PAVEMENT SURFACE EVALUATION USING MOBILE TERRESTRIAL LiDAR SCANNING SYSTEMS

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ABSTRACT

Periodic measurement of pavement surfaces for pavement management system (PMS) data collection is vital for state transportation agencies. Vehicle-based mobile light detection and ranging (LiDAR) systems can be used as a versatile tool to collect point data throughout a roadway corridor. The overall goal of this research is to investigate if mobile terrestrial LiDAR Scanning (MTLS) systems can be used as an efficient and effective method to create accurate digital pavement surfaces for. LiDAR data were collected by five MTLS vendors. In particular, the research is interested in three things: 1) how accurate MTLS is for collecting roadway cross slopes; 2) what is the potential for using MTLS digital pavement surfaces to do materials calculations for pavement rehabilitation projects; and 3) examine the benefit of using MTLS to identify pavement rutting locations.

Cross slopes were measured at 23 test stations using traditional surveying methods (conventional leveling served as ground-truth) and compared with adjusted and unadjusted MTLS extracted cross slopes. The results indicate that both adjusted and unadjusted MTLS derived cross slopes meet suggested cross slope accuracies (±0.2%). Application of unadjusted MTLS instead of post-processed MTLS point clouds may decrease/eliminate the cost of a control surveys.

The study also used a novel approach to process the MTLS data in a geographic information system (GIS) environment to create a 3-dimension raster representation of a roadway surface. MTLS data from each vendor was evaluated in terms of the accuracy and precision of their raster surface. The resultant surfaces were compared between vendors and with a raster surface created from a centerline profile and 100-ft. cross-section data obtained using traditional surveying methods. When comparing LiDAR data between compliant MTLS vendors, average raster cell height differences averaged 0.21 inches, indicating LiDAR data has considerable potential for creating accurate pavement material volume estimates.

The application of MTLS data was also evaluated in terms of the accuracy of collected transverse profiles. Transverse profiles captured from MTLS systems have been compared to 2-inch interval field data collection using partial curve mapping (PCM), Frechet distance, area, curve length, and Dynamic Time Warping (DTW) techniques. The results indicated that there is potential for MTLS systems for use in creating an accurate transverse profile for potential identification of pavement rut areas. This research also identified a novel approach for determining pavement rut areas based on the shape of grid cells. This rather simplistic approach is easily implementable on a network wide basis depending on MTLS point cloud availability. The method does not require the calculation/estimation of an ideal surface to determine rut depths/locations.

Keywords: mobile terrestrial LiDAR Scanning, digital pavement surfaces, cross slope measurement, pavement material volume estimates, transverse profiles, pavement rutting evaluation.

In memory of:

Healthcare workers who have lost their lives through pandemic Covid-19

DEDICATION

This dissertation is dedicated to my wife Dr. Tahereh Nabizadeh, and our parents Bahman Famili, Mahnaz Moghimi, Marzieh Nabizadeh.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

INTRODUCTION

The advent of Mobile Terrestrial LiDAR Scanning (MTLS) systems has led to collection of high-resolution 3D data and numerous other related technology advancements in asset management and pre-construction activities. Applicability of LiDAR technology has provided increased proficiency for mapping a route corridor and its surrounding environment as a result of the rapid, continuous, and cost-effective data acquisition capability (1). Panoramic scans obtained from MTLS systems need to be acquired along with Global Navigation Satellite System (GNSS) positioning data so post-processing can produce accurate georeferenced point clouds (2). MTLS systems are currently the fastest ground-based method for acquiring 3D surface information across large areas (3). MTLS systems have numerous applications, including, but not limited to highway surveying (4, 5), sandy coast morphology (6, 7), environmental management (8, 9) and railway geometry extraction and railway monitoring (10).

Problem Statement

Pavement Management Systems (PMSs) have been widely implemented by state DOTs. There is no doubt that data collection from the pavement plays a vital role in a PMS. Pavement surface information such as cross slope, estimated material quantity for pavement rehabilitation, and pavement distress such as pavement rutting are among the key elements of PMS data collection.

Understanding the usefulness and limitations of different pavement surface data collection methods is crucial for determining the best method to use for a particular PMS project. Collecting data from the pavement surface using traditional survey methods is tedious and time consuming. In addition, on road data collection may raise safety concerns for road users and survey crews. To ensure safety guidelines, data collectors may require short term lane closures disrupting traffic flow (12), causing road user inconvenience and traffic congestion (13).

