud with attributes (e.g., elevation, intensity, etc.)

PAPER I: HIGHWAY CROSS SLOPE MEASUREMENT USING MOBILE LIDAR

OBJECTIVES

- Develop an efficient work flow for extracting cross slope data from MTLS point clouds
- Evaluating the accuracy of MTLS technologies for system-wide verification of highway cross slope
- Include both mapping grade and survey grade MTLS in the accuracy evaluation.

TASKS

- Task F: Extract the cross slopes from both adjusted and unadjusted point clouds on selected stations
- Task G: Compare the MTLS derived cross slopes and the field surveying measurements
- Task H: Perform statistical analysis to investigate whether the method is accurate and meets the acceptable error specification.

PAPER II: EVALUATION OF AIRBORNE AND MOBILE LIDAR ACCURACY IN HIGHWAY CROSS SLOPE MEASUREMENT

OBJECTIVES

- Develop an efficient work flow for extracting cross slope data from MTLS and ALS point clouds
- Evaluating the accuracy of MTLS and ALS technologies for system-wide verification of highway cross slope.

TASKS

- Task F: Extract the cross slopes from both ALS and MTLS point clouds on selected stations using two methods 1) Acquisition the elevation of the two ends of the travel lane along the transverse reference line. 2) The elevation data were extracted along the reference line every 0.2 feet (2.4 inches). Then, a regression line for the association between the extracted elevations and the transverse offset of the center line is fitted to extracted points.
- Task G: Compare the LiDAR-derived cross slopes and the field surveying measurements.
- Task H: Perform statistical analysis to investigate whether the deviation between field measurements and LiDAR-derived cross slopes is acceptable.
- Task I: Perform statistical analysis to compare the accuracy of MTLS and ALS.
- Task J: Perform statistical analysis to compare the accuracy of MTLS on a different traveling lane (e.g., passing and non-passing travel lanes).

PAPER III: THE HYDROPLANING POTENTIAL WITH REGARD TO HIGHWAY CROSS SLOPE

OBJECTIVE

- Defined the critical water depth at which hydroplaning occurs with regard to the range of vehicle speed, tire tread depth, tire pressure, pavement surface texture, pavement width, and highway cross slope.

TASKS

- Task F: Estimate the water depth on the pavement surface regarding the rain intensity, cross slope, longitude grade, pavement width, and pavement surface texture depth.
- Task G: Estimate the critical water depth, and the potential of hydroplaning with regard to the range of vehicle speed, tire tread depth, tire pressure, and pavement cross slope.

The next three chapters (Chapter Two, Chapter Three and Chapter Four) contain the three research papers introduced in this chapter, followed by the dissertation conclusion in Chapter Five and then appendices.

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CHAPTER TWO

PAPER I: HIGHWAY CROSS SLOPE MEASUREMENT USING MOBILE LIDAR

This chapter has been published as the following journal article:

Shams, A., W. A. Sarasua, A. Famili, W. J. Davis, J. H. Ogle, L. Cassule, and A. Mammadrahimli. Highway Cross-Slope Measurement Using Mobile LiDAR. Transportation Research Record Journal of the transportation Research Board. DOI: 10.1177/0361198118756371

Abstract

Ensuring adequate pavement cross slope on highways can improve driver safety by reducing the potential for ponding to occur or vehicles to hydroplane. Mobile Terrestrial LiDAR Scanning (MTLS) systems provide a rapid, continuous and cost-effective means of collecting accurate 3D coordinate data along a corridor in the form of a point cloud. This study provides an evaluation of MTLS systems in terms of the accuracy and precision of collected cross slope data and documentation of procedures needed to calibrate, collect, and process this data. Mobile Light Detection and Ranging (LiDAR) data were collected by five different vendors on three roadway sections. The results indicate the difference between ground control adjusted and unadjusted LiDAR derived cross slopes and field surveying measurements was less than 0.19% at a 95 % confidence level. The unadjusted LiDAR data did incorporate corrections from an integrated inertial measurement unit and high accuracy real-time kinematic GPS however was not post-processed adjusted with ground control points. This level of accuracy meets suggested cross slope accuracies for mobile measurements (±0.2 %) and demonstrates that MTLS is a reliable method for cross slope verification. Performing cross slope verification can ensure existing pavement meets minimum cross slope requirements, and conversely is useful in identifying roadway sections that do not meet minimum standards. The latter is much more desirable than through crash reconnaissance where hydroplaning was evident. Adoption of MTLS would enable South Carolina Department of Transportation (SCDOT) to address cross slope issues through efficient and accurate data collection methods.

Keywords: Mobile Terrestrial LiDAR Scanning (MTLS), Cross slope, Semi-Automatic data extraction, Point cloud

Introduction

Highway pavement cross slope is a crucially important cross-sectional design element as this provides the means to drain water from the roadway surface laterally and helps to minimize the occurrence of ponding. Providing adequate pavement cross slopes ensures positive drainage on highways and improves driver safety by reducing potential for hydroplaning.

SCDOT minimum cross slope design criteria apply to tangent alignments. On high-speed roadways, the normal crown cross slope is ¼” per foot (2.08%) on tangent sections with some exceptions depending on the number of lanes (1). Accommodating other horizontal design features (e.g. super elevation for circular and spiral curves) requires transitioning from a normal cross slope.

While it is important for roadways to meet minimum pavement cross slope design criteria, it is also important that maximum criteria are not exceeded. Cross slopes that are too steep can cause vehicles to drift, skid laterally when braking, and become unstable when crossing over the normal crown to change lanes. Table 2-1 shows potential adverse impacts to safety and operations if minimum and maximum design criteria are not met.

Table 2-1 Potential Adverse Safety Impact of Deviation from Design Criteria

Safety &Operational Issues	Freeway	Expressway	Rural 2-Lane	Urban Arterial
Run-off-road crashes	×	×	×	
Slick pavement	×	×	×	×
Water ponding on the pavement surface	×	×	×	×
Water spreading onto the traveled lanes				×
Loss of control when crossing over a high cross-slope break	×	×	×	

Freeway: high-speed, multi-lane divided highway with interchange access only (rural or urban).
Expressway: high-speed, multi-lane divided arterial with interchange access only (rural or urban).
Rural 2-Lane: high-speed, undivided rural highway (arterial, collector, or local).
Urban Arterial: urban arterial with speeds 45 mph or less

One of the primary objectives for conducting this research was to investigate efficient methods for identifying highway sections that do not meet minimum criteria for pavement cross slope. Currently the location of problematic cross slope sections are identified for improvement using a number of approaches including roadway ponding, cross slope verification (particularly after rehabilitation projects) using conventional surveying techniques, crash analysis, and tort litigation. In cases of bodily injury and/or fatalities related to hydroplaning crashes, when site investigations determined prevailing pavement cross slope did not meet minimum design criteria, SCDOT has been found at-fault in tort claims brought against the Department. Application of conventional survey methods to determine locations of pavement cross slope problems system wide, for all practical purposes, is cost prohibitive. Mobile Terrestrial LiDAR Scanning (MTLS) may provide an efficient and practical solution to addressing this difficult challenge. Accurate pavement cross slope data is crucial for implementing successful and cost-effective repaving and rehabilitation programs and projects that can provide targeted corrective action to addressing cross slope problems.

The researchers recently conducted a survey of state highway agencies across the U.S. (Sarasua et al., 2017), which determined that while 70% collect some type of cross slope data, only 23% of respondents did so to determine cross slope compliance and relatively none did so system-wide. Most of the states only performed cross slope verification on Interstate and primary routes. The fundamental reason for adopting this limited approach is states lack necessary resources to conduct surveying work needed to inventory and verify pavement cross slopes. Furthermore, conventional surveying for cross slope verification can only be conducted at sample locations and may not be representative of segments between the samples. SCDOT's emphasis on ensuring that adequate pavement cross slopes are maintained through verification is predicated upon two principles: 1) deployment of a safe and efficient method for collecting cross slope data; and 2) adoption occurs system wide so an accurate and comprehensive network-based cross slope database can be maintained.

A variety of techniques can be used for acquiring roadway cross slope data including contractor as-built plans if available, photogrammetry using high-resolution stereo images, conventional surveying, attitudinal GPS, remote sensing data such as USGS Digital Elevation Models (DEMs), and measuring with an inertial device such as a digital gyroscope or an accelerometer (2) (4). Factors such as accuracy, safety, cost, and time of performance play important roles in selection of one method over another (4). Conventional surveying methods provide accurate results at sampled locations; however, this approach is very time-consuming (especially for short intervals) and poses safety risks to personnel due to close proximity to traffic (2). Stereo photogrammetry is an accurate method for collecting topographic data but processing time and the need for extensive ground control to produce reasonable cross slope accuracy, plus collecting high-resolution aerial imagery, is an expensive option (2). A vehicle mounted inertial device can collect data at highway speeds however can only obtain measurements for one travel lane at a time. Multiple lanes would require several passes to determine cross slopes for the entire roadway. MTLS is capable of collecting an entire cross section , with an exception at steep side slopes, at highway speeds in a single pass (5)**.**

MTLS strengths include continuous and comprehensive data collection, high-resolution capability, reduced number of field visits, elimination of roadside work hazards for survey crews, and multiple end users and opportunities to share for various applications (6). MTLS weaknesses include: expensive up-front cost, line of sight requirements, adjustment for vehicles scanned within the traffic stream, and need to automate classification of large numbers of points (6). Further, very accurate ground control points is needed to adjust and calibrate MTLS data for applications that require a high level of accuracy.

This research evaluates the use of MTLS for collecting accurate cross slope to ensure that adequate cross slope and proper drainage exist on highways. The LiDAR data was collected on three roadway test sections, including representative urban and rural restricted roadway locations, and rural parkways. MTLS data from five vendors were used in conducting this evaluation. MTLS is evaluated in terms of the accuracy of the collected cross slope data, as well as procedures to calibrate, collect, and process the data. Conventional surveying methods were also used for comparison purposes.

Literature Review

The literature review focused on mobile methods for collecting cross slope data and the relative accuracies of the collected data. Inertial devices as a sole cross slope data collection device is not covered because, while they can be extremely accurate, they can only collect a single lane of data with one pass. The use of MTLS to collect cross slope data requires an integrated inertial measurement unit (IMU) for location adjustments and to compensate for the roll of the vehicle.

Baffour (2002) discussed the need of the roadway geometry in many transportation projects. Although some geometry information may be extracted from existing road plans, but some of the current characteristics may not match with the original design due to undocumented changes. The paper discussed the use of multi antenna configurations that are synchronized with a single Global positioning System (GPS) receiver to determine the three-dimensional orientation of the moving vehicle. After designing the antenna platform all of the data collected was compared with standard data collected by conventional surveying. The cross slopes were collected at 50’ intervals, and the accuracy was at 0.01%. Therefore, the results showed attitudinal GPS has exceptional promise as a tool for collecting this data (4). A drawback of attitudinal GPS is that, similar to an inertial device, only one lane can be collected and thus, multiple passes would be required for multi-lane roads.

Sourleyrette et al. (2003) attempted to collect grade and cross slope from LiDAR data on tangent highway sections. Measurements were compared against grade and cross slope collected using an automatic level for 10 test sections along Iowa Highway 1. The physical boundaries of shoulders and lanes were determined by visual inspection from (a) 6-in resolution orthophotos (b) 12-in ortho photo by Iowa DOT and (c) triangular irregular network (TIN) from LiDAR. Multi linear regression analysis was conducted to fit the plane to the LiDAR data corresponding to each analysis section. Vendor accuracy was 0.98-ft RMSE and vertical accuracy of 0.49 ft. While the grade was successfully calculated within 0.5% for most sections, and 0.87% for all sections, the accuracy of the cross-slope data was much less accurate. Cross-slope estimated from LiDAR deviated from field measurements by 0.72% to 1.65%. Thus, results indicated cross-slope could not be practically estimated using a LiDAR surface model (2).

Jaakkola et al. (2008) discussed that laser-based mobile mapping is necessary for transportation study due to the large amount of data produced. Data was collected by the Finnish Geodetic Institute (FGI) Roamer Mobile Mapping System (MMS). The authors classified points belonging to the painted marking on the road, and found the curb stones from the height of the image. Finally, they modeled the pavement as a TIN. Therefore, they processed the raster image, which is more efficient than point cloud. The proposed method was able to locate most curbstones, parking spaces, and a zebra crossing with mean accuracies of about 80% or better (5).

Zhang and Frey (2012) attempted to model road grade using LiDAR to estimate vehicle emissions. It was difficult to measure road grade directly from portable emissions monitoring systems (PEMS). The available GPS data has not been proven to be reliable for road grade estimation. Therefore, the LiDAR based method was used to model the road grade on interstate highways I-40 and I-540, as well as major arterials. The LiDAR data was used to fit a plane using regression techniques. The precision of LiDAR data was quantified by root mean square error (RMSE). The RSME of LiDAR data used in this work was reported to range from 7.7 to 25 cm, which was much smaller than changes in elevation that were significant with respect to emissions. Finally LiDAR data was shown to be reliable and accurate for road grade estimation for vehicle emission modeling (7).

Tsai et al. (2013) proposed a mobile cross slope measurement method, which used emerging mobile LiDAR technology, a high-resolution video camera, and an accurate positioning system composed of a GPS, an inertial measurement unit, and a distance measurement instrument. Accuracy and repeatability of the proposed method were critically validated through testing in a controlled environment. Results showed the proposed method achieved desirable accuracy with a maximum difference of 0.28% cross slope (0.17°) and an average difference of less than 0.13% cross slope (0.08°) from the digital auto level measurement. Repeatability results showed standard deviations within 0.05% (0.03°) at 15 benchmarked locations in three runs. However, the acceptable accuracy is typically 0.2% (or 0.1°) during construction quality control. The case study on I-285 demonstrated the proposed method could efficiently conduct the network-level analysis. The GIS-based cross slope measurement map of the 3-mile section of studied roadway can be derived in fewer than two person hours with use of the collected raw LiDAR data (8).

Holgado-Barco et.al. (2014) attempted to extract road geometric parameters through the automatic processing of mobile LiDAR system point clouds. Their methodology was carried out in several different steps: 1) data capture, 2) segmentation to simplify the point cloud to extract the road platform, 3) applying principal component analysis (PCA)-based on orthogonal regression to fit the best plane on points, and 4) extracting vertical and cross section geometric parameter and analysis. The study's method proposed an alternative automated development of the as-built plan. The experiment results validate the method within relative accuracies under 3.5% (9).

Study Area

This research evaluated the use of MTLS from five vendors to obtain accurate cross slope data. Three roadway test sections were used in performing the research evaluation including: 1) a 4-lane parkway without any curb cuts (driveways) in Anderson, SC 2) a section of urban restricted access highway in Spartanburg, SC, and 3) a rural restricted access highway just west of Easley, SC.

Study Section 1: East West Parkway (Using Adjusted Point Cloud)

The first study section is a 3-mile corridor along East West Parkway (EW Pkwy) in Anderson, SC shown in Figure 2-1. The study section originates at US-76 (Clemson Boulevard) and terminates at the SC-81 (E Greenville St). EW Pkwy is a limited access 4-lane 2-way mostly divided highway. It has a variety of geometric design elements including

15-vertical curves, 7-horizontal curves (all super elevated), one-bridge, two-intersections, traversable and non-traversable medians, two-lanes per direction with an additional turning lane at intersections, and sections with adjacent bike lane and separate bike path.

MTLS combines precise ranging, with high accuracy GPS and an integrated IMU to obtain a very dense point cloud. The resulting point cloud can be useful for many applications such as asset data collection (lane widths, presence of median, etc.) or navigation but may not be accurate enough for surveying or some engineering applications such as precise quantity take-offs. To improve accuracy for this research, a ground control survey was conducted that identified primary and secondary geodetic control point (GCP) locations throughout the corridor. At least two primary GCPs were used by venders as base station locations for GPS differential correction and all of the GCPs (both primary and secondary) were used for post-processing adjustment. Figure 2-1 shows the GCP locations along the study corridor.

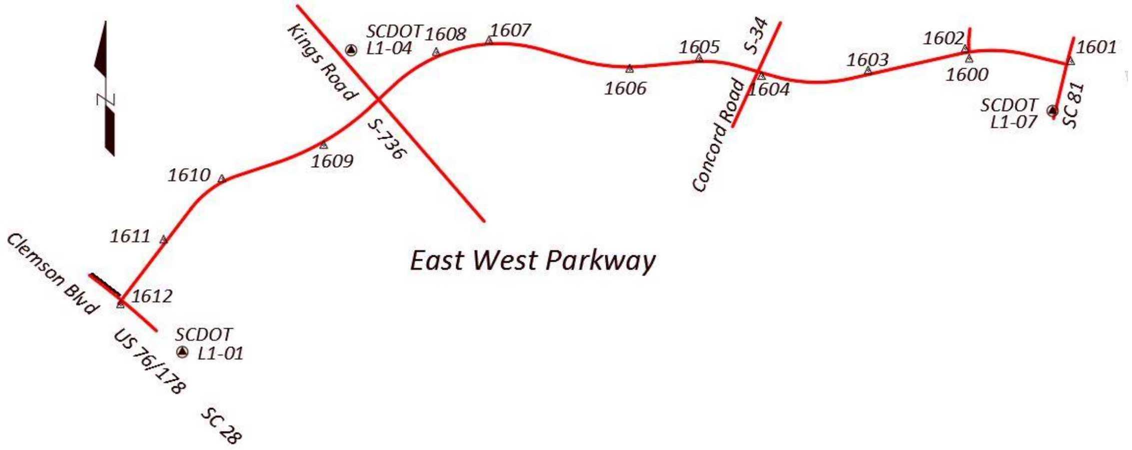

Figure 0-1 GCPs and check points along the 3-mile study area section 1

The corridor was also surveyed to locate 100-ft. stations along white edge lines. These locations were marked with PK surveying nails. Eight of these locations were selected along the corridor as cross slope test sections. The test sections were selected to ensure diverse roadway cross slope characteristics including differing lane geometry, normal crown, and super elevated sections. PK surveying nails were also added to the yellow centerline markings. Reflective pavement marking tape was used to ensure that PK nail locations could be identified in the LiDAR data using the intensity attribute.

Study Section 2: Intestate 85 Business Loop (Using Adjusted Point Cloud)

The second study section is a 3.4-mile corridor along Interstate 85 business loop (I-85 BL) in Spartanburg, SC shown in Figure 2-2. The study section originates at I-585 and terminates at I-85. I-85 BL is a restricted access 4-lane 2-way divided freeway. Researchers measured cross slopes at selected locations prior to the test. These locations correspond with panel points P78, P91, P98, P103, P126 and P127 (note that P103, P126 and P127 are on ramps). All panel points are marked with a painted chevron, yellow reflective pavement marking tape, and a PK nail. Detailed surveying of horizontal/vertical elements was not conducted within the travel way of this study section, however, primary and secondary GCPs were established along paved shoulders. The GCPs were used for GPS differential correction and for post-process adjustment.