The benefits of using MTLS systems for PMS data collection include high-resolution data collection capability, reduced number of field visits, and multiple end users and opportunities to share data (such as consortiums in Oregon, Alaska and South Carolina) (14). MTLS can enable a rapid as-built, geospatial record of completed maintenance as well as prevent repeat surveys (15). Data collected for roadways can also be useful for several geometric analyses including adequate alignment layouts, slope, drainage properties, travel lane width, and pavement surface wear (15). Several roadway resurfacing contractors have found LiDAR data to be effective in reducing change orders and over-run costs for resurfacing projects (15).

The focus of this dissertation is to provide a basis for evaluating the effectiveness of MTLS technology and equipment for addressing accuracy and traceability of high-resolution raster surfaces. The main objective of this research is to investigate if MTLS systems can be used as an efficient and effective method to create accurate digital pavement surfaces.

Research Objectives

As previously discussed, collection of pavement surface data can be challenging for state DOTs. Traditional surveying methods are limited to collecting pavement cross sections rather than continuous surface data. For pavement rutting data collection, depressions need to be visually evident and then rutting depth can be collected using actual pavement rutting data collection instruments. Pavement profilers that use multiple sensors directed downward toward the pavement are capable of collecting continuous pavement data however they can only collect a single lane of data in one pass. MTLS systems have overhead rotating lasers that can collect a much wider swath in a single pass including the entire road surface and adjacent shoulder area. This makes MTLS systems much more versatile than pavement profilers because MTLS systems can be used to collect the locations and associated attributes of a wide variety of roadway assets and characteristics such as signs, pavement markings, and roadside foreslope and backslope information. Because of the significant cost of both MTLS and pavement profiler systems, there is significant value added potential if an MTLS can be used in place of a pavement profiler for PMS applications. Thus, the primary goal for conducting this research is to investigate if MTLS systems can be used as an efficient and effective method to create accurate digital pavement surfaces which can serve multiple users in the South Carolina Department of Transportation (SCDOT) and other state highway agencies across the country. The objectives towards achieving the research goal are as follows:

- Develop an efficient workflow for extracting pavement raster surfaces from MTLS point clouds.
- Conduct a comprehensive technical evaluation of multiple MTLS systems to evaluate the accuracy and precision of collected raster surfaces and required procedures to calibrate, collect and process LiDAR data.
- Examine if accurate cross slope measurements can be extracted from the digital pavement surface and if MTLS can be used for system-wide verification of highway cross slopes.

- Examine if accurate pavement material estimates can be made for pavement resurfacing and rehabilitation purposes.

In order to achieve the research objectives, LiDAR data was collected on three different roadway test sections: 1) an urban section in Anderson, SC; 2) a highway section at Anderson, SC; and 3) a freeway section in Spartanburg, SC. The collected data from five MTLS vendors were used for evaluation of the accuracy and resolution of the digital pavement surfaces created from the MTLS point clouds. Conventional surveying measurement including high accuracy GNSS, total station, and leveling was used as ground truth on selected test stations for comparison purposes.

Organization of Dissertation

This dissertation document consists of three research papers on pavement surface measurement using MTLS systems, and each paper accounts for one chapter of the dissertation. The data acquisition sections of the three papers are the same.

PAPER I: HIGHWAY CROSS SLOPE MEASUREMENT USING MOBILE LIDAR

OBJECTIVES

- Investigate efficient methods for identifying highway sections that do not meet minimum criteria for pavement cross slope
- Evaluating MTLS systems in terms of the accuracy and precision of collected cross slope data on pavement surfaces and documentation of procedures needed to calibrate, collect, and process this data.
- Evaluating the impact of changes in cross slope on water depth accumulation.

TASKS

- Task A: Extract the cross slopes from both ground control adjusted and unadjusted point clouds on selected stations.
- Task B: Comparing cross slope data collection using MTLS systems with traditional surveying methods (collected by leveling in the field)
- Task C: Examine whether MTLS can be used as an efficient and accurate method and meets the acceptable error specification.
- Task D: Cross slope sensitivity analysis to examine the impact of changes in cross slope on water depth accumulation by rainfall intensity.

PAPER II: Improving Quantity Estimating for Pavement Rehabilitation and Resurfacing Using Mobile LiDAR

OBJECTIVES

- Conduct a comprehensive technical evaluation of multiple MTLS systems to evaluate accuracy and precision of collected raster surfaces and required procedures to calibrate, collect and process LiDAR data.
- Determine if accurate pavement material estimates can be made for rehabilitation purposes.

TASKS

- Task E: Clip ground control adjusted and unadjusted point cloud between edge lines and exclude median to reduce noises.
- Task F: Apply Gaussian Filtering to create a smooth surface.
- Task G: Cut and fill estimation for five MTLS data collectors.
- Task H: Sensitivity analysis of surface volume estimation based on cell raster size.
- Task I: Comparisons between the MTLS raster surfaces of each of the vendors
- Task J: Extract raster surface from geocoded data collected using traditional surveying and exclude median in GIS environment.
- Task K: Comparison of each MTLS raster surface with the surface created from traditional surveying.

PAPER III: Application of Mobile Terrestrial LiDAR in Identifying Potential Pavement Rutting Locations

OBJECTIVE

- Develop a semi-automatic method to identify pavement rutting locations from a digital pavement surface and evaluate the accuracy of the method.
- Examine the benefit of using MTLS to identify potential pavement rutting locations.

TASKS

- Task M: Apply Edge Detection method using SIFT key point to extract pavement surface.
- Task N: Validate the method using one profile section collected with traditional surveying.
- Task O: Applying the method to a digital pavement surface to collect cross sectional data at a user-defined interval.

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

- A Draft of this Paper is also Included in Alireza Shams Doctoral Dissertation.

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.

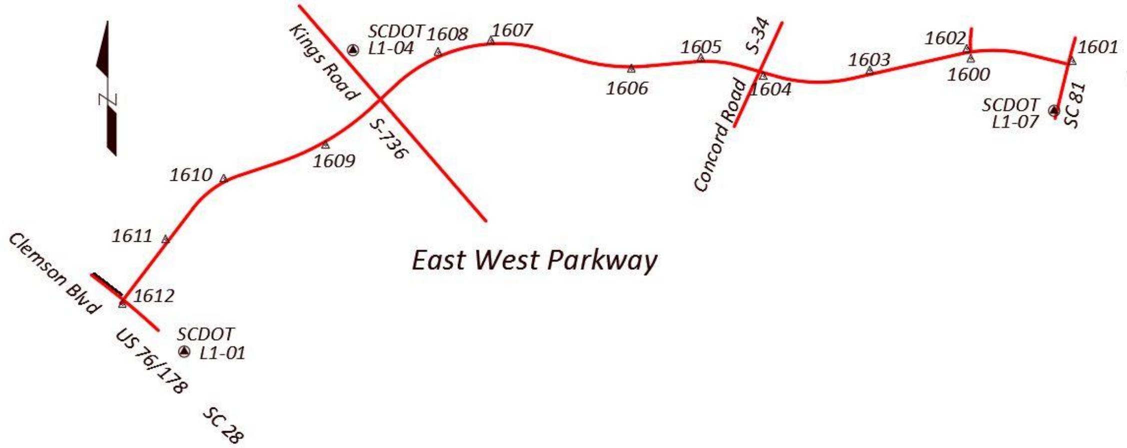

Figure 2-1 GCPs and check points along the 3-mile study area section 1

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 2-1 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 $30^{th,}$ 2016 and 2 other vendors on August $30^{th,}$ 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.