Figure 2-2 GCPs and panel point along the study area section 2

Study Section 3: US-123 (using unadjusted point cloud)

The third study section is a 1-mile corridor along US-123 just west of Easley, SC. This section of US-123 is a restricted access 4-lane 2-way divided highway. The survey crew measured cross slopes at selected locations prior to the test. These locations correspond with different traffic signs located at six pre-designated stations along the corridor. As with previous study sections the LiDAR measurements were combined with high accuracy GPS and IMU measurements to create a point cloud. However, on US-123 the point cloud was not adjusted through post-processing with GCPs. It is not uncommon to use unadjusted mobile LiDAR point clouds for applications that do not require the highest level of accuracy such as statewide asset management or autonomous vehicle applications.

Data Collection

Field Surveying Using Auto Level

Conventional surveying (auto leveling combined with taping and total station measurements) was used to develop ground truth cross slopes for all 3 test sections. Each of the cross section stations were leveled using two different instrument setups to ensure accuracy and adjust for random error. The cross slope along each section was computed for each lane from the elevation difference between lane lines, along with horizontal distances in between, which was measured by tape or total station.

LiDAR Data Collection

LiDAR data for sections 1 and 2 were collected by 2 vendors on June 30th, 2016 and 2 other vendors on August 30th, 2016. Section 3 data was collected in 2015. The section

1 and 2 vendors and their stated equipment specifications are provided in table 2-2. On section 3, the vendor's LiDAR system was a Reigl VMX 450. Vendors were allowed to calibrate their systems both before and after data collection runs. A primary benefit of a MTLS is that point cloud data can be collected for multiple travel lanes with a single pass. For this study, vendors were asked to collect data by direction by driving in the right lane. Only a single pass was allowed for each direction. Vendors were asked to follow a lead vehicle that drove at the posted speed limit. For section 1, traffic control was provided by two trailing SCDOT vehicles driving side by side so that no cars could pass the vendor data collection vehicles; however, for practical purposes, there was no traffic control for the opposing travel direction. There was no traffic control for section 2 or section 3.

Table 2-2 Vendor Data Collection Specifications for Test Sections 1 and 2

	Vendor A	Vendor B	Vendor C	Vendor D
Brand	Riegl	Teledyne Optech	Teledyne Optech	Leica
Model	VMX450	M1	SG1	9012
Single/Dual Laser	Dual	Dual	Dual	Single
Measurement rate	1100 kHz	500 kHz / sensor	600kHz (each Laser)	1000 kHz

Extracting Cross Slope from Point Cloud

There were two potential methods to define the cross section line at each test section as follows: 1) in cases where the location of the PK nails on two ends of the test section were distinctly identified, a reference line was drawn between the two points, else 2) the LiDAR image of the pavement marking tape pointing to the PK nails was used to create the reference line. Using the reference line from either method, a 4-inch buffer of points was clipped in an automated fashion using ArcGIS. Two separate mesh grid surfaces were fitted to the LiDAR derived points using nearest neighbor interpolation within the buffer area. One mesh grid included continuous values of easting, northing, and elevation, fitted to the LiDAR points (Figure 2-3). The second mesh grid included the easting, northing and Intensity of the points.

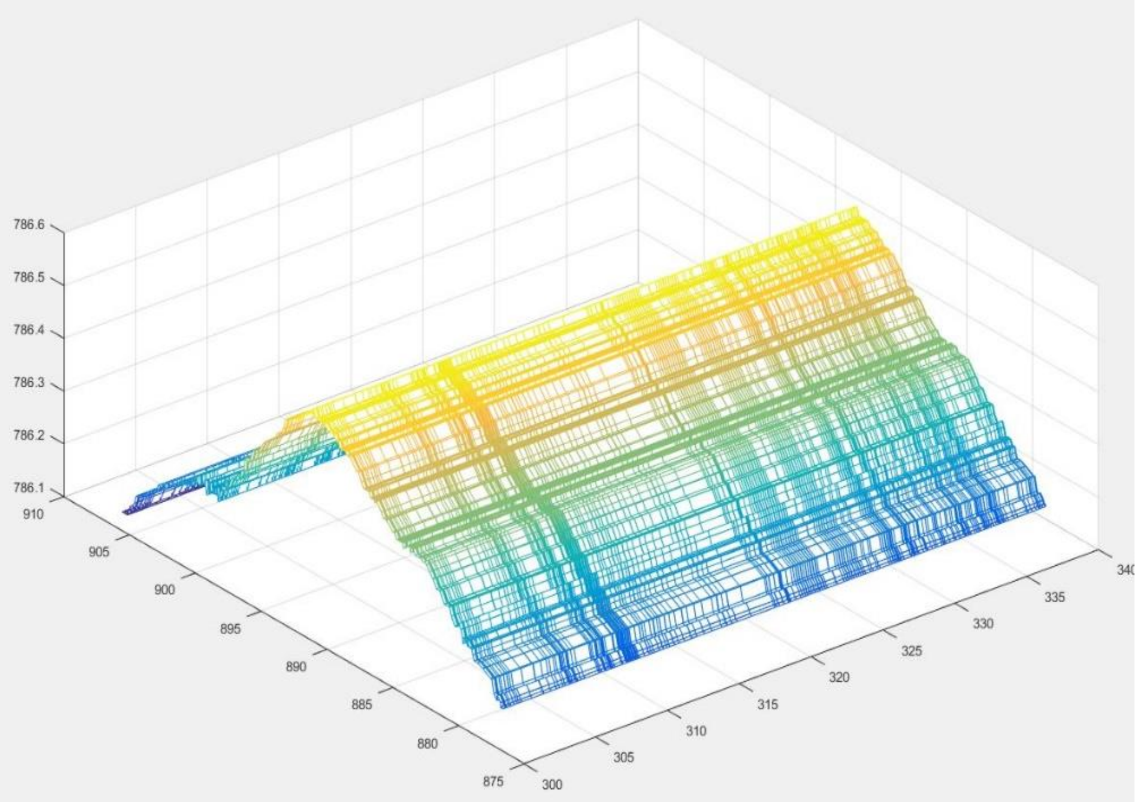

Figure 0-3 Mesh grid fitted to points within buffer area

Using the reference line, a continuous cross section is extracted including elevation and intensity. Because the yellow and white pavement markings have higher intensity values, they are easily identifiable (Figure 2-4). The cross slope is calculated from the rise and run between the lane lines. These LiDAR derived cross slopes are directly comparable to the field survey cross slopes.

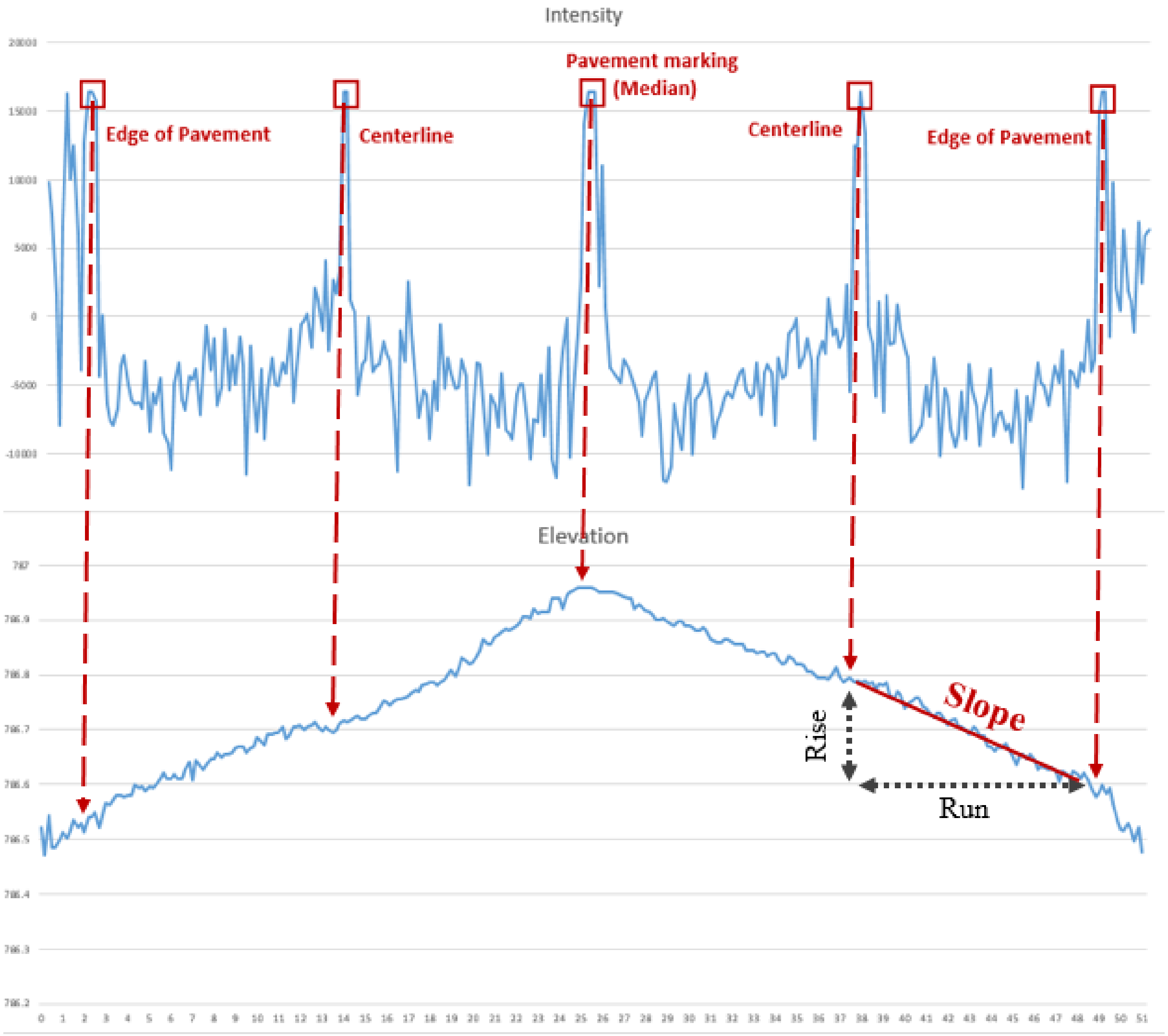

Figure 2-4 Pavement marking extraction and corresponding elevations

Comparison of LiDAR and Conventional Survey Data

The use of LiDAR to extract pavement cross slope dimensions on three study sections was compared against cross slope measurements collected using conventional surveying for eight specific roadway stations along EW Pkwy Anderson, SC, six-stations on I-85 BL and at six sign locations on US-123. The MTLS data collected by the vendors was provided as dense point clouds and evaluated using a number of comparative methods. Reference lines within each roadway study location were created between two distinct surveyed points established with PK nails and reflective pavement marking tape. Elevation and intensity of points along the reference lines were extracted from the mesh grid fitted to LiDAR point clouds within 4-inches thickness at across each station of interest. Due to the difference of reflectivity of the materials, which resulted in different intensities in the point cloud, the edge of the pavement, lane lines and centerline were readily extracted from LiDAR data by matching intensity and elevation results. After which, the pavement cross slope for each travel lane was calculated by dividing the difference in elevations by the distance between two pavement markings. Additionally, pavement cross slopes were directly measured in the field for each test section using automatic leveling. Field measurements were used as reference data for comparison against vendor collected LiDAR derived data.

A cross slope comparison for different test sections at three different study areas are shown in tables 2-3, 2-4, and 2-5 respectively. The comparison is based on each travelling lane and the vendor names have been removed and are shown in random order.

Table 2-3 Cross Slope Comparison between Surveyed Data and LiDAR Derived Cross Slope - Section 1

Station	Lane	Lane width (HD)	Surveyed Data	Difference from surveyed data			
				Vendor A	Vendor B	Vendor C	Vendor D
110+00	EB Outer	12.02	1.75%	0.25%	0.30%	0.34%	0.11%
	EB Inner	12.18	1.97%	0.00%	0.22%	0.71%	0.11%
	WB Outer	12.04	1.83%	0.07%	0.10%	0.24%	0.22%
	WB Inner	11.74	2.22%	0.14%	0.00%	0.55%	0.22%
124+00	EB Outer	11.72	4.61%	0.23%	0.18%	0.07%	0.08%
	EB Inner	12.93	5.14%	0.30%	0.55%	0.40%	0.54%
	Turning	14.41	4.82%	*	0.42%	0.66%	0.80%
	WB Outer	11.7	4.79%	0.20%	0.90%	0.24%	0.35%
	WB Inner	12.04	4.32%	0.02%	0.47%	0.04%	0.02%
128+00	EB Outer	11.72	2.39%	0.24%	0.02%	0.10%	0.09%
	EB Inner	12.19	2.26%	0.10%	0.11%	0.15%	0.37%
	Turning	12	1.58%	0.26%	0.19%	0.23%	0.37%
	WB Outer	12	0.46%	0.24%	0.16%	0.02%	0.00%
	WB Inner	12	0.04%	0.03%	0.20%	0.05%	0.00%
149+00	EB Outer	11.6	0.86%	0.26%	0.01%	0.03%	0.56%
	EB Inner	11.64	0.69%	*	0.10%	0.01%	0.21%
	WB Outer	11.77	2.63%	0.22%	0.15%	0.12%	0.19%
	WB Inner	11.96	2.80%	0.05%	0.39%	0.12%	0.19%
203+00	EB Outer	11.94	3.81%	0.09%	0.22%	0.02%	0.00%
	EB Inner	11.83	4.65%	0.08%	0.02%	0.04%	0.23%
	WB Outer	11.57	3.59%	0.07%	0.50%	0.09%	0.07%
	WB Inner	11.86	4.60%	0.06%	0.46%	0.00%	0.19%

208+00	EB Outer	11.62	2.32%	0.28%	0.08%	0.07%	0.05%
	EB Inner	11.88	2.48%	0.17%	0.06%	0.06%	0.02%
	Turning	11.19	2.01%	0.30%	0.01%	0.06%	0.02%
	WB Outer	11.9	1.09%	0.06%	0.34%	0.15%	0.12%
	WB Inner	11.42	0.00%	0.24%	0.12%	0.00%	0.00%
227+00	EB Outer	11.73	2.39%	0.00%	0.29%	0.03%	0.19%
	EB Inner	12.13	2.14%	0.03%	0.37%	0.00%	0.19%
	WB Outer	11.81	1.91%	0.98%	*	*	0.46%
	WB Inner	11.95	1.88%	0.04%	0.32%	0.01%	0.05%
232+00	EB Outer	11.7	2.48%	0.00%	0.04%	0.07%	0.10%
	EB Inner	11.75	2.77%	0.12%	0.50%	0.03%	0.01%
	WB Outer	11.48	2.79%	0.02%	0.13%	0.05%	0.05%
	WB Inner	11.92	1.97%	0.02%	0.57%	0.02%	0.00%

*data were missing in point cloud

Table 2-4 Cross Slope Comparison between Surveyed Data and LiDAR Derived Cross Slope – Section 2

Station	Lane	Lane width (HD)	Surveyed Data	Difference from surveyed data		
				Vendor A	Vendor B	Vendor C
P-78	WB Outer Lane	12.04	3.26%	*	0.12%	0.08%
	WB Inner Lane	11.62	1.40%	*	0.18%	0.02%
	EB Inner Lane	11.87	1.31%	0.42%	0.15%	0.31%
	EB Outer Lane	12.09	1.45%	0.24%	0.11%	0.06%
P-91	WB Outer Lane	12.01	3.41%	0.12%	0.19%	0.07%
	WB Inner Lane	11.82	1.27%	0.07%	0.23%	0.12%
	EB Inner Lane	11.72	1.71%	0.03%	0.19%	0.03%
	EB Outer Lane	12.07	1.91%	0.02%	0.16%	0.13%
P-98	WB Outer Lane	12.04	1.96%	0.00%	0.00%	0.04%
	WB Inner Lane	11.62	1.03%	0.42%	0.25%	0.34%
	EB Inner Lane	11.87	1.60%	0.01%	0.19%	0.01%
	EB Outer Lane	12.07	2.50%	0.03%	0.12%	0.05%
P-103	WB Outer Lane	11.77	6.69%	0.63%	0.73%	0.70%
	WB Inner Lane	11.51	7.54%	0.54%	0.56%	0.57%
P-126	WB Outer Lane	11.97	3.97%	*	0.14%	0.12%
	WB Inner Lane	12.09	4.47%	*	0.33%	0.24%
P-127	WB Outer Lane	11.43	1.40%	0.48%	*	0.04%
	WB Inner Lane	12.24	1.12%	0.67%	0.80%	0.12%

*data were missing in point cloud

Table 0-5 Cross Slope Comparison between Surveyed Data and LiDAR Derived Cross Slope – Section 3

Station	Lane	Lane width	Surveyed Data	Vendor E	Difference from surveyed data
34+31	EB outer lane	11.98	1.50%	1.30%	0.20%
	EB Inner lane	12.00	1.92%	2.08%	0.16%
38+52	EB outer lane	12.00	1.75%	1.91%	0.16%
	EB Inner lane	11.96	0.92%	1.08%	0.16%
44+20	EB outer lane	11.98	2.00%	2.17%	0.17%
	EB Inner lane	12.00	1.16%	1.33%	0.17%
44+68	EB outer lane	12.00	2.16%	2.25%	0.09%
	EB Inner lane	11.95	1.25%	1.42%	0.17%
45+92	EB outer lane	12.00	1.92%	2.00%	0.08%
	EB Inner lane	11.97	0.92%	1.16%	0.24%
57+39	EB outer lane	11.96	8.08%	8.08%	0.00%
	EB Inner lane	11.97	6.58%	6.41%	0.17%

Evaluation of Results

In evaluating cross sectional data at reference station locations, cross slope estimates from adjusted LiDAR differed from field surveyed measurements ranging from 0% to 0.98% with an average of 0.19% for all vendors, as shown in table 2-6. Similarly, the comparison between unadjusted LiDAR data and field surveying varies from 0% to 0.24%. With regard to SHRP2 guide specification a slope tolerance value of ± 0.2% of the design value would be acceptable for final measurement after project completion (10). The LiDAR derived point clouds on section 1 and 2 were adjusted using IMU measurements and through post-processing with ground control points, however, the section 3 point cloud was adjusted only with the integrated IMU data. The one sided t-test for both adjusted and unadjusted LiDAR indicates at a 95 % confidence level the difference of the LiDAR derived slopes and field surveying was less than 0.19% (table 2-6). Cross slope calculations are based on relative elevation of points along reference lines. Therefore, study results indicate that regardless of whether data is adjusted or unadjusted through post-processing with ground control points, cross slopes can accurately be estimated, within acceptable tolerance, using LiDAR surface model data.