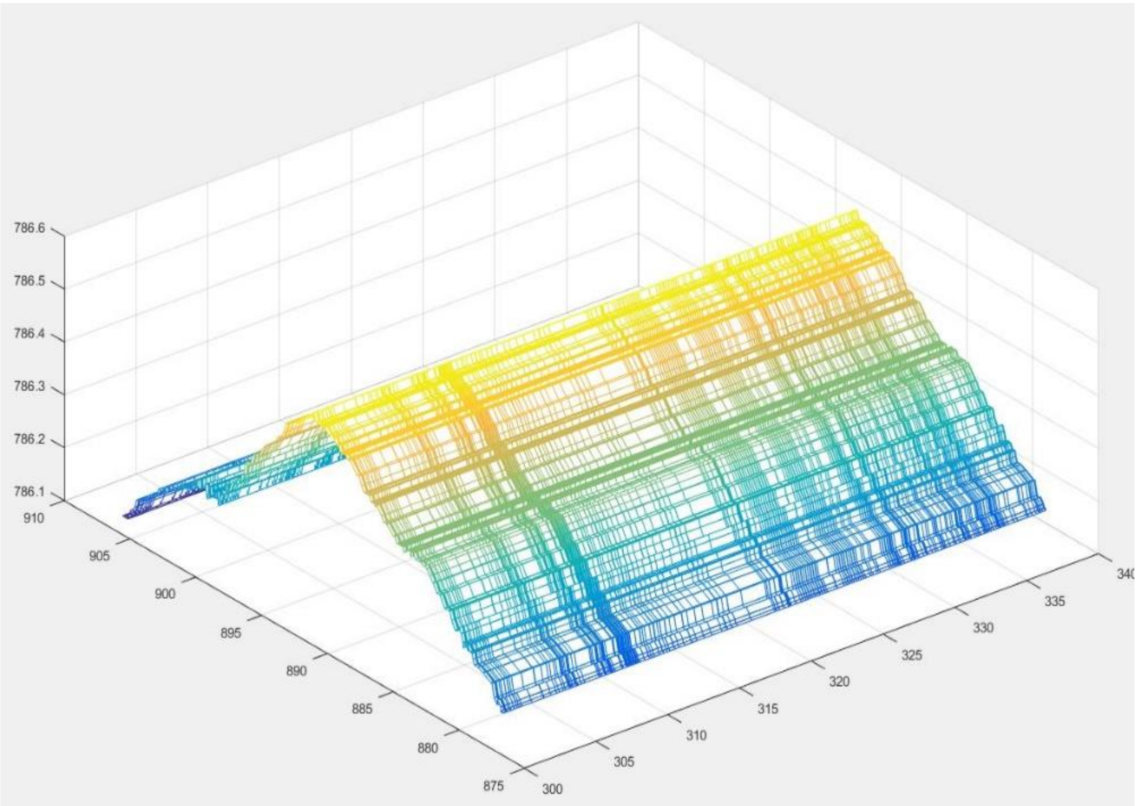

Figure 2-2 Mesh grid fitted to points within buffer area

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.

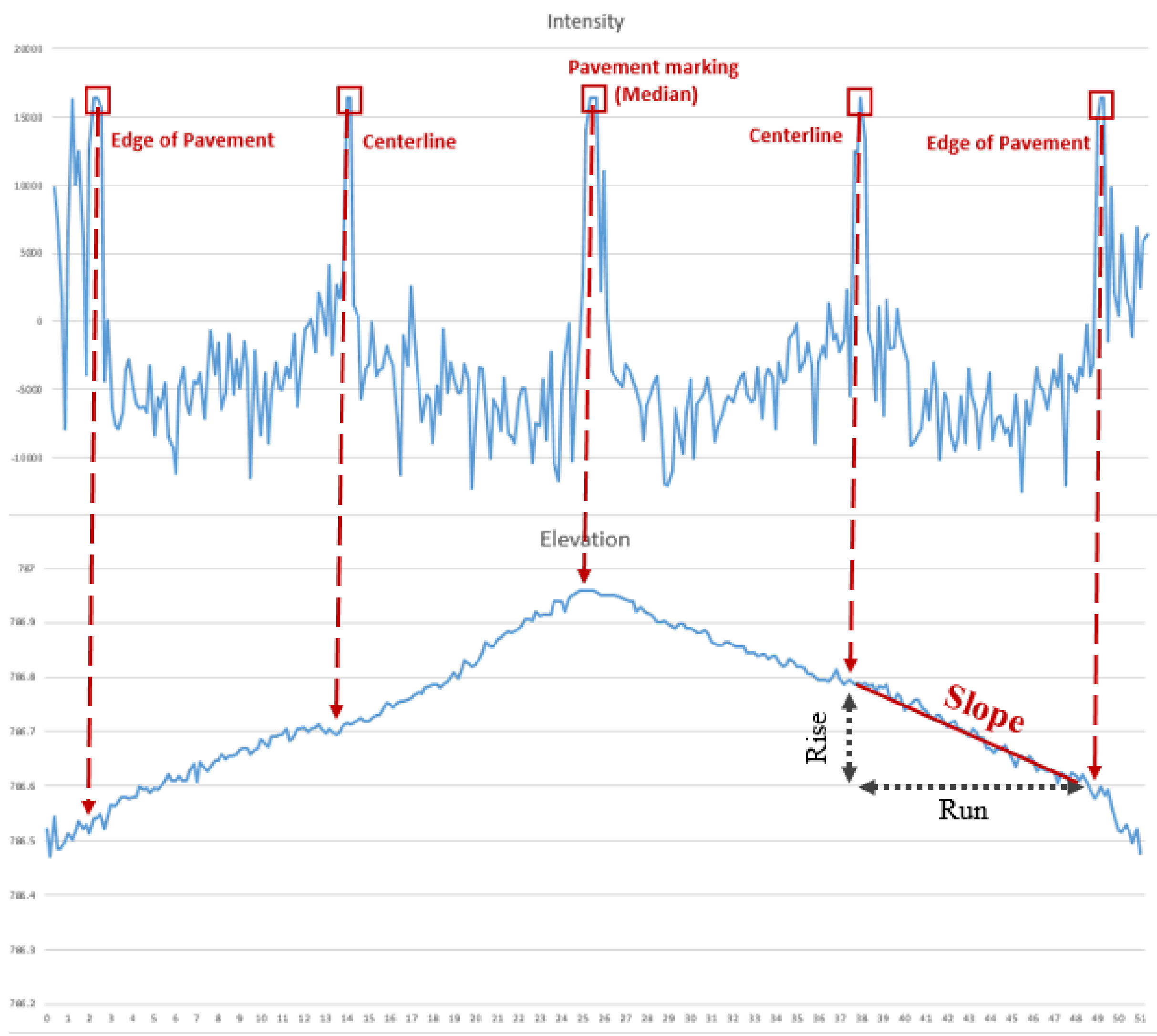

Figure 20-3 Pavement marking extraction and corresponding elevations

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 2-1 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 2-2 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 0-3 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 2-1 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).

$$L_f = L_x\,((1 + (S_g/S_x)^2)^{0.5} \quad (2\text{-}1)$$

$$WD_0 = 0.00338\, TXD^{0.11} L_f^{\,0.43} I^{0.59}\, S_x^{\,-0.42} - TXD \quad (2\text{-}2)$$

$$WD = (WD_0 + TXD) \times \sqrt{1 + (S_g/S_x)^2} - TXD \quad (2\text{-}3)$$

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.