Table 2-6 Summary of Cross slope Comparison

Section 1, East West Parkway					
	EB-Outer Lane	EB-Inner Lane	Turning Lane	WB-Inner Lane	WB-Outer Lane
Min	0%	0%	0.01%	0%	0%
Max	0.56%	0.71%	0.80%	0.57%	0.98%
Mean	0.14%	0.19%	0.30%	0.14%	0.22%
Median	0.09%	0.11%	0.26%	0.05%	0.15%

One side t-test	Margin of error	n	p-value	Significant
	0.18%	136	<0.05	Yes

Section 2, I-85 Business Loop				
	EB-Outer Lane	EB-Inner Lane	WB-Inner Lane	WB-Outer Lane
Min	0.02%	0.01%	0.02%	0.00%
Max	0.24%	0.42%	0.80%	0.73%
Mean	0.1%	0.15%	0.34%	0.23%
Median	0.11%	0.15%	0.29%	0.12%

One side t-test	Margin of error	n	p-value	Significant
	0.19%	49	<0.05	Yes

Section 3, US -123		
	EB-Outer Lane	EB-Inner Lane
Min	0.16%	0.00%
Max	0.24%	0.20%
Mean	0.18%	0.12%
Median	0.17%	0.13%

One side t-test	Margin of error	n	p-value	Significant
	0.18%	12	<0.05	Yes

Cross Slope Sensitivity Analysis

The typical range for cross slopes along urban arterials is 1.5 to 3 percent (11); the lower portion of this range is appropriate where drainage flow is across a single lane and higher values are appropriate where flow is across several lanes (11). On high-speed roadways, SCDOT recommends that the normal cross slope be 2.08% on tangent sections with some exceptions depending on the number of lanes (1). Inherent characteristics of paving operations leads to deviations from design cross slope values. As previously discussed, these deviations can potentially compromise safety. Identifying roadway sections that do not meet minimum criteria requires accurate cross slope measurements. To quantify the safety effects of MTLS cross slope measurement errors the researchers conducted a cross slope sensitivity analysis on hydroplaning potential.

When rain falls on a sloped pavement the path that runoff takes to the pavement edge is called the drainage path and the water depth that accumulates on pavement can be calculated from the following equations (12).

$$L_f = L_x \left(\left(1 + \left({}^{S_g}\!/_{S_x} \right)^2 \right)^{0.5} \right. \tag{2-1}$$

$$WD_0 = 0.00338\, TXD^{0.11} {L_f}^{0.43} I^{0.59}\, {S_x}^{-0.42} - TXD \tag{2-2}$$

$$WD = (WD_0 + TXD) \times \sqrt{1 + \left({}^{S_g}\!/_{S_x} \right)^2} - TXD \tag{2-3}$$

Where,

S_x = cross slope (ft/ft)

S_g = longitudinal grade (ft/ft)

L_x = pavement width (ft) from crown of the pavement

L_f = length of flow path

WD = water depth above the top of the surface asperities (in)

TXD = texture depth (in)

I = intensity of rainfall in (in/hr)

On wet pavement, when tires lose contact with the pavement due to water film depth, hydroplaning is likely to occur (12). A water depth of 0.15 inches can lead to hydroplaning for a passenger vehicle traveling at highway design speeds (12). To determine how the difference in cross slope values impact the water depth, the following assumption has been made (S_g = 4.5%, TXD = 0.04 (50 percentile) (12)). Using the above equations, the impact of changes in cross slope on water depth accumulation by rainfall intensity were calculated and the results are shown in Figure 2-5.

Driving visibility is reduced when rainfall intensity exceeds 2 in/hr, and becomes poor when intensity exceeds 3 in/hr (14). So, it is expected that vehicle operators will refrain from driving or drive very slowly during such heavy rainfall periods (12). The SCDOT uses a maximum construction tolerance of +/- 0.348% (1). For a highway section with a typical cross slope of 2.08%, an allowable minimum cross slope would be 1.73%. Using the SHRP 2 suggested slope acceptable measurement error ± 0.2% (10) which is greater than the average MTLS measurement error of +/- 0.19% found in this research a cross slope of 1.93% can potentially be considered acceptable when incorporating a +0.2% error. According to Figure 2-5, a cross slope of 1.93% corresponds to a water depth of 0.05 inches which has a low potential for hydroplaning for vehicles traveling at highway speeds for rain fall intensities less than 1 in/hr. For longitudinal grade over than 4.5% the MTLS needs supplemented sample survey data. This suggests that typical MTLS measurement error is acceptable for cross slope verification purposes.

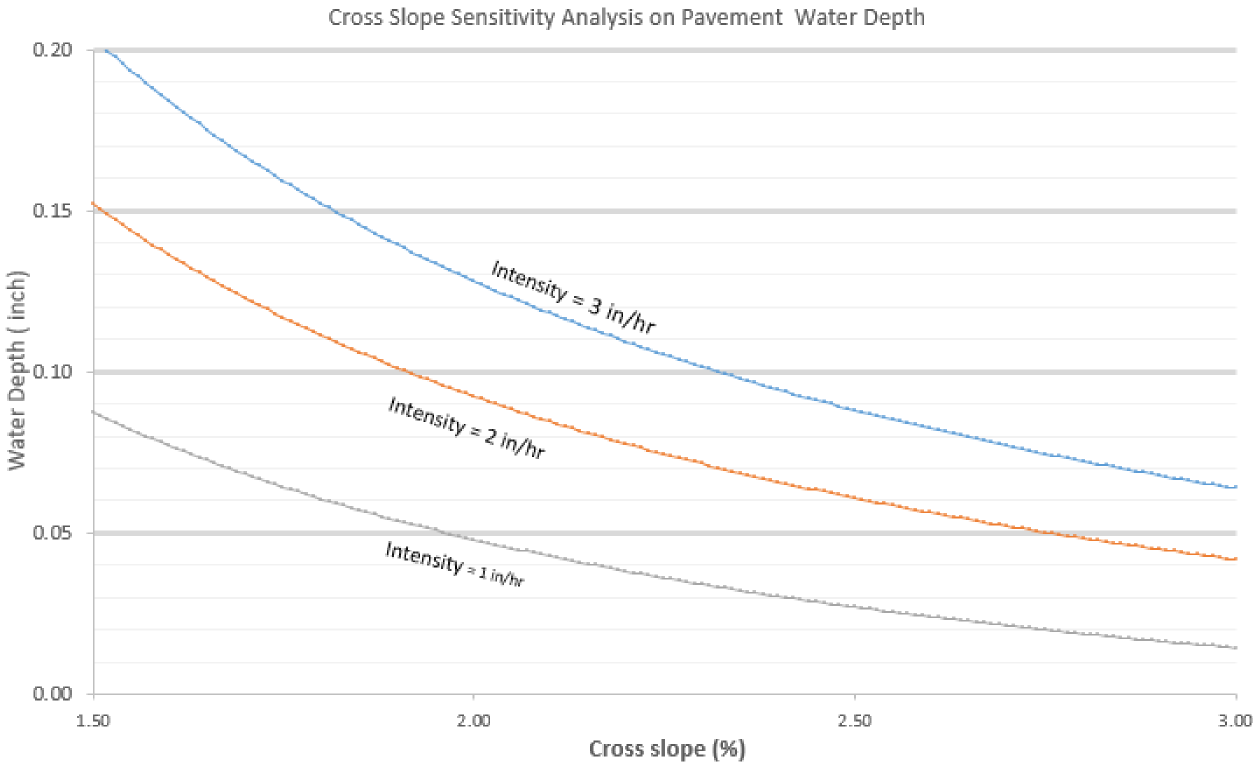

Figure 0-5 Cross slope sensitivity analysis on pavement water depth

Conclusion

The use of MTLS to extract the cross slope was evaluated on 20 stations including 65 travel lanes. Results of this research proved the feasibility of automated data collection vehicles in comparison to human collection methods to collect data efficiently, accurately, and reliably. The results of t-test statistical analysis indicated the average deviation between LiDAR data and field surveying measurements was less than the minimum acceptable accuracy value (±0.2% specified by SCDOT and SHRP 2) at a 95 % confidence level. It is noteworthy that both adjusted and unadjusted LiDAR data met the SCDOT standard.

Common survey data collection methods are time consuming and require data collectors to be located on the road, which poses a safety issue. However, new efficient methods such as MTLS are available to capture accurate cross-slope, grades, location, and a variety of other geometric design characteristics. These new applications increase productivity and minimize road crew exposure and create robust information products that serve multiple uses such as flood mapping, hydroplaning, and road inventory.

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CHAPTER THREE

PAPER II: EVALUATION OF AIRBORNE AND MOBILE LIDAR ACCURACY IN HIGHWAY CROSS SLOPE MEASUREMENT

This Chapter has been submitted as a paper for presentation at the 98th Transportation Research Board Annual Meeting and publication in the Transportation Research Record: Journal of the Transportation Research Board

Abstract

Adequate water drainage on highways is crucial in minimizing the potential of hydroplaning. The highway cross slope has a significant effect of draining water laterally from the pavement surface. Currently, field surveying techniques and other manual methods are used to collect cross slope data on a limited basis in most states despite the fact that field surveying and other manual methods are labor intensive and expose personnel to traffic. Further, field surveying cannot provide continuous data; it can only be conducted at sample locations. This study provides a technical evaluation of Aerial LiDAR Scanning (ALS) and Mobile Terrestrial LiDAR Scanning (MTLS) systems to measure cross slopes. The ALS and MTLS data are from a 3.4-mile freeway segment in Spartanburg, South Carolina. The cross slopes extracted from the Light Detection and Ranging (LiDAR) point clouds were from five selected test sections, using two different methods 1) End to End method using elevations only from the pavement edge lines to generate the cross slope; and 2) 0.2 feet interval point extraction along the cross-section and using a fitted linear regression line as the basis for the cross slope. The cross slopes were also measured on test sections using conventional surveying methods and compared with the LiDAR extracted cross slopes. Results demonstrate that LiDAR methods are reliable for collecting accurate pavement cross slopes and should be considered for statewide cross slope verification purposes to proactively address cross slope and drainage issues.

Keywords: Airborne LiDAR Scanning (ALS), Mobile Terrestrial LiDAR Scanning (MTLS), Cross slope, Point cloud

Introduction

Effective water drainage from the pavement surface is an essential element of highway design (*1*). Water above the pavement surface may interrupt traffic, reduce skid resistance, and increase the potential for hydroplaning (*1*). Water drainage from the pavement surface is dependent on pavement longitudinal grade, cross slope, width, surface texture, and rainfall intensity (*2*). Although longitudinal grade may have a significant effect on flow path length, it does not appreciably effect pavement water depth (*2*, *3*). However, the cross slope has a substantial impact on water film thickness on the pavement surface because it helps to drain water laterally and minimize ponding (*4*). Flat pavements reduce driver safety by failing to drain water adequately leading to ponding (*5*). Conversely, steeper cross slopes may cause a vehicle to drift toward the low edge of the travel lane. Drifting is a significant concern where rain, snow, and icy conditions are common (*5*). On paved two lane roadways crowned at the center, the acceptable rate of cross slope ranges from 1.5 to 2 % (*5*). When three or more lanes are inclined in the same direction, the rate may be increased by approximately 0.5 to 1 %. However, a cross slope should not typically exceed 3 % on tangent alignments unless there are three or more lanes in one direction of travel (*5*). Cross slopes up to 4 % on tangents are acceptable in areas with intense rainfall (*5*).

The South Carolina Department of Transportation (SCDOT) minimum cross slope design criteria apply to tangent alignments. On high-speed roadways, the standard crown cross slope is ¼" per foot (2.08%) on tangent sections with some exceptions depending on the number of lanes (*6*). Accommodating other horizontal design features (e.g., super elevation for circular and spiral curves) requires transitioning from a typical cross slope.

A survey of state highway agencies across the U.S. determined that while 70% collect some cross slope data, none did so on a system-wide basis. Most of the states surveyed performed cross slope verification only on Interstate and primary routes and only at locations with apparent drainage problems or locations that experience a high number of weather-related crashes (*4*, *7*). SCDOT is interested in identifying technology that can be used to efficiently collect pavement cross slope data on a wide scale basis.

Currently, conventional surveying techniques or other manual methods are used to collect cross slope data in most states at selected locations. Conventional surveying and other manual methods are labor intensive, expose personnel to traffic, and cause delays to the traveling public (*8*). Furthermore, conventional surveying for cross slope verification purposes can only be conducted at sample locations and may not be representative of segments between the samples (*4*). SCDOT's emphasis on ensuring that adequate pavement cross slopes are maintained through verification is predicated upon two principles: 1) deployment of a safe and efficient method for collecting cross slope data; and 2) adoption occurs system-wide so an accurate and comprehensive network-based cross slope database can be maintained (*7*).

Light Detection and Ranging (LiDAR) techniques may provide an efficient and practical solution to addressing this difficult challenge. Accurate pavement cross slope data is crucial for implementing successful and cost-effective repaving and rehabilitation programs and projects that can provide targeted corrective action in addressing cross slope problems. Low altitude Airborne LiDAR Scanning (ALS) is aerial mapping technology where airplanes are flown at approximately 1,500 feet above ground level (*9*), while in Mobile Terrestrial LiDAR Scanning (MTLS) the data is captured from a vehicle traveling at highway speeds. In both systems, the LiDAR sensor is scanning the ground while simultaneously recording positional data using a Global Positioning System (GPS), Inertial Measurement Units (IMU), a Distance Measurement Indicator (DMI), and cameras (*10*). The resulting point data cloud contains highly accurate three dimensional (3D) locations of topographic features of the roadway and nearby areas (*10*). The ALS platform is capable of scanning large areas and a typical survey can collect data up to 20,000 acres per day (*9*). MTLS systems collect field data of up to 150 road-miles a day (7); however, the airborne derived point cloud is typically less dense in comparison to mobile LiDAR point cloud because of the relative distance of the LiDAR scanner to the pavement surface. MTLS is capable of collecting an entire cross-section (within line of sight) at highway speeds in a single pass (*11*)**.** Accurate ground control points are often needed to adjust the LiDAR data locations for applications that require a high level of positional accuracy.

This research evaluates the use of MTLS and ALS for collecting accurate cross slope data along a corridor to ensure that adequate cross slopes and proper drainage exist on highways. The LiDAR data was collected along a 3.4-mile corridor of Interstate 85 Business Loop (I-85 BL) in Spartanburg, SC.

Literature Review

Uddin (*9*) evaluated the accuracy, efficiency, and cost-effectiveness of airborne LiDAR technology compared with conventional aerial photogrammetry and field surveying using a total station. High resolution satellite imagery (e.g., QuickBird 2) with a spatial resolution of less than a meter can be used in place of aerial photography as a backdrop for LiDAR topography, but does not provide sufficient elevation accuracy for accurate terrain mapping. The study was focused on an 8 km (5.9 miles) highway section of the Raleigh Bypass near Jackson, Mississippi. The results showed there was no statistical difference between, airborne LiDAR, aerial photogrammetry, and ground surveying using a total station. However, the Root Mean Square (RMSE) value between the LiDAR and the total station was 15 to 18 cm.

Sourleyrette et al., (*12*) attempted to collect grade and cross slope information from airborne LiDAR data on tangent highway sections. Measurements were compared against grade, and cross slope collected using an automatic level for 10 test sections along Iowa Highway 1. The physical boundaries of shoulders and lanes were determined by visual inspection from (a) 6-inch resolution orthophotos (b) 12-inch ortho photo by Iowa DOT and (c) a LiDAR-derived triangular irregular network (TIN). Multilinear regression analysis was conducted to fit the plane to the LiDAR data corresponding to each analysis section. The horizontal accuracy was 0.98 feet and vertical accuracy of 0.49 feet. While roadway grade was successfully calculated within 0.5% for most sections, and 0.87% for all sections, the cross slope data was much less accurate. Cross slope estimated from LiDAR deviated from field measurements by between 0.72% to 1.65%. Therefore, the results indicated cross slope could not be practically estimated using the acquired aerial LiDAR-derived surface model. It is noteworthy that LiDAR technology has improved significantly since this study was completed.

Miller et al., (*10*) investigated the potential of MTLS technology (using Riegl VMX-250) instead of traditional survey methods to collect data for highway improvement projects. The project area selected for evaluation was the I-35/IA 92 interchange in Warren County, Iowa. The elevation comparison was made on 1823 points on the pavement, which were surveyed using a total station and generated through the MTLS process. The MTLS derived data met Iowa DOT specifications for surveying with a RMSE of the error was 0.0695.

Tsai et al., (*13*) proposed a mobile LiDAR cross slope measurement method, which included mobile LiDAR system (Riegl LMS-Q120i), a high-resolution video camera, and an accurate positioning system composed of a GPS, an IMU, and a DMI. In this system thethe scanning line of the forward shooting LiDAR system was aligned parallel to the transverse direction as the vehicle moves in the longitudinal direction on the road. Accuracy and repeatability of the proposed method were validated through testing in a controlled environment with results showing the proposed method achieved desirable accuracy with a maximum difference of 0.28% cross slope (0.17°) and an average difference of less than 0.13% cross slope (0.08°) from the digital auto level measurement. Repeatability results showed standard deviations within 0.05% (0.03°) at 15 benchmarked locations in three runs. However, the acceptable accuracy is typically 0.2% (or 0.1°) during construction quality control. The case study on I-285 in Atlanta, Georgia, demonstrated the proposed method could efficiently conduct the network-level analysis. The GIS-based cross slope measurement map of the 3-mile section of studied roadway can be derived in fewer than two person-hours using collected raw LiDAR data.

Beck et al., (*14*) conducted a study to examine the accessibility of a forest road network especially for non-standard (typically larger) vehicles. The authors developed an algorithm to extract geometry of forest roads from airborne LiDAR using LiDAR intensity value and ground return intensity. LiDAR intensity, in theory, is determined by an object's reflectance, which can be used to identify objects when data is calibrated (*15*). The intensity value varies with material properties, and the ground return on the road is often distinct from surrounding areas since canopy mostly covers the forest floor. The road extraction process requires easting, northing, and elevation coordinates, intensity values, canopy type, and the maximum road grade. To compare the results of the process, nine road segments were field surveyed with terrestrial LiDAR to create ground truth control. The cross-section view of the road was extracted using the TopCAT toolbar in ArcGIS, and the resulted average difference in road cross slope was two percent.

Shams et al., (*4*) evaluated the use of adjusted and unadjusted mobile LiDAR data for collecting cross slope on three roadway sections in South Carolina. The unadjusted LiDAR data incorporated corrections from an integrated IMU. For adjusted data, the point cloud was also processed in real-time using a high accuracy differential correction GPS. The cross slopes were extracted from the LiDAR-derived point cloud by corresponding two separate mesh grid surfaces that were fitted to the points using nearest neighbor interpolation. One mesh grid included the elevation and the second mesh grid included the intensity of the return pulse from the points. Since the intensity of the returned pulse for the reflective pavement marking is higher than highway surface, the travel lanes could be extracted from the point cloud. Then the cross slope was measured along each travel lane and compared with field surveyed cross slope data. The deviation between LiDAR-derived cross slopes and field measurements were less than 0.19%, which met SHRP2 (*22*) and suggested cross slope accuracies for mobile measurements (±0.2%) and demonstrated that mobile LiDAR is a reliable method for cross slope verification.

Previous studies have evaluated the accuracy of either MTLS or ALS as an effective alternative to use of current conventional surveying methods but few recent studies have looked at using MTLS or ALS to extract continuous cross slope data and no recent studies have compared the two. This study not only evaluates the use of LiDAR technology for cross slope verification purposes, but also compares the accuracy of both ALS and MTLS according to two sampling methods 1) End to End data acquisition 2) 0.2 feet interval point extraction.