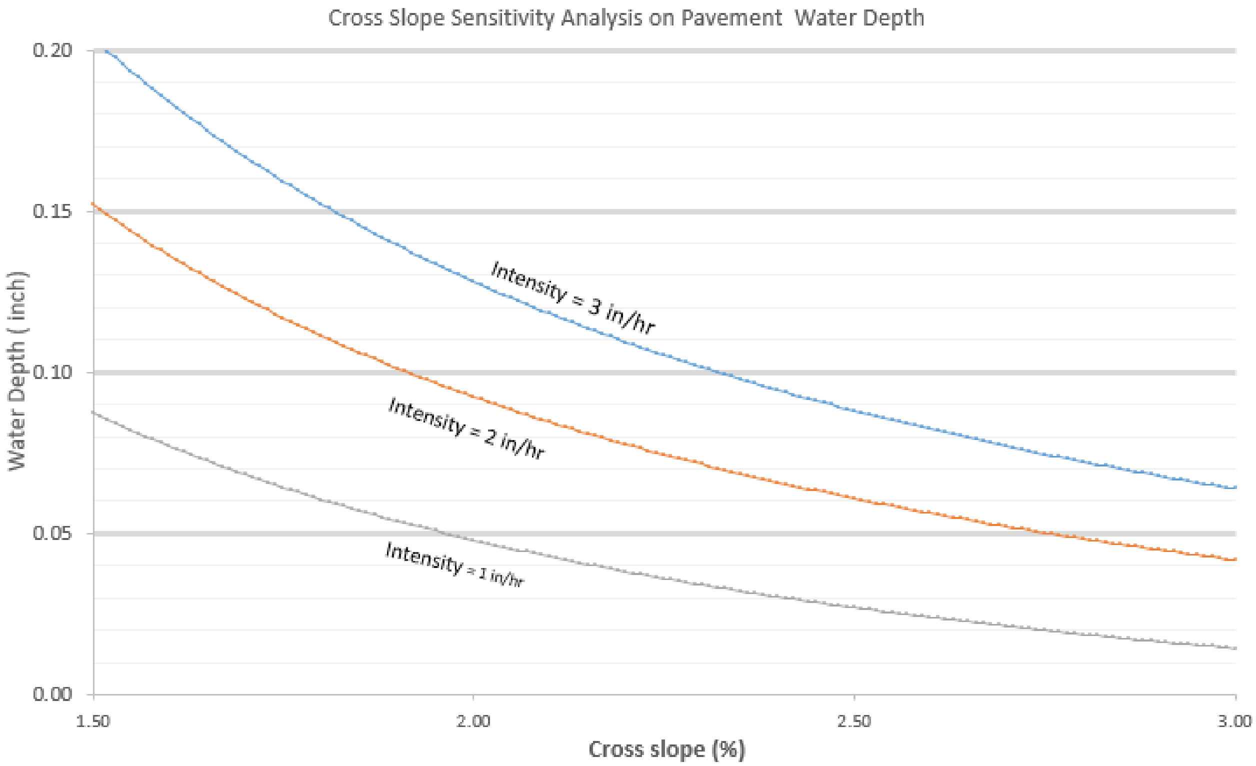

Figure 0-5 Cross slope sensitivity analysis on pavement water depth

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: Improving Quantity Estimating for Pavement Rehabilitation and Resurfacing Using Mobile LiDAR

Abstract

Repaving, rehabilitation, and pavement maintenance are routine tasks of all state and local transportation agencies. Compared with traditional surveying techniques, vehicle-based mobile light detection and ranging (LiDAR) systems can be used to estimate material volumes needed for pavement rehabilitation and resurfacing in a cost-efficient manner. An innovative approach based on use of mobile LiDAR data and geographic information system (GIS) analysis was developed to create 3-dimnesion raster representation of roadway surfaces. The research approach involved conducting a comprehensive technical evaluation of multiple mobile scanning systems to evaluate accuracy and precision of collected raster surfaces and required procedures to calibrate, collect and process LiDAR data. A testbed study site located along a 2.9-mile urban parkway in Anderson, South Carolina was used to investigate accuracy of high-resolution raster surface modeling of the roadway paved surface. LiDAR data was collected by five mobile laser scanning (MLS) vendors. MLS data from each vendor was evaluated regarding the accuracy and precision of the raster surfaces. The resultant surfaces were compared between vendors and with a raster surface created from profile and 100-ft. cross section data obtained from traditional surveying methods. LiDAR produced more precise surface data and pavement material estimates as compared with traditional survey data averaged linearly over 100-ft increments. In comparing LiDAR data between compliant MLS vendors, average raster cell height differences averaged 0.21 inches, ranging from 0.01 to 0.63 inches, indicating LiDAR data has considerable potential for creating accurate

pavement material volume estimates.

Keywords: Mobile light detection and ranging, Pavement rehabilitation and resurfacing, Surface modeling

Introduction

Repaving, rehabilitation, and pavement maintenance is a necessary investment required to protect the traveling public, extend roadway pavement life, and avoid extensive reconstruction costs. Traditionally, conventional profile and cross section surveys have served as the basis for repaving projects, pavement maintenance applications, and quantity estimating. However, traditional survey methods limit the development of accurate pavement leveling, base course and adjustments of cross slopes for pavement rehabilitation and resurfacing projects because of the resolution of survey data. Inaccurate pavement material estimates during the design phase can cause problems during construction, ultimately resulting in costly contractor change orders. LiDAR Mobile Laser Scanning (MLS) provides transportation agencies with the ability to create surface models at a much higher resolution, which can potentially be used in the pavement reconstruction and rehabilitation design process to produce better construction drawings and pavement material estimates. More accurate pavement deficiency detection and material estimation required for pavement resurfacing and rehabilitation projects are essential for effective budgeting of maintenance costs and improving financial control of program-level road maintenance operations.