LiDAR Data Collection

This research evaluates the use of ALS and MTLS from five vendors to obtain accurate cross slope data to ensure that roadways have adequate pavement cross slope and proper drainage. MTLS data from five vendors was used to conduct this evaluation. However, only a single vendor participated in ALS data collection in this research study. Both ALS and MTLS were evaluated regarding the accuracy of the collected cross slope data, as well as procedures to calibrate, obtain, and process the data. The LiDAR data was collected on a 3.4-mile corridor along I-85 BL in Spartanburg, SC. The study section originates at I-585 and terminates at I-85. I-85 BL is a restricted access four-lane dual direction divided freeway. Researchers measured cross slopes at selected locations prior to the LiDAR test data collection. These locations correspond with aerial chevron panel points P-78, P-91, P-103, P-126, and P-127 (note that P-103, P-126, and P-127 are located on ramps). Aerial chevron painted panels are V shape, having approximately 1.5 feet long and 4 inches wide yellow reflective pavement marking tape with an interior angle of 60 degrees, along with the edge of the paved roadway surface. A PK nail is set at the tip of the target panel (*16*). Figure 3-1 shows a sample of panel points and CU points.

Figure 3-6 Aerial chevron panel point, and CU point

The research team conducted an MTLS vendor rodeo from June 30, 2016, to August 30, 2016. The rodeo occurred over multiple dates to maximize participation. Seven vendors participated in the rodeo data collection; however, only five vendors submitted collected data. Vendors' equipment and data collection capabilities are summarized in Table 3-1.

Table 3-1 MTLS Rodeo Vendors' Equipment Specification (7)

Equipment		Vendor A	Vendor B	Vendor C	Vendor D	Vendor E
LiDAR	Brand	Riegl	Optech	Optech	Optech	Leica
	Model	VMX450	SG1	M1	M1	9012
	Single / Dual laser	Dual	Dual	Dual	Dual	Single
	Measurement rate	1.1 MHz	600 kHz/sensor	500 kHz/sensor	50,100,200 and 500 kHz	1 MHz
DMI	Brand	Applanix	Applanix	Applanix	Applanix	*
	Model	BEI HH5	HS35F	LV	LV	*
IMU	Brand	Applanix	N/A	Northrop Grumman	Northrop Grumman	NovAtel
	Model	AP50	FMU P301	LN 200	LN 200	SPAN IMU-FSAS
	Roll/pitch accuracy	0.005°	0.005°	0.25°	0.25°	0.008°
	Heading Accuracy	0.015°	0.015°	0.50°	0.50°	0.023°
Camera	Type	NIKON/RIEGL	Point Grey 360°	Optech	Optech	Leica
	No. of Cameras	4	6	4	4	7
	Focal Points of Cameras	2 front, 2 rear	N/A	2 front, 2 rear	2 front, 2 rear	2 front, 2 sides, 2 rear, 1 above
	Frame Rate	15 fps	3 fps	2 fps	3 fps	8 fps
	Resolution	5 MP	5 MP	5 MP	5 MP	4 MP
Vehicle Mounted GPS/GNSS	Brand	Trimble	Trimble	Trimble	*	NovAtel
	Model	Zepher model 2	AT1675-540TS	Zephyr Model 2	*	GPS-702-GG
	Accuracy	10 mm	0.02' H; 0.04' V	Survey Grade	*	N/A

* Equipment Specification was not provided

A primary benefit of an MTLS is that point cloud data can be collected for multiple travel lanes with a single pass (*7*). For this study, vendors were asked to collect data by direction and by driving in the right lane (outer lane). Only a single pass was allowed for each direction. To improve the accuracy of MTLS data collection vendors were allowed to calibrate their systems both before and after data collection runs using Primary Survey Control (PSC) points. The ground control survey was conducted using Trimble R-7 GPS receivers with Trimble Zephyr Geodetic antenna on two-meter fixed height tripods (*16*). A minimum of two separate 10-minute observations was taken on different days for each PSC point using the South Carolina VRS Network for differential corrections (*16*). The coordinates projected on NAD 83 (2011) South Carolina State Plane datum and NAVD 88 vertical Datum for horizontal and elevation coordinates, respectively (*16*). Figure 3-2 shows the location of PSCs, panel points, and CU points along the study area.

Figure 3-7 PSC points, CU points, and panel points along the study area

In addition to checking the accuracy of the resulting point clouds, the point location data was extracted from vendors' point clouds for four points (CU points) that were marked with reflective chevron panels pointing to PK nails. The CU points were surveyed with static GPS using Trimble R-4 receivers with differential correction through Online

Positioning User Service (OPUS) post-processing (*17*). The assumption is that the field survey points are control, however, a static OPUS corrected survey with a 1-hour observation period has an expected error of about 2 centimeters or 0.067 feet. Accounting for this, data falls within medium to high levels of accuracy (*18*). Table 3-2 shows the positional accuracy of the MTLS collected CU points.

Table 3-2 MTLS Accuracy of CU Points

Points	CU - 1		CU - 2		CU - 3		CU - 4	
	Easting	Northing	Easting	Northing	Easting	Northing	Easting	Northing
Field survey	1715033.0	1151326.9	1720068.7	1153070.7	1717564.1	1152302.6	1713893.1	1151031.8
Difference between the LiDAR-derived coordinates and Static GPS data collection								
Vendor A	-0.047	-0.022	0.226	-0.192	-0.191	0.134	-0.024	0.361
Vendor B	0.061	0.029	0.046	-0.073	0.342	0.015	-0.186	0.349
Vendor C	*	*	0.104	0.212	0.094	-0.076	0.297	0.344
Vendor D	0.098	0.108	0.157	0.094	-0.187	-0.092	-0.152	0.434
Vendor E	-0.168	-0.082	-0.013	-0.131	*	*	*	*
Root Mean Square of the Horizontal Error (RMSE)								
Vendor A	0.052		0.297		0.233		0.362	
Vendor B	0.068		0.086		0.342		0.395	
Vendor C	*		0.236		0.121		0.454	
Vendor D	0.146		0.183		0.208		0.460	
Vendor E	0.187		0.132		*		*	
Average	0.113		0.187		0.226		0.418	

* Missing data in the point cloud

Figure 3-3 is the sample point cloud resulted from MTLS. Yellow and white pavement markings and the chevron panel point are differentiated from the asphalt due to the different material which led to higher intensity of the return pulse of light in MTLS point cloud.

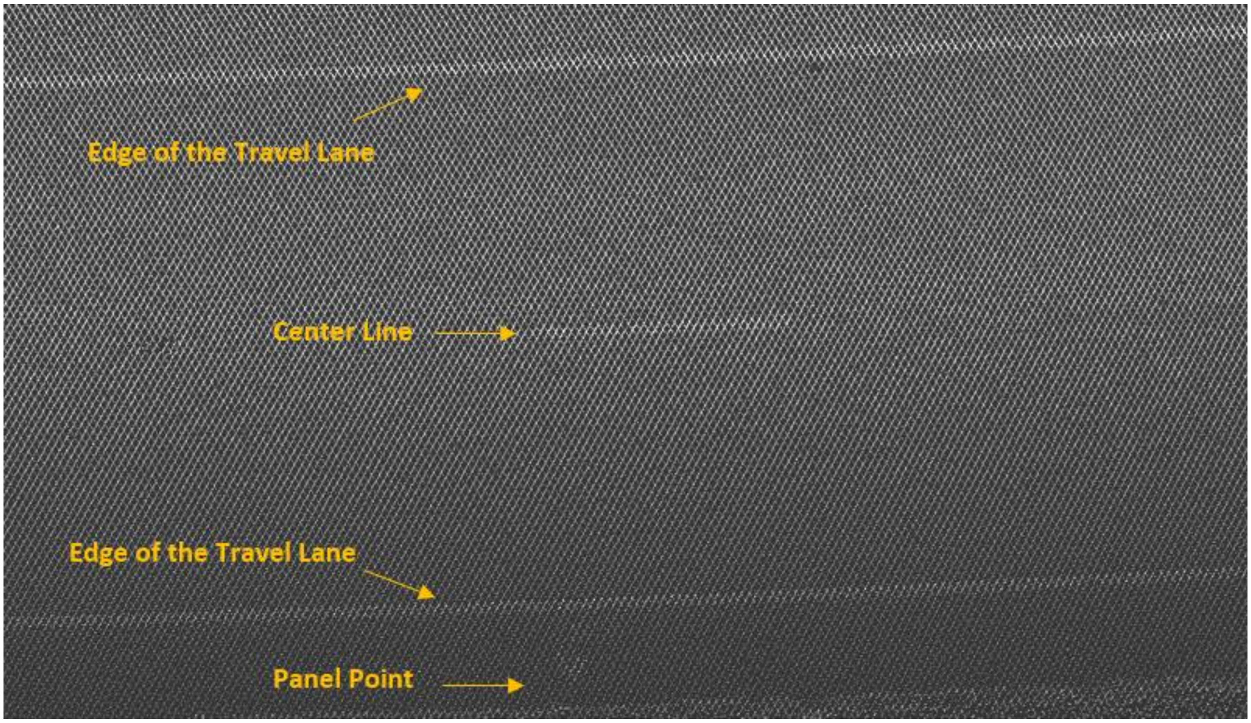

Figure 3-8 Sample point cloud resulted from MTLS showing the pavement markings and panel point

Vendor A was the only vendor to participate in ALS data collection. Vendor A provided airborne LiDAR low attitude mapping for an approximately 19-mile section of I-85, I-26, and I-85 BL in Spartanburg, SC (*19*). The imagery data was collected on December 06, 2015 using Digital Mapping Camera at a pixel size of smaller than 0.2 feet (*19*). The ALS acquisition was performed on December 10, 2015. The mission consisted of 15 flight line passes, with an average flight height of 1,400 feet at 90 knots (*19*). The data was acquired utilizing a Riegl LMS-Q680I. According to the flight plan, there are 6-8 points per square meter (approximately 10.7 square feet) (*19*). The airborne LiDAR data was calibrated and adjusted to the PSCs using Terrasolid suite software (*20*), and the RMSE of the data was 0.027 (*19*). The difference between the field surveying and ALS derived coordinates are provided in Table 3-3. The horizontal coordinate of the chevron panels was obtained using Trimble R-8 Receivers for 3-minute observation with a differential correction from the South Carolina VRS Network (*16*). The elevation of the chevron panels and the primary control points were obtained by differential level runs using digital Leica DNA 03 Levels (*16*).

Table 3-3 Difference between Field Surveying and Airborne LiDAR-Derived Coordinates on Panel Points

Panel points	Easting	Residual	Northing	Residual	Elevation	Residual
P-78	1,713,137.996	0.012	1,150,770.491	-0.056	842.430	0.010
P-91	1,713,210.505	0.005	1,150,698.831	0.017	841.390	0.040
P-103	1,726,199.153	0.028	1,157,176.271	-0.039	840.540	0.020
P-126	1,727,320.707	-0.034	1,158,179.231	0.000	852.230	0.010
P-127	1,726,217.910	-0.004	1,157,665.319	0.028	856.310	0.000

Cross Slope Measurement Using Conventional Surveying Methods

Conventional surveying (auto leveling combined with taping measurements) was used to develop ground truth cross slopes for test sections. Each of the cross-section stations was leveled using two different instrument setups to ensure accuracy and adjust for random error. The cross slope along each section was computed for each lane from the elevation difference between lane lines, along with horizontal distances in between, which was measured by tape.

Extracting Cross Slope From A Point Cloud

The cross slope typically is a uniform transverse slope from the crown line on each side of the road (5). Each cross slope for a single travel lane falls within two pavement marking lines. For the both the MTLS and ALS derived point cloud, the cross-section reference line was drawn perpendicular to the travel lanes at the panel point coordinates. Each of the LiDAR points incorporates the coordinate of the point, including the elevation value along the reference line. Therefore, once the elevation of the two ends of the travel lane along the reference line was determined, the transverse slope of the travel lane could be calculated. Also, for MTLS, the elevation data was extracted along the reference line every 0.2 feet (2.4 inches) using a nearest neighbor interpolation. Because the density of the ALS point cloud was much less than the MTLS point cloud, a 0.2 ft-resolution raster Digital Elevation Model (DEM) representing the elevation of the pavement surface was created from the airborne LiDAR point cloud using ArcMap. Next, the elevation of points along the cross-section reference line was extracted from the DEM at the same interval (e.g., 0.2 feet). To estimate the cross slope percentage a linear regression line was fitted to the 0.2 foot point data along the reference line. Figure 3-4 demonstrates the cross slope calculation on each test section for both the two end method and the linear regression method. According to the elevation of the two ends of the travel lane, the rise represents the difference of elevation and the run presents the horizontal distance between the noted points. Then, the transverse slope of the travel lane could be measured by dividing the rise over the run and multiply by 100 to determine the cross slope in percent (Cross slope = 100 × Rise / Run). Whereas, the slope of the regression fitted line to the 0.2 feet point interval represents the cross slope on the corresponding reference line (Cross slope = regression coefficient × 100).

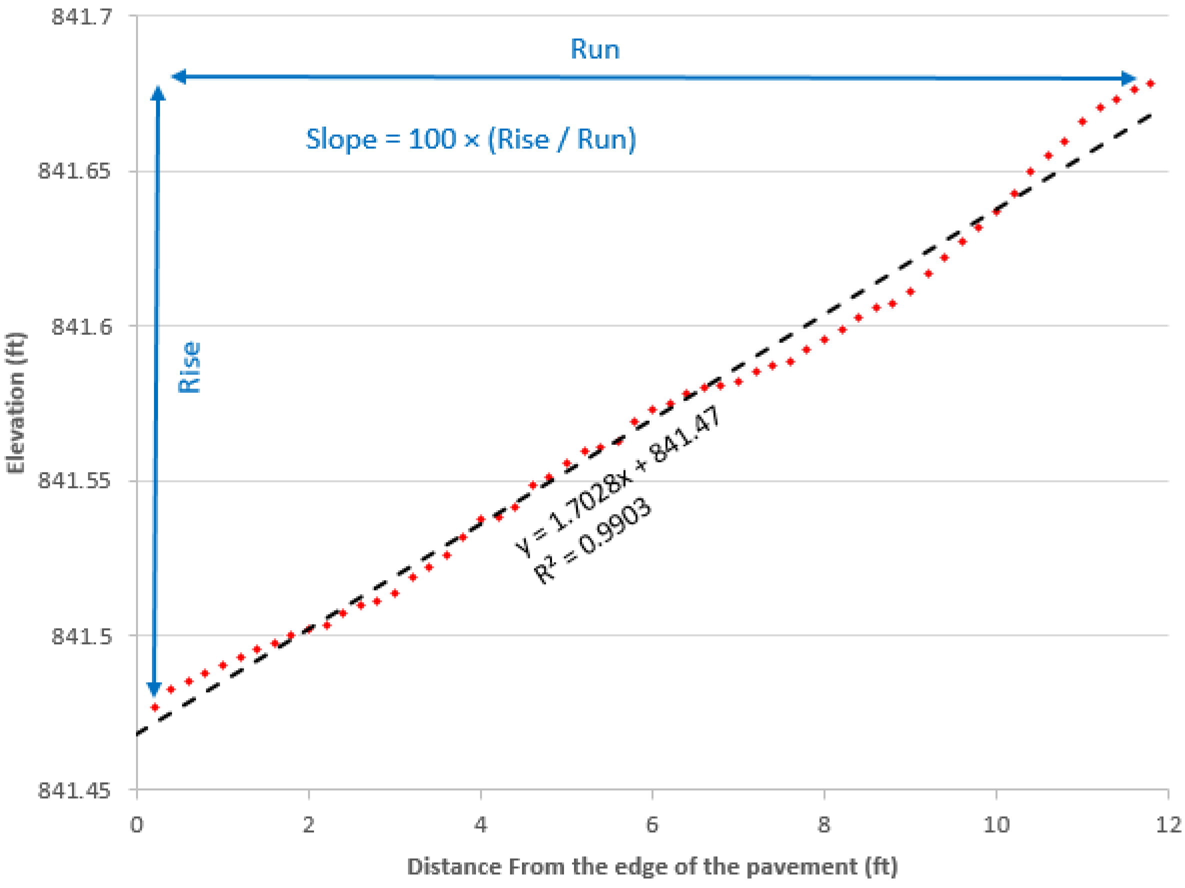

Figure 3-4 A sample of a cross-section of the roadway surface along the reference line

Comparison Between Field Surveyed Cross Slope And LiDAR Derived Data

The use of ALS and MTLS to extract pavement cross slope was compared against cross slope measurements collected using conventional surveying on five specific roadway stations (panel points) along I-85 BL. Field measurements were used as reference data for comparison against vendor collected LiDAR-derived data. Table 3-4 and Table 3-5 show the extracted cross slopes from the LiDAR point cloud and the measured cross slopes using an auto level and tape. The measurements are based on each travel lane, and the vendor names have been removed and are shown in random order.

Table 3-3 Cross Slope Comparison between Surveyed Data and LiDAR-Derived Cross Slope (End to End Data Acquisition)

Panel Point	Travel Lanes	Field Surveyed Cross slope	End to End data Acquisition					
			ALS	Vendor A	Vendor B	Vendor C	Vendor D	Vendor E
P-78	WBO	3.33%	3.18%	3.43%	3.39%	3.41%	3.08%	*
	WBI	1.38%	1.62%	1.33%	1.30%	*	1.44%	*
	EBI	1.30%	1.66%	1.51%	1.72%	*	*	1.49%
	EBO	1.46%	1.72%	1.62%	1.59%	1.58%	1.51%	1.53%
P-91	WBO	3.42%	3.23%	3.47%	3.51%	3.61%	3.47%	*
	WBI	1.28%	0.96%	1.26%	1.22%	1.32%	1.20%	1.35%
	EBI	1.66%	1.91%	1.79%	1.80%	1.83%	*	1.71%
	EBO	1.92%	1.77%	1.83%	1.79%	1.82%	*	1.74%
P-103	WBO	6.85%	6.99%	6.93%	6.90%	6.99%	6.92%	*
	WBI	7.43%	7.39%	7.35%	7.43%	7.47%	7.13%	7.34%
P-126	WBO	3.97%	3.95%	*	3.75%	3.83%	*	*
	WBI	4.47%	4.30%	*	4.11%	4.19%	*	*
P-127	WBO	1.38%	1.51%	1.39%	1.40%	1.39%	*	*
	WBI	1.15%	*	*	*	*	*	*

WBO = West Bound Outer lane, WBI = West Bound Inner lane, EBO = East Bound Outer lane, EBI = East Bound Inner lane
* Missing Data

Table 3-4 Cross Slope Comparison between Surveyed Data and LiDAR-Derived Cross Slope (0.2 feet interval point extraction)

Panel Point	Travel Lanes	Field Surveyed Cross slope	0.2 feet interval point extraction					
			ALS	Vendor A	Vendor B	Vendor C	Vendor D	Vendor E
P-78	WBO	3.33%	3.32%	3.43%	3.38%	3.41%	3.32%	*
	WBI	1.38%	1.41%	1.46%	1.39%	*	*	*
	EBI	1.30%	1.64%	1.67%	1.83%	1.63%	*	1.60%
	EBO	1.46%	1.50%	1.47%	1.39%	1.30%	1.48%	1.42%
P-91	WBO	3.42%	3.45%	3.56%	3.61%	3.53%	3.42%	*
	WBI	1.28%	1.14%	1.32%	1.24%	*	1.26%	1.36%
	EBI	1.66%	1.73%	1.82%	1.78%	1.77%	*	1.74%
	EBO	1.92%	1.76%	1.78%	1.79%	1.71%	1.93%	1.70%
P-103	WBO	6.85%	7.00%	6.93%	6.92%	6.96%	6.97%	*
	WBI	7.43%	7.42%	7.40%	7.44%	7.44%	7.30%	7.39%
P-126	WBO	3.97%	3.84%	*	3.71%	3.72%	*	*
	WBI	4.47%	4.31%	*	4.33%	4.36%	*	*
P-127	WBO	1.38%	1.35%	1.33%	1.39%	1.36%	*	*
	WBI	1.15%	*	*	*	*	*	*

WBO = West Bound Outer lane, WBI = West Bound Inner lane, EBO = East Bound Outer lane, EBI = East Bound Inner lane

* Missing Data

Evaluation of Results

The estimated cross slope is a function of the LiDAR platform used (mobile or airborne), the instrument for collecting data (varies by vendor), the data collection station (panel points), and the travel lane. Linear Mixed Models (LMM) were used to analyze the accuracy of the abilities of both ALS and MTLS to estimate the cross slopes on highways to account for both fixed and random effects. LMMs are an extension of one way analysis of variance (ANOVA) models and are employed in this analysis to account for the dependence between measurements taken at the same locations and lanes (*21*). The cross slope obtained via vendor i, panel point (location) j, and travel lane k is modeled by:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_{k(j)} + \varepsilon_{ijk} \tag{3-1}$$

The treatment effect associated with the i th vendor is given by α_i, $\beta_j \sim N(0,\sigma_\beta^2)$ are the independent random effects associated with location, $\gamma_{k(j)} \sim N(0,\sigma_\gamma^2)$ are the independent random effects associated with lane nested in location, and $\varepsilon_{ijk} \sim N(0,\sigma_\varepsilon^2)$ are independent random errors. For both data collection methods (End to End data acquisition and 0.2 feet interval point extraction), the statistical hypothesis to test is whether the mean of the deviation between LiDAR derived cross slopes and field surveying measurement is less than 0.2% (upper limit of acceptable cross slope measurement accuracy (*22*)) is performed according to LMM models using JMP statistical discovery software (*23*).

End to End Data Acquisition

When the elevation data was extracted along the cross-section line on two ends of the travel lane the difference between the MTLS and field survey measurement ranged from -0.42% to 0.36%. Similarly, the comparison between ALS data and field surveying varies from -0.36% to 0.31%. The p-values greater than 0.05 of the paired comparison between the ALS and five MTLS data collection show at the 5% level, there is no statistical difference between methods (vendors) for collecting highway cross slope. Although, the point estimation of difference between the LiDAR-derived cross slopes and field surveying is less than 0.2%, but due to the upper limit 95% confidence interval greater than 0.2% and the one-tailed t-test p-value greater than 0.05, the ALS is not significantly accurate for cross slope verification using the end to end cross slope calculation. While the upper limit of the confidence interval (CI) for MTLS data collection is less than 0.2% and the p-value less than 0.05 demonstrates that MTLS meets the acceptable error for cross slope data collection using the end to end cross slope calculation. Although, the results for Vendor D are slightly over the acceptable error, the p-value is less than 0.05. Therefore, the one-tailed test is rejected, but the 95% CI includes values that are greater than 0.2%. This is because the CI corresponds with the two-tailed test. However, the missing data and small sample size undermines the reliability of the results for Vendor D.

Table 3-5 Comparison between LiDAR-Extracted Cross Slopes and Field Surveying (End To End Method)

Data Collector	Estimation of mean difference from surveyed data	Standard Error	df	Lower 95%	Upper 95%	p-value
Aerial	0.157	0.032	12.110	0.088	0.226	0.099
Vendor A	0.077	0.036	12.701	-0.002	0.156	0.002
Vendor B	0.107	0.032	12.110	0.038	0.176	0.006
Vendor C	0.113	0.033	13.232	0.043	0.184	0.009
Vendor D	0.120	0.043	14.709	0.027	0.212	0.041
Vendor E	0.092	0.051	20.596	-0.015	0.199	0.023

0.2 feet interval point extraction

The results indicate when the elevation data was extracted every 0.2 feet along the reference line, the difference between the MTLS, ALS and field survey measurements range from -0.53% to 0.26% and -0.34% to 0.16% respectively. Similarly, the p-values greater than 0.05 of the paired comparison between the ALS and five MTLS data collections show at the 5% level, there is no statistically difference between ALS and MTLS for collecting highway cross slope. Also, the result of the study indicates the difference between both MTLS and ALS derived cross slopes and the field surveying measurement are less than 0.2%. These findings were indicated by the p-value less than 0.05 of the one way t-test at the 5% level.

Table 03-6 Comparison between LiDAR-Extracted Cross Slopes and Field Surveying (0.2 Interval Points)

Data Collector	Estimation of mean difference from surveyed data	Standard Error	df	Lower 95%	Upper 95%	p-value
Aerial	0.0776	0.0283	6.2330	0.0089	0.1463	0.002
Vendor A	0.0919	0.0300	7.2838	0.0215	0.1624	0.004
Vendor B	0.0878	0.0283	6.2330	0.0191	0.1565	0.003
Vendor C	0.1088	0.0289	6.8929	0.0403	0.1775	0.008
Vendor D	0.0523	0.0326	9.3512	-0.0210	0.1256	0.001
Vendor E	0.0930	0.0360	12.4610	0.0148	0.1711	0.005

Summary of Results

The comparison between the mean estimation of the difference between ALS extracted cross slopes and surveyed data shows that the slope of the fitted regression line to 0.2 feet interval extracted points is the better representation of the actual cross slope of the travel lane rather than calculating the uniform slope based on the elevation difference between the two ends of the travel lane.

For the MTLS data collection in this study, vendors were asked to collect data by direction by driving in the right lane (outer traveling lane). Table 3-8 summarizes the absolute deviation between the LiDAR-derived cross slopes and field surveying based on the driving traveling lane.

Table 3-7 Summary of Cross Slope Comparison Based on the Travel Lane

	Inner travel lanes (left lane)				Outer travel lanes (right lane)			
	End to End data Acquisition		0.2 feet Interval data Acquisition		End to End data Acquisition		0.2 feet Interval data Acquisition	
	ALS	MTLS	ALS	MTLS	ALS	MTLS	ALS	MTLS
Min	0.04%	0.00%	0.01%	0.00%	0.02%	0.01%	0.00%	0.01%
Max	0.36%	0.42%	0.34%	0.53%	0.25%	0.24%	0.16%	0.26%
Median	0.24%	0.08%	0.10%	0.09%	0.14%	0.09%	0.04%	0.08%
Mean	0.23%	0.13%	0.13%	0.13%	0.15%	0.10%	0.08%	0.10%

Although according to the two tail t-test, there is no statistical difference between the MTLS LiDAR-derived cross slopes on the outer travel lane and the inner traveling lane at a 5 % level, the average deviation for the outer lanes is less than the inner lanes. This is to be expected because the MTLS distance to the outer lane pavement is shorter with a more direct angle than the MTLS distance to the inner lane pavement.

Conclusion

The use of ALS and MTLS to extract cross slopes was evaluated on five stations including 13 travel lanes along I-85 BL in Spartanburg, SC. Results of this research showed that both ALS and MLS have comparable cross slope accuracies to conventional manual surveying methods. As a result, collection of ALS and MTLS cross slope data provides an efficient means for identifying cross slope deficiencies and addressing potential hydroplaning issues on a system wide basis.

According to SHRP2 guide specifications, a slope tolerance value of ± 0.2% of the design value would be acceptable for final measurement after project completion (*22*). By fitting a regression line to the extracted points every 0.2 feet interval used to estimate the cross slope, the LMM statistical analysis indicates the deviation between both MTLS and ALS derived cross slopes and field surveying measurements were less than acceptable accuracy at the 5% level. Whereas, for MTLS data collection using the elevation of the two sides of the travel lane met the acceptable accuracy of the cross-sectional calculation; the difference between the ALS derived cross slopes and the field surveying is over the upper limit of acceptable error; and this is statistically significant at the 5% level. Therefore, it is recommended that a fitted regression line be used for determining cross slopes from ALS point clouds to account for lower point density along the pavement surface. Generally, MTLS cross slope data collection can be expected to be more accurate than ALS cross slope data collection especially if MTLS is collected using at least one pass for each lane.

Finally, conventional surveying methods are time consuming and require a survey crew to be located on the road, which poses safety and traffic issues. However, efficient LiDAR scanning platforms are available to capture cross slope, grades, location, and a variety of other geometric design characteristics. These new applications increase productivity and minimize road crew exposure and create robust information products that serve multiple uses beyond cross slope measurement such as highway asset management.

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CHAPTER FOUR

PAPER III: THE HYDROPLANING POTENTIAL WITH REGARD TO HIGHWAY CROSS SLOPE

This Chapter has been submitted as a paper for presentation at the 98th Transportation Research Board Annual Meeting and publication in the Transportation Research Record: Journal of the Transportation Research Board

Abstract

Highway pavement cross slope is a crucially important cross-sectional design element to properly drain water on highways and improve driver safety by reducing the potential for ponding. When rain falls on the pavement surface, the water depth that accumulates can result in hydroplaning. Previous research has not clearly defined a water depth at which hydroplaning occurs; however, there is considerable agreement that a water depth equal to 0.06 inches is the acceptable upper limit of water depth above the pavement. In reality, there are situations where hydroplaning can occur at water depths less than 0.06 inches depending on road, vehicle, and environmental characteristics. This research estimates the water depth and presents the potential of hydroplaning with regard to a range of vehicle speed, tire tread depth, tire pressure, pavement surface texture, and cross slope. The paper includes a series of tables and figures that state highway agencies can use to help assess hydroplaning potential based on roadway pavement and cross sectional design characteristics.

Keywords: Roadway hydroplaning, Cross Slope, Critical water depth

Introduction

Although highway safety statistics indicate that most crashes (approximately 94%) result from driver error (*1*), there are many factors that can contribute to the cause and severity of a crash. Adverse weather is one of these factors (*2*,*3*). Specifically, rain rain can reduce pavement friction and impair driver visibility (*4*), both increasing the likelihood of roadway crashes (*5*). Rainy weather can lead to hydroplaning, which is the separation of the tire from the road surface due to a sheet of water (*6*). In rainy weather, the typical pavement friction coefficient of 0.7 to 0.9 be reduced to 0.3 to 0.6 for automobiles, significantly increasing vehicle stopping distance (*7*). The National Transportation Safety Board (NTSB) stated that fatal accidents on wet pavement occur 3.9 to 4.5 times more often than might be expected on dry pavements (*7*). If motorists were to drive more slowly during adverse weather (rainy conditions), hydroplaning should have no significant influence on crashes (*8*). Unfortunately, many motorists risk driving too fast for conditions and are more susceptible to hydroplaning consequences. In these instances, hydroplaning has been found to have a considerable impact on wet pavement crashes (*6*). Hydroplaning crashes constitute a considerable risk to drivers. Florida, for example, experienced over 25,000 hydroplaning related crashes from 2006 to 2011 (*9*). Table 4-1 presents a summary of US weather related crashes from 2005 to 2014.

Table 4-1 Weather Related Crash Statistics (Annual Average) (10)

Road Weather Conditions	Weather-Related Crash Statistics		
	Crashes (2005-2014)	10-year Percentages	
Wet Pavement	907,831 crashes	16% of vehicle crashes	73% of weather-related crashes
	352,221 persons injured	15% of crash injuries	80% of weather-related injuries
	4,488 persons killed	13% of crash fatalities	77% of weather-related fatalities
Rain	573,784 crashes	10% of vehicle crashes	46% of weather-related crashes
	228,196 persons injured	10% of crash injuries	52% of weather-related injuries
	2,732 persons killed	8% of crash fatalities	47% of weather-related fatalities
Weather-Related Crashes	1,258,978 crashes	22% of vehicle crashes	
	445,303 persons injured	19% of crash injuries	
	5,897 persons killed	16% of crash fatalities	

To improve the safety of roadways, it is important to identify the problematic conditions cause by weather interaction with roadway geometry and traffic conditions, then address potential safety issues before crashes occur (*4*). It is essential to understand the relative significance of various factors that influence the accumulation and drainage of surface water on pavement surfaces. Highway cross slope promotes water drainage from the roadway in a lateral direction, which helps minimize ponding of water on the pavement surface (*11*). Ensuring adequate cross slopes and proper drainage on highway facilities can improve driver safety by reducing the potential for hydroplaning. It is highly desirable to ensure that adequate cross slopes exist even after freeway repaving and rehabilitation projects. Freeways with inadequate cross slopes are especially susceptible to hydroplaning because these facilities have higher design speeds and longer drainage path lengths. Therefore, sections with inadequate cross slope should be identified by transportation agencies and corrected though timely maintenance practices (*11*). It is crucial for transportation agencies to have an efficient method for collecting highway cross slope data to identify inadequate cross slope sections. Mobile Light Detection and Ranging (LiDAR) is one such method that is capable of collecting cross slope data at highway speeds in a single pass (*12*).

In general, a cross slope range of 1.5% to 4% is recommended for pavement surfaces in the United States (*13*). The lower portion of this range is appropriate where drainage flow is across a single lane, and higher values are appropriate where the flow is across multiple travel lanes (*13*). While cross slope is desirable, cross slopes that are too steep can cause vehicles to drift and become unstable when crossing over the crown to change lanes.

This research estimates water depth above the pavement surface and presents the potential of hydroplaning with regard to the range of vehicle speed, tire tread depth, tire pressure, and pavement surface texture. The paper also discusses how mobile LiDAR can be used to create a cross slope database to support a cross slope verification program.

Literature Review

Gallaway et al., (*6*) provided a study that included a comprehensive literature review, a multistate questionnaire, mathematical models, and field testing to establish a relationship between geometric and pavement surface characteristics to minimize hydroplaning. Pavement surface water depth is the most critical factor for hydroplaning.

The absolute minimum cross slope acceptable in this study was identified to be 1.5%; however, the study recommended 2% for most pavements. A 2% cross slope is used as a design value for many roads in the United States. A standard ¼ inch per foot (2.08%) on tangent sections is used on South Carolina Department of Transportation (SCDOT) highways as shown in Figure 4-1 (*14*).

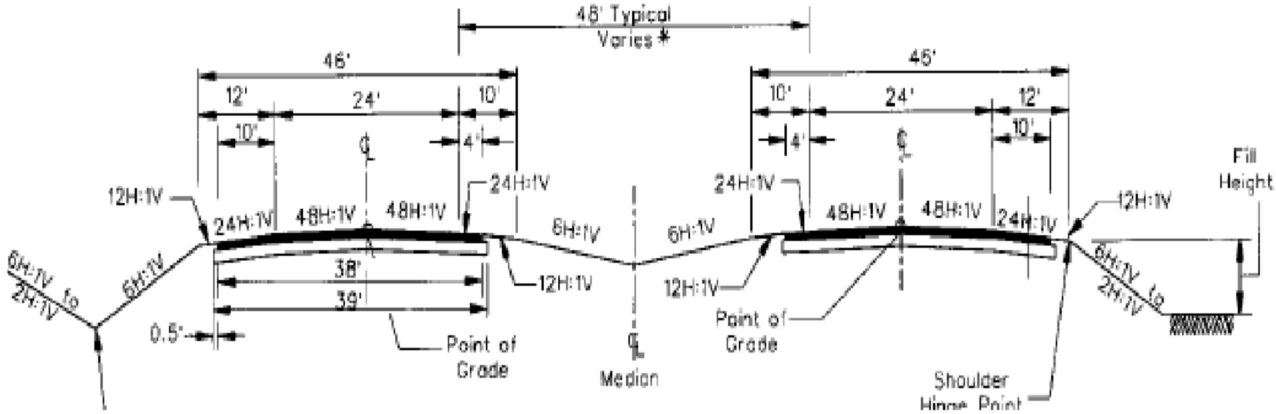

Figure 4-9 Normal cross slope at South Carolina highways (14)

The most desirable water depth to ensure that a vehicle will not hydroplane is zero; however, water buildup on roadways up to 36 feet wide will not result in hydroplaning for a cross slope of 2% or higher and rainfall intensity below 0.5 in/hr (*6*). According to the experimental study, hydroplaning was observed at a water depth as low as 0.01 inches for tires without tread; however, no hydroplaning was reported for tread tires with water depths less than 0.08 inches (*6*).

Guven and Melville (*8*) provided a discussion related to the selection of cross slope in the design of highway pavements. They indicated that longitudinal grade does not have an enormous effect on water depth, but they found the primary factors influencing the water depth at the edge of pavement are the width of the pavement and the cross slope. They also suggested that a water depth (WD) of 0.06 inches, as an acceptable upper limit for design purposes. The study further stated that water accumulation in ruts and puddles on the pavement surface presents a more severe threat to vehicle safety than water occurring as surface sheet flow. Therefore, periodic resurfacing of roadway pavements is a necessary and effective means to prevent or minimize the adverse effects of pavement rutting.

Ong and Fwa (*15*) developed an analytical model using three dimensional finite element models to predict skid residence and potential of hydroplaning under wet pavement conditions. Skid resistance is a measure of resistance of the pavement surface to sliding or skidding of the vehicle (*16*). Within the normal passenger car operation, the hydroplaning speed (i.e., the vehicle speed at which hydroplaning occurs) is affected most by tire inflation pressure followed by water film thickness. Wet pavement skid resistance decreases with increasing water film thickness and tends to level-off for a water film thickness of more than 6 mm (i.e., 0.24 in).

Long et al., (*17*) developed a methodology to identify a threshold level of pavement skid resistance for highways. The quantitative relationships between crash risk and skid resistance were quantified using the Crash Rate Ratio (CRR) method. Based on an analysis of the data, the authors found that skid resistance has a negative impact on crash risk. Additionally, based on the developed CRR- Skid Number (SN) model, skid resistance thresholds can be determined easily according to the target crash risk level or expected crash reduction. The recommended statewide skid resistance thresholds are 14, 28, and 73 for all weather crashes, and 17, 29, and 73 for wet weather crashes. Table 4-2 indicates the suggested actions to be taken based on skid resistance thresholds.

Table 4-2 Suggested Actions to be taken for Each Pavement Group (17)

SN Range	Recommended Action
$SN < SN_1$	Potential project for short-term treatment action(s)
$SN_1 < SN < SN_2$	Detailed project-level testing recommended
$SN_2 < SN < SN_3$	Vigilance recommended
$SN > SN_3$	Increased SN may have little effect on reducing crash rates

There are techniques available to predict the hydroplaning speed, such as using NCHRP's PAVDRN computer software (*18*). However, the PAVDRN program only predicts hydroplaning speeds under heavy rain fall condition. Also, the PAVDRN program is relatively unreliable for predicting hydroplaning for inner lanes. Therefore, some of its limitations warrant more detailed investigation. Gunaratne et al., (*19*) initiated a systematic investigation to validate the analytical procedure and developed the Florida Department of Transportation (FDOT) guideline to estimate hydroplaning risk. The research team evaluated hydroplaning potential, the effect of each attribute on hydroplaning, and hydroplaning risk. The researchers provided models to estimate the wet weather speed reduction as well as analytical and empirical methods for predicting hydroplaning speed. In addition, the investigators formulated an analytical equation for predicting the critical water film thickness under road geometric conditions such as on tangent sections and super elevated curves. Also, wet weather crash analysis was performed using crash statistics, geometric data, pavement condition data, and other information collected by FDOT. The results indicated that wider sections are more likely to produce hydroplaning crashes. They also found that dense grade pavement surfaces are more likely to induce conditions conducive for hydroplaning than open graded pavements.

Although a great deal of research has been conducted on the most influential factors that affect water depth on the pavement surface, previous research has not clearly defined the critical water depth at which hydroplaning occurs. However, there is considerable agreement on the water depth equal to 0.06 inches is the acceptable upper limit of water depth above the pavement (*8*) (*13*). This research focused on providing an evaluation of the potential of hydroplaning with regard to the range of vehicle speed, tire tread depth, tire pressure, pavement surface texture, and cross slope.

Hydroplaning Potential

Skid resistance and hydroplaning speed for roadway pavements are primarily dependent on the following contributing properties and factors (*20*):

1. Pavement properties: Pavement mix design, aggregate type, and surface texture
2. Vehicle factors: Vehicle speed, tire inflation pressure, tire slip ratio, and tire tread depth
3. Environmental factors: Water-film thickness on the pavement surface

On a given pavement with a known rut depth filled with water, the skid resistance characteristics and hydroplaning potentials of the pavement are dependent on the operating vehicle speed and pavement surface characteristics. This means that for a given rut depth, pavement sections belonging to different highway classes (hence different prevailing operating speeds), or having different pavement micro-texture and macro-texture, will exhibit different skid resistance characteristics and hydroplaning potentials (*20*).

When rain falls on a sloped pavement, the path that runoff takes to the pavement edge is called the drainage path. The drainage path length is a function of the number of the travel lanes, width of the travel lanes, longitudinal grade of the roadway, and the pavement cross slope. It can be calculated using equations 4-1 and 4-2 (*6,8*). Based on these equations, the surface runoff drainage flow path length increases as the pavement width increases or the roadway longitudinal grade is steepened.

$$S_f = \left(S_x^2 + S_g^2\right)^{0.5} \tag{4-1}$$

$$L_f = L_x \left(\frac{S_f}{S_x}\right) \tag{4-2}$$

Where,

S_x = Cross slope (ft/ft)

S_g = Longitudinal grade (ft/ft)

S_f = Flow path slope (ft/ft)

L_x = Pavement width (ft) from crown of the pavement

L_f = Length of flow path

The water depth that accumulates on pavement depends on the rainfall intensity, length of flow path, slope of the flow path, and the texture depth. The texture depth (TXD) is a function of the roughness or macro-texture of the pavement which consists of the asperities associated with the voids in the pavement surface between particles of aggregates

(*8*). The 50th percentile texture depth for typical pavements is equal to 0.04 inch, however, a TXD = 0.02 inch is recommended for design purposes (*13*). The water depth above the pavement surface can be calculated using the empirical equations 4-3 and 4-4 (*6,8*):

$$\mathrm{WD_0} = 0.00338\ \mathrm{TXD}^{0.11}\mathrm{L_f}^{0.43}\mathrm{I}^{0.59}\ \mathrm{S_x}^{-0.42} - \mathrm{TXD} \tag{4-3}$$

$$\mathrm{WD} = (\mathrm{WD_0} + \mathrm{TXD}) \times \sqrt{1 + ({}^{S_g}\!/_{S_x})^2} - \mathrm{TXD} \tag{4-4}$$

Where,

WD = Water depth above the top of the surface asperities (in)

TXD = Texture depth (in)

I = Intensity of rainfall in (in/hr)

Water thickness above the pavement is measured relatively from the top of the pavement surface asperities. In other words, when the water depth is zero or negative, it means water surface is below the top of the asperities (*8*). Previous studies showed that longitudinal grade does not affect water depth significantly because while the flow path is lengthened for steeper grades the flow velocity increases because of the increased resultant slope (*6,8,13)*. This increase in velocity helps drain water from the road more quickly which offsets the longer flow path length. To determine how the difference in pavement cross slope impacts the water depth, the following assumption has been made (S_g = 0%, TXD = 0.02 inch (design value), TXD = 0.04 inch (50 percentile value)). The impact of cross slope on pavement water depth accumulation by rain fall intensity is shown in Figure 4-2 and Figure 4-3.

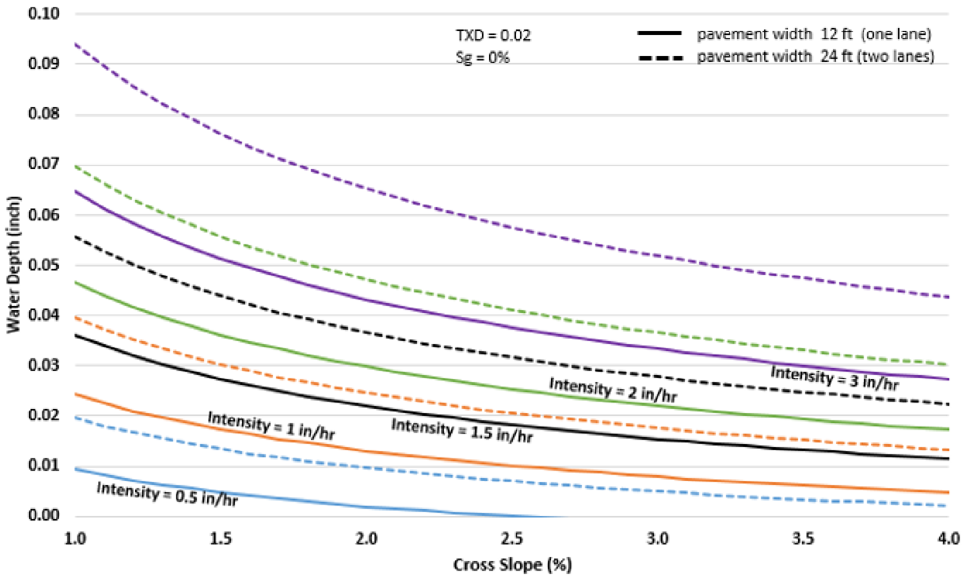

Figure 4-10 Cross slope sensitivity analysis on pavement water depth (TXD = 0.02”)

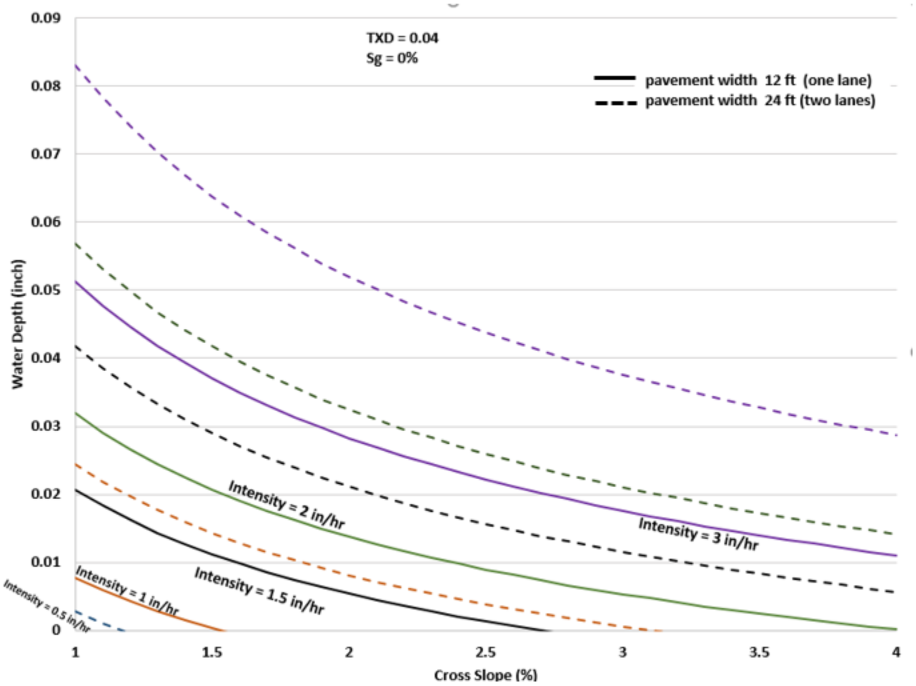

Figure 4-11 Cross slope sensitivity analysis on pavement water depth (TXD = 0.04”)

Figures 4-2 and 4-3 show that the water depth above the pavement increases in higher rainfall intensity conditions, whereas, the steeper cross slope helps to drain water from the pavement surface. While steeper cross slopes can help drainage, cross slopes that are too steep can cause vehicles to drift, skid laterally when braking, and become unstable when crossing over the normal crown to change lanes. So, while it is important for roadways to meet minimum pavement cross slope design criteria, it is also important that maximum criteria are not exceeded (*11*). Furthermore, higher pavement texture results in lower water depth above the pavement. It is generally accepted that the critical water depth at which hydroplaning occurs is 0.06 inch, thus producing sufficient loss of tire friction to present a significant driving hazard *(6,8,13)*. A rainfall intensity of 2 in/hr can result in pavement water depths approaching 0.06 inches at the edge line when the crown of pavement and the edge line is approximately 24 feet apart (e.g., two travel lanes). For cross slopes less than 1.5% having a TXD = 0.02 inches, the water depth exceeds 0.06 inches for SCDOT standard cross slopes of 2.08% for rainfall intensities of 3 in/hr (see Figures 4-2 and 4-3). Even though rainfall intensity of 3 in/hr can create hazardous driving conditions for virtually all vehicles traveling at the speed limit regardless of tire pressure, previous studies have shown that driving visibility is difficult when rainfall intensity exceeds 2 in/hr, and becomes extremely poor when intensity exceeds 3 in/hr. Thus, there is an expectation that vehicle operators will avoid driving or drive very slowly during such heavy rainfall periods (*8*). Based on this expectation, the American Association of State Highway and Transportation Officials (AASHTO) recommended minimum cross slope of 1.5% is a safe standard even in heavy rainfall events of 2 in/hr (*13*).

Accelerating, braking, or cornering forces may cause the driver to lose control due to lost contact between the tire and the pavement surface when hydroplaning occurs (*8*). The wheel spin down (SD) is used to detect hydroplaning and the influencing variables tire tread depth, tire inflation pressure, water depth, and wheel load (*21*). The spin down (reduction in wheel speed) of a wheel is an indication of a loss in the tire-ground frictional force and is regarded as a manifestation of hydroplaning (*21*). Spin down occurs when the hydrodynamic lift effects combine to cause a moment which opposes the regular rolling action of the tire caused by the drag forces (*20*). Equation 4-7 defines an approximate "spin down" water depth (WDs) at or above which hydroplaning occurs for a range of vehicle speeds, tire pressures, tire tread depths and pavement texture depths. Using a critical value of 10 for the spin down percent (*8*) resulted in equation 4-6.

$$\mathrm{SD} = 100 \times \frac{(\mathrm{W_d} - \mathrm{W_w})}{\mathrm{W_d}} \qquad (4\text{-}5)$$

$$\mathrm{A_s} = \mathrm{V}/[\mathrm{SD}^{0.04}\mathrm{P}^{0.3}(\mathrm{TD}+1)^{0.06}], \text{ when SD = 10} \qquad (4\text{-}6)$$

$\mathrm{WD_s} =$

$$\text{The smaller of } [10.409/(\mathrm{A_s} - 3.507)]^{16.67} \text{ or } [28.952/(\mathrm{A_s}/\mathrm{TXD}^{0.14} + 7.817)]^{16.67} \qquad (4-7)$$

Where,

V = Vehicle speed (mph)

SD = Spin down (%)

$\mathrm{W_d}$ = Rotational velocity of a rolling wheel on a dry pavement

W_w = Rotational velocity of a rolling wheel after spinning down due to contact with a flooded pavement

P = Tire pressure (psi)

TD = Tire tread depth (units of 1/32 inch)

WD_s = Spin down Water Depth (inches)

TXD = Pavement texture depth (inches)

The variation of the critical water depth for nearly bald tire vehicle (TD=2/32”) and vehicle speed for two different pavement texture depths (TXD = 0.02 and 0.04 inch), and tire pressures (P = 24 and 32 psi) is shown in Figure 4-4. A lower tire pressure provides larger contact area between the tire and road, thus making fast acceleration and braking possible. On the other hand, rolling resistance reduces by increasing tire pressure which reduces the probability of spin down (and hydroplaning) (*22*). Typical air pressure in passenger car tires is about 32 psi (220 kPa) (*22*) and the design value is 24 psi (*8*).

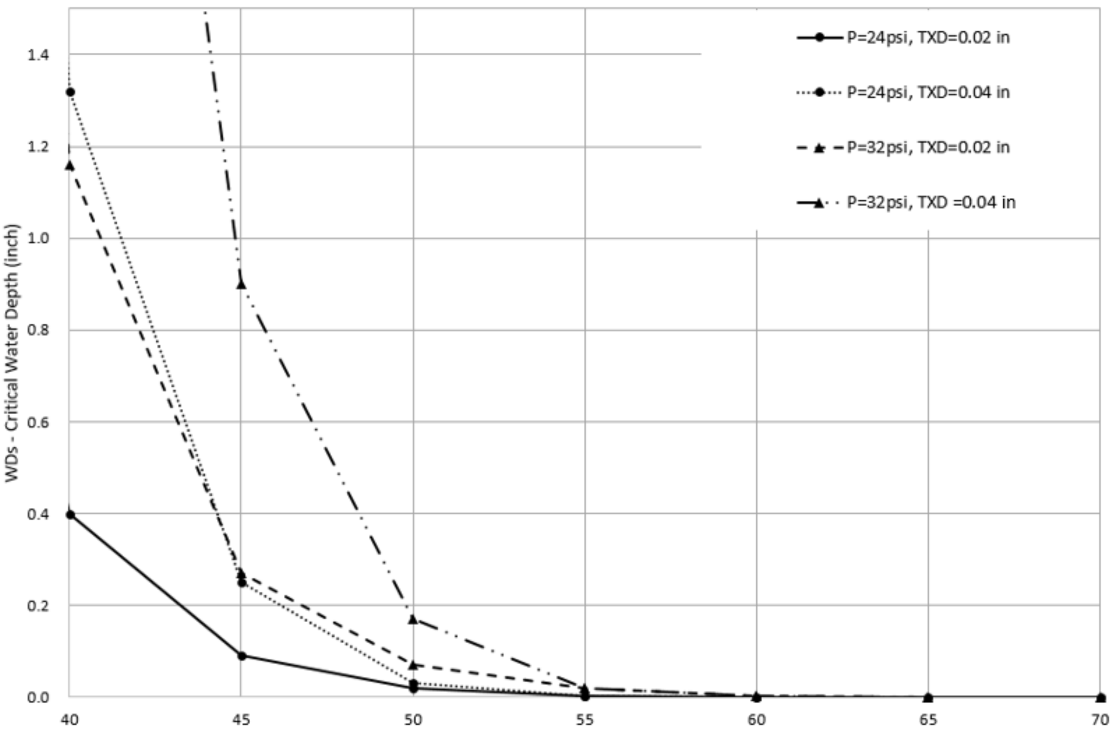

Figure 4-12 Variation of critical water depth as a function of vehicle speed (TD = 2/32")

Figure 4-4 shows that when vehicle speed is high (V>50 mph), the texture depth has little effect on critical water depth. Also, any water above the pavement asperities may cause hydroplaning because the critical water depth is close to zero. It may also be seen that hydroplaning may occur at lower spin down water depth due to lower tire pressure. Based on equations 4-1 to 4-4, vehicles traveling at 60 mph or less should not hydroplane with a water depth of 0.06 inches if their tires are fully inflated and have remaining tread life. For vehicles with nearly bald tires and low tire pressure (e.g., 24 psi), hydroplaning can occur at speeds as low as 48 mph if the water depth is 0.06 inches.

Results

Accumulated water at or above the spin down water depth (critical water depth) may result to hydroplaning (*8*). Figure 4-5 represents the variation of spin down water depth as a function of vehicle speed, tire tread and tire pressure.

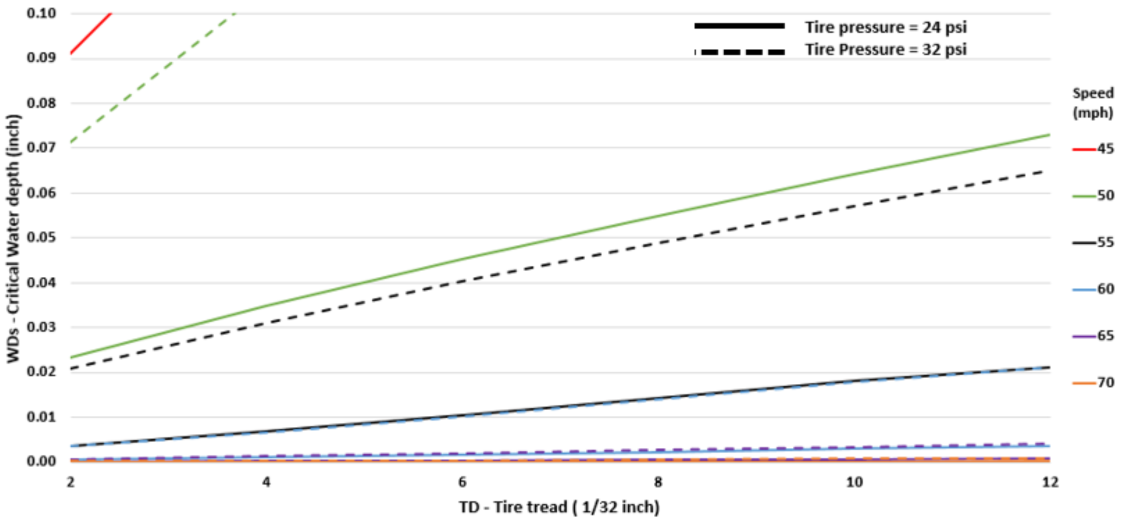

Figure 4-13 Critical water depth as a function of speed, tire tread, and tire pressure (TXD = 0.02")

Due to the lower spin down water depth, drivers are more vulnerable to hydroplaning related crashes at speeds greater than 50 mph. However, the higher tire pressure and the tire tread increases the spin down water depth, which translates to improved safety for vehicles on the roadway. Hence, drivers should be aware of the safety benefits of having sufficient tire tread and tire pressure according to manufacturer recommendations. The typical minimum tire tread is about 0.06 inch (2/32 inch) (*23*), however, most manufacturers recommend replacing tires when the tread depth reaches 4/32 inch. The average tread depth for new tires typically exceeds 8 mm (10/32 inch) (*24*).

For the minimum pavement texture depth (TXD = 0.02”), the comparison between the critical water depth and the accumulated water above the pavement is shown in Table 4-3 for low tire pressure. When the water above the pavement flows along one travel lane, the comparison shows for vehicles with nearly bare tires combined with low tire pressure, hydroplaning will not occur up to a speed of 45 mph. However, when rainfall intensity reaches 1 in/hr, hydroplaning can occur at speeds as low as 50 mph for vehicles with poor tire tread depth (<=4/32 inch) if there is insufficient cross slope.

When the flow path is two travel lanes (approximately 24 ft) for vehicles with poor tires and low tire pressure, hydroplaning will not occur up to speeds of 45 mph. If rain intensity reaches 2 in/hr, under these conditions even vehicles with good tire tread but poor tire pressure can hydroplane if cross slopes are not greater than 2.2%. In most low tire pressure scenarios, vehicle speeds of 55 mph or greater can result in hydroplaning unless the rainfall intensity is as low as 0.5 in/hr.

Table 4-3 Potential of Hydroplaning for Low Tire Pressure Vehicles (P=24 psi; TXD=0.02”)

Speed (mph)	NO. lane = 1			NO. lane = 2		
	Tire Tread Depth (1/32 inch)					
	TD = 2	TD = 6	TD = 10	TD = 2	TD = 6	TD = 10
Rain Intensity = 0.5 in/hr						
V <50	OK	OK	OK	OK	OK	OK
V = 55	1.7%	OK	OK	3.5%	1.9%	OK
V = 60	2.4%	2.1%	1.9%	NO	NO	3.7%
V = 65	2.5%	2.5%	2.4%	NO	NO	NO
V = 70	2.5%	2.5%	2.5%	NO	NO	NO
Rain Intensity = 1 in/hr						
V <45	OK	OK	OK	OK	OK	OK
V = 50	OK	OK	OK	2.2%	OK	OK
V = 55	NO	2.5%	OK	NO	NO	2.9%
V = 60	NO	NO	NO	NO	NO	NO
V >65	NO	NO	NO	NO	NO	NO
Rain Intensity = 1.5 in/hr						
V <45	OK	OK	OK	OK	OK	OK
V = 50	1.9%	OK	OK	3.8%	OK	OK
V = 55	NO	NO	2.6%	NO	NO	NO
V >60	NO	NO	NO	NO	NO	NO
Rain Intensity = 2 in/hr						
V <45	OK	OK	OK	OK	OK	OK
V = 50	2.8%	OK	OK	NO	2.2%	OK
V = 55	NO	NO	3.8%	NO	NO	NO
V >60	NO	NO	NO	NO	NO	NO
Rain Intensity = 3 in/hr						
V <45	OK	OK	OK	OK	OK	OK
V = 50	NO	1.9%	OK	NO	3.8%	2.1%
V = 55	NO	NO	NO	NO	NO	NO
V >60	NO	NO	NO	NO	NO	NO

Note: Cross slope 1.5% - 4%

Typical tire pressure for passenger cars is 32 psi, however, the recommended tire pressure is usually between 30 and 35 psi (*22*). Table 4-4 represents the comparison between the critical water depth and the accumulated water above the pavement for passenger cars with a tire pressure of 32 psi and texture depth of 0.02 inch. When the water above the pavement flows along one travel lane, the comparison shows for vehicles with nearly bare tires, hydroplaning would not occur up to the speed of 50 mph. For rain intensities up to 1.5 in/hr, hydroplaning will not occur for vehicle speeds up to 55 mph if the cross slope is greater than 2.2%. When the flow path is two travel lanes, vehicles with nearly bald tires will not hydroplane when traveling at speeds up to 55 mph for rain intensities as low as 1 in/hr if the cross slope is higher than 2.5%. There is a risk of hydroplaning for rain intensities at 1.5 in/hr or greater for speeds of 55 mph or greater if vehicle tires are nearly bald.

Table 4-04 Potential of Hydroplaning for Typical Tire Pressure Vehicles (P=32 psi; TXD=0.02”)

Speed(mph)	Tire Tread Depth (1/32 inch)					
	NO. lane = 1			NO. lane = 2		
	TD = 2	TD = 6	TD = 10	TD = 2	TD = 6	TD = 10
Rain Intensity = 0.5 in/hr						
V <50	OK	OK	OK	OK	OK	OK
V = 55	OK	OK	OK	OK	OK	OK
V = 60	1.8%	OK	OK	3.5%	2.0%	OK
V = 65	2.4%	2.1%	1.8%	NO	NO	>3.5%
V = 70	2.5%	2.4%	2.3%	NO	NO	NO
Rain Intensity = 1 in/hr						
V <45	OK	OK	OK	OK	OK	OK
V = 50	OK	OK	OK	OK	OK	OK
V = 55	OK	OK	OK	2.5%	OK	OK
V = 60	NO	2.5%	OK	NO	NO	3.0%
V >65	NO	NO	NO	NO	NO	NO
Rain Intensity = 1.5 in/hr						
V <45	OK	OK	OK	OK	OK	OK
V = 50	OK	OK	OK	OK	OK	OK
V = 55	2.2%	OK	OK	NO	1.8%	OK
V >60	NO	NO	*	NO	NO	NO
Rain Intensity = 2 in/hr						
V <45	OK	OK	OK	OK	OK	OK
V = 50	OK	OK	OK	OK	OK	OK
V = 55	3.3%	OK	OK	NO	2.6%	OK
V >60	NO	NO	**	NO	NO	NO
Rain Intensity = 3 in/hr						
V <45	OK	OK	OK	OK	OK	OK
V = 50	OK	OK	OK	1.7	OK	OK
V = 55	NO	2.3%	OK	NO	NO	2.6%
V >60	NO	NO	NO	NO	NO	NO

Note: Cross slope 1.5% - 4%

* No hydroplaning if V = 60 and cross slope greater or equal to 2.6%

****** No hydroplaning if V = 60 and cross slope greater or equal to 3.9%

Pavement Surface Influences on Hydroplaning

Pavement macro-texture is a significant contributor to wet-pavement safety (25,18) and among the critical factors affecting hydroplaning, transportation departments have most control over the texture of the pavement surface, whereas the other factors identified fall under the domain of the user (i.e., speed, tire tread depth, and tire pressure). Pavements with greater macro-texture generally exhibit greater friction and also facilitate improved drainage, which helps to minimize hydroplaning. Pavement texture is largely defined by the aggregate gradation and construction quality of the wearing course. Dense graded mixtures exhibit lower texture levels and more open graded mixtures possess higher texture levels. A typical dense fine-graded asphalt mix will possess a texture depth in the range of 0.015 to 0.025 inches and a dense coarse graded mix can have a texture depth up to 0.05 inches. Gap graded mixes such as Stone Matrix Asphalt (SMA) typically have a texture depth greater than 0.4 inches and open graded mixtures, such as Open Graded Friction Courses (OGFC) that are designed to be porous to promote water drainage, have texture depths ranging from 0.06 to 0.14 inches (*26*). In addition to safety benefits, the macro-texture of OGFC has also been reported to increase fuel economy and reduce tire wear (*27*).

Given this information and an understanding of how mixture proportions influence macro-texture and overall performance, pavement mixtures can be engineered to optimize safety and durability. Additionally, with proper pavement management techniques, pavements can be preserved to maintain texture and, therefore, wet weather safety. Several highway departments have implemented asphalt mix selection and design guidelines to maximize texture appropriate to the design speed and traffic of the roadway (*26*). Many states, utilize OGFC on high speed roadways primarily for the safety benefits resulting from the open texture and porous nature.

Table 4-5 provides a comparison of the hydroplaning potential of pavement surfaces having different texture depths (TXD) ranging from 0.02 inches (dense fine graded asphalt) to 0.14 inches (OGFC). In this scenario, the tire tread depth (TD) was low (4/32”) and the tire pressure was typical at 32 psi. The results clearly demonstrate the benefits of macro-texture on the pavement safety with respect to hydroplaning, especially for high speed, multi-lane roadways. Even at the highest rainfall intensity of 3 in/hr, the OGFC having average TXD of 0.1 inches would have little chance of hydroplaning with appropriate cross slope at typical interstate speeds.

Table 4-5 Hydroplaning Potential of Pavement Surfaces for Different Texture Depths

Cross Slope 1.5% - 4.0% Tire Tread (TD) = 4/32" Tire Pressure = 32psi										
	Flow path = 12 ft (1 lane)					Flow path = 24 ft (2 lanes)				
	Rainfall intensity (in/hr)					Rainfall intensity (in/hr)				
	I=0.5	I=1	I=1.5	I=2	I=3	I=0.5	I=1	I=1.5	I=2	I=3
Speed (mph)	TXD = 0.02 inch (e.g. Minimum Pavement Texture Depth)									
V = 45	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
V = 50	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
V = 55	OK	OK	OK	1.9%	3.4%	OK	OK	2.6%	3.9%	NO
V = 60	OK	3.4%	NO	NO	NO	2.6%	NO	NO	NO	NO
V = 65	2.2%	NO	NO	NO	NO	NO	NO	NO	NO	NO
V = 70	2.5%	NO	NO	NO	NO	NO	NO	NO	NO	NO
Speed (mph)	TXD = 0.04 inch (e.g. Typicall non-OGFC Pavement Texture Depth)									
V = 45	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
V = 50	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
V = 55	OK	OK	OK	OK	OK	OK	OK	OK	1.6%	2.7%
V = 60	OK	OK	1.9%	2.8%	NO	OK	2.2%	3.9%	NO	NO
V = 65	OK	OK	2.6%	3.8%	NO	OK	2.9%	NO	NO	NO
V = 70	OK	1.6%	2.7%	4.0%	NO	OK	3.1%	NO	NO	NO
Speed (mph)	TXD = 0.06 inch (e.g. Minimum OGFC Pavement Texture Depth)									
V = 45	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
V = 50	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
V = 55	OK	OK	OK	OK	OK	OK	OK	OK	OK	1.8%
V = 60	OK	OK	OK	OK	2.4%	OK	OK	1.9%	2.8%	NO
V = 65	OK	OK	OK	1.7%	2.9%	OK	OK	2.3%	3.4%	NO
V = 70	OK	OK	OK	1.7%	3.0%	OK	OK	2.3%	3.5%	NO

Speed (mph)	TXD = 0.1 inch (e.g. Average OGFC Pavement Texture Depth)									
V = 45	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
V = 50	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
V = 55	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
V = 60	OK	OK	OK	OK	OK	OK	OK	OK	OK	1.8%
V = 65	OK	OK	OK	OK	OK	OK	OK	OK	OK	2.1%
V = 70	OK	OK	OK	OK	OK	OK	OK	OK	OK	2.1%
Speed (mph)	TXD = 0.14 inch (e.g. Maximum OGFC Pavement Texture Depth)									
V = 45	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
V = 50	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
V = 55	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
V = 60	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
V = 65	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK
V = 70	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK

Conclusion

In the absence of adequate cross slope on a roadway surface, especially during severe rainfall and associated inclement weather, the likelihood of ponding will increase (*11*). However, practical pavement cross slope provides a means to drain water from the surface laterally, minimizing ponding, reducing the potential of hydroplaning, and decreasing the likelihood of wet-pavement crashes (*11*). There is considerable agreement that a water depth equal to 0.06 inches is the acceptable upper limit of water depth above the pavement *(8,13)*, however, this value remains debatable given an absence of evidence-based analytical support. For any given pavement surface, the hydroplaning potential depends on the operating vehicle speed, tire characteristics, pavement surface characteristics, and environmental factors (*20*).

This research evaluated different scenarios with variation of vehicle operating condition and geometric characteristics including pavement width and pavement cross slope to define the critical water depth at which hydroplaning occurs and the potential of hydroplaning. Due to lower critical water depth at higher speed (especially for vehicle speeds greater than 50 mph), drivers are more vulnerable to hydroplaning related crashes. Maintaining appropriate tire pressure and tire tread increases the critical water depth and consequently improves the safety of vehicles traveling on the roadways.

Also, maintaining a comprehensive, an updated geometric characteristics (e.g. cross slope) dataset helps transportation agencies to identify problematic sections and address the problem promptly. Mobile LiDAR provides an efficient, high resolution, reliable cross slope measurement, which is capable to measuring and monitoring pavement along the roadway at highway speed; and it is practical solution to addressing this problematic challenge.

The typical cross slope of South Carolina highways is 2.08%, therefore, according to the SCDOT's maximum construction tolerance of ± 0.348% (*14*); an allowable minimum cross slope would be 1.73%. Using average Mobile Terrestrial LiDAR Scanning (MTLS) measurement error of ± 0.19% found in previous research (*11*) a cross slope of 1.54% corresponds to a water depth 0.035 and 0.055 inches near the edge of pavement for a rainfall intensity equal to 2 in/hr, when the travel lane is one and two lanes, respectively. This resulted in the low potential of hydroplaning for vehicles traveling at speeds of 45 mph for rainy/wet conditions with the rain intensity less than 2 in/hr. While, due to lack of sight vision there is an expectation for drivers to avoid driving, or to drive very slowly, during such heavy rainfall periods (*8*).

Although most traffic crashes result from drivers' errors (behavioral factors), with a better understanding of non-behavioral factors, such as geometric design parameters of the road, transportation engineers will be able to design and maintain roadways with higher safety standards (28). The pavement properties and the roadway geometry including pavement cross slope, number of the travel lanes, and width of pavement, longitudinal grade, pavement texture, design speed and stated speed limits are the parameters that can be controlled by states highway agencies. Therefore, the state DOTs are able to design and maintain roadway safety by minimizing the potential of hydroplaning and utilizing efficient methods such as MTLS to identify problematic sections and promptly address problems as they arise. It important for all transportation stakeholders to understand that regardless of how safe a road is designed, hydroplaning is possible, especially if vehicles are poorly maintained. As a result, driver education is crucial ensuring drivers understand the dangers of hydroplaning and how keeping adequate tire pressure and maintaining safe speeds is critical for their safety.

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CHAPTER FIVE

CONCLUSION

As stated in Chapter One, the primary goal for conducting this research was to investigate if MTLS and ALS can be efficient, effective, and safe methods for collecting a system-wide, reliable, continuous, and comprehensive cross slope dataset which can serve multiple users in SCDOT and other state highway agencies across the country. There were four objectives established and achieved over the three research papers in this dissertation that help to reach the goal. They are restated here:

1. Develop an efficient work flow for extracting cross slope data from MTLS and ALS point clouds
2. Evaluating the accuracy of MTLS and ALS technologies for system-wide verification of highway cross slope.
3. Include both mapping grade and survey grade MTLS in the accuracy evaluation.
4. Defined the critical water depth at which hydroplaning occurs with regard to the range of vehicle speed, tire tread depth, tire pressure, pavement surface texture, pavement width, and highway cross slope.

Papers I and II found the LiDAR technology could be an effective and reliable method for cross slope verification (objectives 1 and 2). Paper I also showed that unadjusted MTLS can be used to collect accurate cross slope data (objective 3). This is a significant finding because the cost of a control survey is typically more than the cost of

MTLS. Thus, eliminating extensive control surveys can make collecting cross slope data much more affordable for state highway agencies. It is noteworthy that control surveys are important when positional accuracy of the LiDAR point cloud is paramount such as for roadway design applications. The relative accuracy which does not require control survey data is sufficient for accurate cross slope measurements. Paper III focused on the critical water depth at which hydroplaning occurs based on various roadway and vehicle parameters (objective 4). The paper clearly indicates that adequate cross slope is of greatest importance to minimize the potential for hydroplaning however other factors are important as well. In fact, hydroplaning can occur regardless of cross slope which makes these other factors important considerations for state highway agencies. Developing a deeper understanding of the relationship between cross slope and these other factors can help state agencies to implement measures to minimize hydroplaning on their roads.

In the first paper, the use of MTLS to extract cross slope was evaluated on 20 stations along US-123 in Easley, SC, I-85 business loop in Spartanburg, SC, and East West Parkway in Anderson, SC. Since the cross slope is uniform on each travel lane, the interest area (travel lane) was identified using difference in intensity of the return laser from the roadway surface. The higher intensity of the return pulse from the white and yellow pavement markings at two ends of the travel lane defines the interest area. The MTLS provides the roadway information in the form of a dense point cloud which includes the easting, northing, elevation, and the intensity of all points within the point cloud. The cross slope was calculated at each travel lane by dividing the difference in elevation by the horizontal width of the travel lane and multiplying by 100 to determine cross slope in percent. The comparison was conducted between both the adjusted and unadjusted MTLS point cloud extracted cross slopes and field survey measurements. The unadjusted LiDAR data did incorporate corrections from an integrated inertial measurement unit, and high accuracy real-time kinematic GPS, however, was not post-processed adjusted with ground control points. The results of a t-test statistical analysis indicated the average deviation between LiDAR data and field surveying measurements was less than the minimum acceptable accuracy value (±0.2% specified by SCDOT and SHRP 2) at the 5 % confidence level. This level of accuracy and the workflow used to extract cross slope data from the LiDAR point cloud demonstrates that MTLS is a reliable method for cross slope verification (Objectives 1 and 2). It is noteworthy that both adjusted and unadjusted LiDAR data met the SCDOT standard achieving the third objective of the dissertation.

The second paper compared the use of airborne and mobile LiDAR to extract the cross slope on five test stations corresponding to specific panel points along I-85 business loop in Spartanburg, SC. At each test station, the cross-section line was drawn across the travel lanes at the panel point coordinates located on the side of the roadway. In this study the elevation of the two ends of the travel lane along the reference line was acquired along with the width of each travel lane. Elevation data were extracted along the cross-sectional line every 0.2 feet (2.4 inches). Results of this research showed the feasibility of both MTLS and ALS to collect cross slope data efficiently, accurately, and reliably. The t-test statistical analysis proved that by fitting a regression line to the extracted points at 0.2 feet intervals the deviation between both mobile and aerial LiDAR-derived cross slopes and field surveying measurements was less than 0.2% at 5 % level. While the MTLS data collection using the elevation of the two sides of the travel lane met the acceptable accuracy of the cross-sectional calculation, the difference between the ALS derived cross slopes, and the field surveying is over the ±0.2%, and this was statistically significant at the 5% level. Therefore, these results indicate that the slope of the fitted regression line is the better representation of the cross slope at each travel lane. Also, MTLS data collection could result in more accurate data for survey grade applications over ALS data collection.

Adverse rainy weather along with inadequate highway cross slope increase the likelihood of water sheeting and ponding and reduce the pavement friction and could result in hydroplaning. Although, there is considerable agreement that a water depth equal to 0.06 inches is the acceptable water depth above the pavement; there are situations where hydroplaning can occur at water depths less than 0.06 inches depending on road, vehicle, and environmental characteristics. Therefore, the third paper estimated the critical water depth and presented the potential of hydroplaning with regard to a range of vehicle speed, tire tread depth, tire pressure, pavement surface texture, and cross slope.

Due to the lower critical water depth at higher speeds greater than 50 mph, drivers are vulnerable to hydroplaning related crashes. Higher tire pressure and tire tread depth increase the critical water depth and consequently improves safety.

Maintaining a comprehensive and updated geometric characteristics (e.g. cross slope) dataset can help the transportation agencies to identify problematic sections and address problems proactively. Mobile LiDAR provides an efficient and reliable method to measure pavement cross slopes at highway speeds and is a practical solution to addressing this problematic challenge.

Sources of Error and Methods to Reduce Error

This research provided a technical evaluation of ALS and multiple MTLS systems with respect to accuracy and precision of collected cross slope data and procedures to calibrate, collect, and process data. The LiDAR scanning systems have different levels of positional accuracy due to error sources in the sensors including GPS, IMU, DMI, the LiDAR scanning device, time synchronization error, and boresight error which is the misplacements between the LiDAR scanner and IMU measurement axes (*1*,*2*). Cross slope measurement accuracy can be improved with the following:

- GPS mission planning should be performed to ensure good satellite availability during data collection.
- High accuracy VRS differential correction or GPS post/real-time processing using base stations occupying Primary Survey Control (PSC) points throughout the project area should be used.
- LiDAR scanning systems should be carefully calibrated prior to data collection.
- For MTLS, making a pass in every travel lane can result in a denser point cloud and will improve measurement angles which will enhance overall accuracy. Note that point density is greatest in the MTLS travel lane and diminishes in adjacent travel lanes due to the distance.
- Least squares adjustment of the point cloud using available survey ground control points will improve accuracy. This adjustment increases absolute accuracy however our research indicated that relative accuracy is still very high without post-process.

Benefits and Drawbacks

LiDAR technology benefits can be divided into two categories safety benefits and product benefits.

Safety Benefits

Use of LiDAR scanning systems can improve safety by considerably reducing the time surveyors and other personnel are exposed to risks associated with working in close proximity to the traveling public. While ground control surveys are required for highest accuracy, the extent of exposure is far less than traditional surveying to acquire cross-sectional measurements. Also, LiDAR scanning measurement minimizes the need for work zones associated with surveying operations. Work zones may include survey vehicles that can impair diver visibility for clear zones, shoulders, or even travel lanes.

Product Benefits

ALS platform is capable of measuring and monitoring large area, however, based on the accuracy and the density of the points the area could range up to 20,000 acres (*3*,*4*). For MTLS data collection up of 150 miles of highway or more per day is achievable (*5).* Also, dense point cloud allows for a nearly continuous surface modeling in the direction of travel and significant point coverage transversely within the line of sight of the LiDAR scanning device(s). The density of the point cloud virtually eliminates the need to interpolate between points (*6*).

Additionally, a point cloud can be used for multiple purposes by multiple users and there are opportunities to share various applications *(7*). There are numerous other applications within states DOTs that can benefit from MTLS and ALS including clear zone and roadside safety audits, asset management, cross sectional measurements (e.g., lane and median width, fore slope, back slope, and ditch parameters), flood plain delineation, transverse profiling, pavement monitoring and maintenance, surface analysis, cost estimating and volume extraction, and numerous others.

Challenges and Drawbacks

LiDAR scanning technologies have an expensive up-front cost (*7*); but in the long term will result in a cost savings with extensive use. For example, purchasing and operating a survey grade mobile LiDAR system and using it over a 6 year lifecycle, can produce a savings ranging from \$1.3 million to \$6.1 million (*8*).

LiDAR scanning devices can only collect data within line of sight (*7).* This is why most vehicles used in an MTLS are trucks, vans, or SUVs that allow for higher LiDAR mounting heights. The higher vantage point allows for increased data collection beyond low lying objects such as guard rail, barriers, vegetation, or even the crown of a median. The point density (and accuracy) diminishes as distance increases from the MTLS travel path in any direction. However, improved accuracy can be achieved by traveling in every lane *(6*).

While a dense point cloud can provide a highly accurate data set, it can be challenging and time consuming to process and interpret the large dataset (*9*). Also, it is time consuming unless some or most processes are automated. The programming languages and available software products that automate several processes helps to overcome this challenge.

Finally, the results of this research verify and support the feasibility of LiDAR technology in comparison to conventional surveying techniques as an efficient, accurate, safe, and reliable method for cross slope verification. The use of LiDAR can increase data collection productivity, minimize road crew exposure to traffic concerns, and create robust, 3D, and continuous datasets which can serve multiple users in state DOTs across the country.

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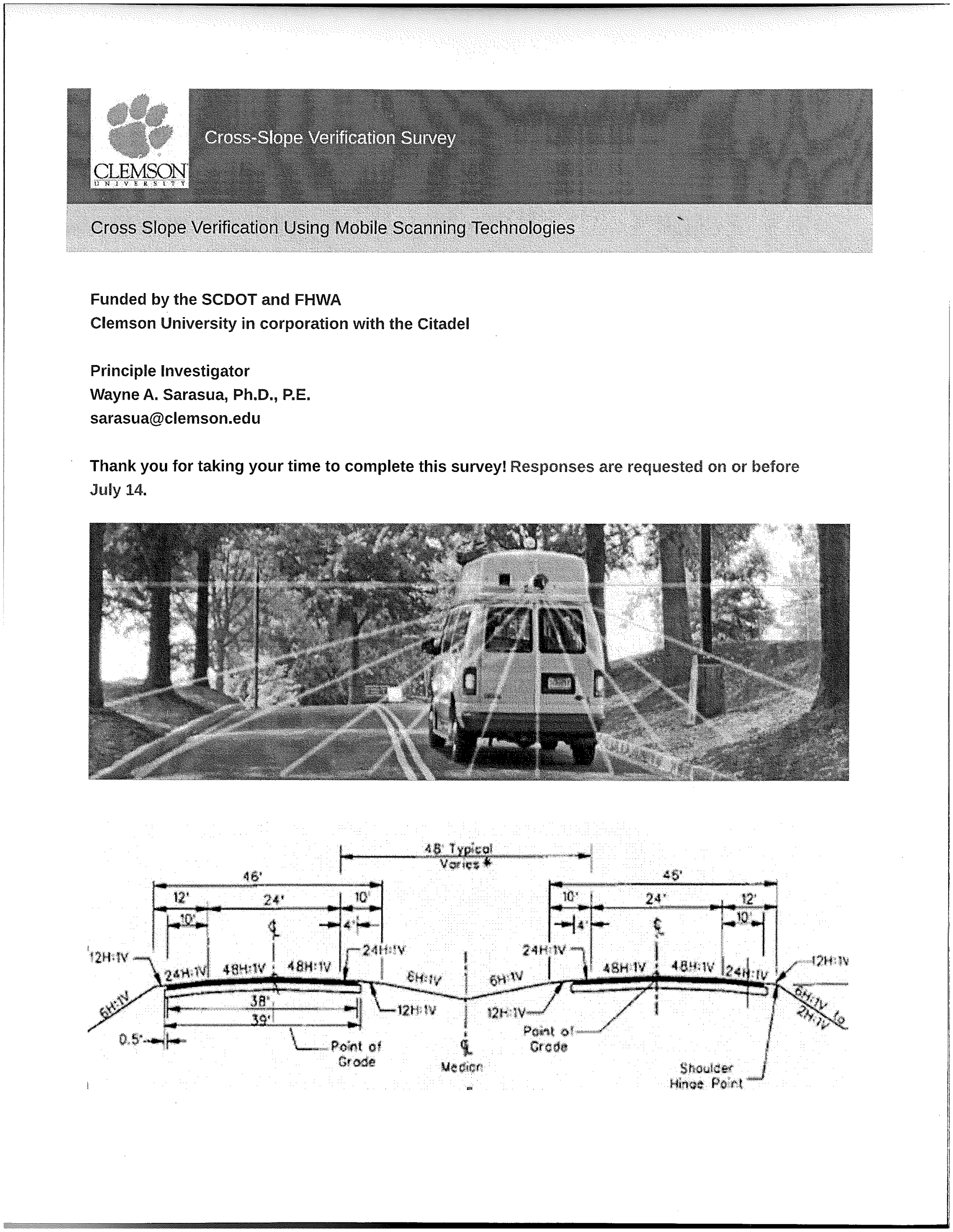
APPENDICES

Appendix A

Survey of States



Cross-Slope Verification Survey

Cross Slope Verification Using Mobile Scanning Technologies

Funded by the SCDOT and FHWA
Clemson University in corporation with the Citadel

Principle Investigator
Wayne A. Sarasua, Ph.D., P.E.
sarasua@clemson.edu

Thank you for taking your time to complete this survey! Responses are requested on or before July 14.

* 1. Contact Information

Name

Agency (e.g. SCDOT)

Department (e.g. Preconstruction)

Title (e.g. Head surveyor)

City/Town

State/Province

Email Address

Phone Number

Data Collection

* 2. Does your agency currently collect cross-slope data for any purpose?

○ Yes

○ No

If the answer is No, then why?

Data Collection

* 3. For what purpose/application do you collect cross-slope data?

○ Material quantity take off

○ Compliance of cross-slope

○ Asset collection

○ Pavement distress

○ Other (please specify)

Data Collection

* 4. Does your agency have any plans to collect cross-slope data in the future?

○ Yes

○ No

If the answer is no, then why?

Data Collection

5. For what purpose/application do you wish to collect cross slope data?

○ Material quantity take off

○ Compliance of cross slope

○ Asset collection

○ Pavement distress

○ Other (please specify)

Data Collection

* 6. On what type of roads does your agency perform cross-slope data collection?

☐ Interstate highways

☐ US highways

☐ Other primary roads

☐ Secondary roads

Additional comments

Cross-Slope Data Collection Methods

* 7. How is cross slope-data collected?

☐ Surveying techniques

☐ Smart level / Slope meter

☐ Carpenter's level combined with tape measure / ruler

☐ Mobile method (e.g. LIDAR and/or Inertial device)

☐ Other (please specify)

Non-mobile Cross-slope Data Collection

* 8. Who does non-mobile cross slope data collection?

☐ In-house Inspector

☐ In-house surveyor

☐ Contracted professional

Please provide contact information the most knowledgeable cross-slope surveyor (in-house or contractor)

* 9. When does your agency collect cross-slope data? (check all that apply)

☐ Inspection after new construction

☐ Inspection after maintenance / rehabilitation

☐ Prior to maintenance / rehabilitation

☐ Road Inventory / Attribute data collection

☐ Other (please specify)

Cross-slope Data Collection Intervals

* 10. At what interval is cross-slope data collected? (non-mobile methods)

Constant interval on tangents (e.g. 100 ft)	
Constant interval on curves (e.g. 50 ft)	
At critical stations (e.g.,PC, PT, end of TRO, beginning of full SE)	
Other (please specify)	

Guidelines to Measure the Cross-Slope (Non-Mobile)

* 11. What guideline does your agency follow to measure cross-slope?

(Please describe and/or provide web link if available on-line)

Construction Specification

* 12. What level of tolerance is accepted for construction specification? (e.g 0.2% of design plan)

(Please describe and/or provide web link if available on-line)

High Speed Data Collection

* 13. Does your agency use mobile LIDAR data collection?

○ Yes

○ No

High Speed Data Collection

14. What applications are LIDAR data used for? (Check all that apply)

○ Cross-slope measurement

○ Breakline extraction

○ Roadway inventory/asset data collection

○ Other (please specify / provide web link)

LIDAR

* 15. Which LIDAR data collection methods does your agency currently use? (Check all that apply)

☐ Mobile LIDAR

☐ Aerial LIDAR

☐ Other (please specify)

* 16. What LIDAR vendors has your agency use?(Check all that apply)

☐ Mandli
☐ Sanborn
☐ Fugro/Roadware, Inc.
☐ Michael Baker
☐ Pathway Services, Inc.
☐ Quantum Spatial
☐ Rice
☐ IMC
☐ ESP
☐ Maser
☐ McKim and Creed
☐ Other (please specify)

* 17. How does your agency extract attribute data from the LIDAR raw data?(Check all that apply)

☐ Manual Extraction
☐ Semi-automated methods
☐ Automated methods
☐ Please describe semi-automates and automated methods

18. What software tools does your agency use to process LIDAR data?

☐ Bentley Pointools
☐ ArcGIS
☐ AutoCAD Civil 3D
☐ TopoDOT
☐ Microstation Suite or Other Bentley Tools (including GeoPak, InRoads, or Descartes)
☐ Other (please specify)

* 19. What is the typical resolution of LIDAR scanning?(e.g. 1 point every 0.04")

20. What level of accuracy does your agency require for LIDAR data collection?
(If you have different levels of accuracy for different applications, please specify)

Laser Transverse Profiler

* 21. Does your agency use a laser transverse profiler?

○ Yes

○ No

Laser Transverse Profiler

* 22. What is the purpose of using a laser transverse profiler?(Check all that apply)

☐ Collect cross-slope data

☐ Pavement 3D Texture

☐ Crack detection

☐ Depth of roadway rutting

☐ Other (please specify)

* 23. What laser transverse profiler does your agency use?

Guidelines to Measure the Cross-Slope (High Speed Methods)

* 24. Which guideline does your agency follow for transverse profiling?(e.g. AASHTO pp 69-10)

Thank You

Thank you for completing this survey

Appendix B

Tukey HSD ALL Pairwise Comparisons

<table>
<tr><td colspan="6">End to End data acquisition</td></tr>
<tr><td colspan="6">Tukey HSD ALL Pairwise Comparisons</td></tr>
<tr><td colspan="2">Quantile = 3.36674</td><td colspan="2">Adjusted df = 11.8</td><td colspan="2">Adjustment = Tukey-Kramer</td></tr>
<tr><td>Method</td><td>Method</td><td>Difference</td><td>Std Error</td><td>t ratio</td><td>p-value</td></tr>
<tr><td>ALS</td><td>Vendor A</td><td>0.0800</td><td>0.0450</td><td>1.79</td><td>0.5080</td></tr>
<tr><td>ALS</td><td>Vendor B</td><td>0.0499</td><td>0.0414</td><td>1.20</td><td>0.8260</td></tr>
<tr><td>ALS</td><td>Vendor C</td><td>0.0436</td><td>0.0421</td><td>1.03</td><td>0.8970</td></tr>
<tr><td>ALS</td><td>Vendor D</td><td>0.0373</td><td>0.0500</td><td>0.75</td><td>0.9718</td></tr>
<tr><td>ALS</td><td>Vendor E</td><td>0.0650</td><td>0.0569</td><td>1.14</td><td>0.8545</td></tr>
<tr><td>Vendor A</td><td>Vendor B</td><td>-0.0305</td><td>0.0450</td><td>-0.68</td><td>0.9812</td></tr>
<tr><td>Vendor A</td><td>Vendor C</td><td>-0.0368</td><td>0.0458</td><td>-0.80</td><td>0.9613</td></tr>
<tr><td>Vendor A</td><td>Vendor D</td><td>-0.0431</td><td>0.0509</td><td>-0.85</td><td>0.9523</td></tr>
<tr><td>Vendor A</td><td>Vendor E</td><td>-0.0154</td><td>0.0576</td><td>-0.27</td><td>0.9998</td></tr>
<tr><td>Vendor B</td><td>Vendor C</td><td>-0.0063</td><td>0.0421</td><td>-0.15</td><td>1.0000</td></tr>
<tr><td>Vendor B</td><td>Vendor D</td><td>-0.0126</td><td>0.0501</td><td>-0.25</td><td>0.9998</td></tr>
<tr><td>Vendor B</td><td>Vendor E</td><td>0.0151</td><td>0.0569</td><td>0.27</td><td>0.9998</td></tr>
<tr><td>Vendor C</td><td>Vendor D</td><td>-0.0063</td><td>0.0509</td><td>-0.12</td><td>1.0000</td></tr>
<tr><td>Vendor C</td><td>Vendor E</td><td>0.0214</td><td>0.0571</td><td>0.37</td><td>0.9989</td></tr>
<tr><td>Vendor D</td><td>Vendor E</td><td>0.0277</td><td>0.0611</td><td>0.45</td><td>0.9969</td></tr>
</table>

<table>
<tr><td colspan="6">0.2 feet interval point extraction</td></tr>
<tr><td colspan="6">Tukey HSD ALL Pairwise Comparisons</td></tr>
<tr><td colspan="6">Quantile = 3.32417 Adjusted df = 12.8 Adjustment = Tukey-Kramer</td></tr>
<tr><td>Method</td><td>Method</td><td>Difference</td><td>Std Error</td><td>t ratio</td><td>p-value</td></tr>
<tr><td>ALS</td><td>Vendor A</td><td>-0.0144</td><td>0.0264</td><td>-0.54</td><td>0.9938</td></tr>
<tr><td>ALS</td><td>Vendor B</td><td>-0.0102</td><td>0.0246</td><td>-0.42</td><td>0.9980</td></tr>
<tr><td>ALS</td><td>Vendor C</td><td>-0.0313</td><td>0.0253</td><td>-1.24</td><td>0.8116</td></tr>
<tr><td>ALS</td><td>Vendor D</td><td>0.0253</td><td>0.0289</td><td>0.87</td><td>0.9466</td></tr>
<tr><td>ALS</td><td>Vendor E</td><td>-0.0154</td><td>0.0323</td><td>-0.47</td><td>0.9964</td></tr>
<tr><td>Vendor A</td><td>Vendor B</td><td>0.0041</td><td>0.0264</td><td>0.16</td><td>1.0000</td></tr>
<tr><td>Vendor A</td><td>Vendor C</td><td>-0.0169</td><td>0.0272</td><td>-0.62</td><td>0.9872</td></tr>
<tr><td>Vendor A</td><td>Vendor D</td><td>0.0396</td><td>0.0297</td><td>1.33</td><td>0.7624</td></tr>
<tr><td>Vendor A</td><td>Vendor E</td><td>-0.0010</td><td>0.0333</td><td>-0.03</td><td>1.0000</td></tr>
<tr><td>Vendor B</td><td>Vendor C</td><td>-0.0211</td><td>0.0253</td><td>-0.83</td><td>0.9558</td></tr>
<tr><td>Vendor B</td><td>Vendor D</td><td>0.0355</td><td>0.0289</td><td>1.23</td><td>0.8167</td></tr>
<tr><td>Vendor B</td><td>Vendor E</td><td>-0.0052</td><td>0.0327</td><td>-0.16</td><td>1.0000</td></tr>
<tr><td>Vendor C</td><td>Vendor D</td><td>0.0565</td><td>0.0295</td><td>1.91</td><td>0.4367</td></tr>
<tr><td>Vendor C</td><td>Vendor E</td><td>0.0159</td><td>0.0333</td><td>0.48</td><td>0.9962</td></tr>
<tr><td>Vendor D</td><td>Vendor E</td><td>-0.0407</td><td>0.0348</td><td>-1.17</td><td>0.8445</td></tr>
</table>