The advent of Mobile Laser Scanning (MLS) has led to collection of high-resolution 3D data and numerous other related technology advancements in asset management and pre-construction activities. Applicability of LiDAR technology has provided increased proficiency for route corridor mapping and surrounding environment as a result of the rapid, continuous, and cost-effective data acquisition capability (1). Panoramic scans obtained from MLS need to be acquired along with Global Navigation Satellite System (GNSS) positioning data so post-processing can produce accurate georeferenced point clouds (2). Laser Mobile Mapping Systems (LMMS) are currently the fastest ground-based method for acquiring 3D surface information across large area locations (3). LMMS has numerous applications, including, but not limited to: highway surveying (4, 5), sandy coast morphology (6, 7), environmental management (8, 9) and railway geometry extraction and railway monitoring (10).

LiDAR benefits include: high-resolution capability, reduced number of field visits, and multiple end users and opportunities to share data (such as consortiums in Oregon, Alaska and South Carolina) (11). LiDAR difficulties include: expensive up-front cost, line-of sight requirements, and need to automate classification of the large number of points (11). Mobile LiDAR can enable a rapid as-built, geospatial record of completed maintenance while preventing repeat surveys (12). Data collected for roadways can also be useful for several geometric analyses including: adequate alignment layouts, slope, drainage properties, travel lane width, and pavement surface wear (12). Several roadway resurfacing contractors have found that LiDAR data effectively reduces change orders and over-run costs for resurfacing projects (12).

Current methods used to determine the accuracy of Mobile LiDAR data employ comparison of isolated ground control points to triangulated meshes, or Triangulated Irregular Networks (TINs) generated from the data. However, the most contemporary methods leverage a small number of isolated points to qualify millions of mobile LiDAR points, ultimately resulting in a less accurate registration process (13). The method used in this research uses millions of high precision LiDAR points to create a raster surface, which can potentially yield a significant improvement in absolute accuracy while providing traceability to survey control.

The focus of this research was to examine multiple mobile scanning systems, with emphasis on accuracy and traceability of high-resolution raster surfaces created from the LiDAR data. A raster surface generated from traditional survey methods along a 2.9-mile urban roadway in South Carolina was evaluated and compared with raster surface data from five mobile scanning systems. This paper describes the analysis of the following: 1) accuracy of mobile LiDAR captured raster surfaces based on data from 5 different vendors; 2) comparison of surfaces between raw and ground control adjusted mobile LiDAR data; and 3) discussion of a sensitivity analysis of raster cell size from an accuracy impact perspective.

Literature Review

The application of MLS has increased in recent years and is becoming a boon for transportation agencies looking to improve safety and efficiency. Financial incentives for the use of 3D technology provided in the recent legislation “Moving Ahead for Progress in the 21st Century Act” push DOTs and transportation agencies to use MLS in wide-ranging mapping applications. The literature review summarizes previous research and studies on application of LiDAR in pavement maintenance, MLS accuracy, surface analysis with LiDAR data, and volume extraction from LiDAR data.

Application of LiDAR in Pavement Maintenance

The California Department of Transportation published a report entitled Advanced Highway Maintenance & Construction Technology (AHMCT) which provides a detailed background and summary of the use of mobile laser scanning to produce digital terrain models of pavement surfaces. The research investigated Mobile Terrestrial Laser Scanning (MTLS) within the context of Caltrans surveying applications. Test methodologies and analysis techniques were developed to evaluate MTLS system data for accuracy, repeatability, and usability. The methodologies and techniques include highly demanding pavement surveys that produce Digital Terrain Models. Results showed that surface fitting of point clouds produces better elevation estimation in comparison with immediate nearest point comparison. It was also concluded that MTLS projects requiring survey grade accuracy must have ground controls for quality assurance/quality control. Results showed the scans suffer from linear/high order vertical offset with respect to position or time of scan. Hence, the scan accuracy may be increased by post-processing high order z-axis offset adjustment of the point cloud (14).

The Center for Earthworks Engineering Research (CEER) investigated the potential for using dense three-dimensional (3D) point clouds generated from LiDAR and photogrammetry to assess roadway roughness. To compare both technologies, the coordinates of the clouds for the same section on the same date were matched using open source computer code. Three gravel road sections, one Portland Cement Concrete (PCC) section, and one asphalt concrete (AC) section were included in a case study analysis. Results indicated the technology could be used as a promising tool for evaluating road roughness. CEER concluded that these technologies would enable capturing large amounts of data, which allows modeling the elevation of the full surface (15).

Schnebele et al. (16) provided a bridge between traditional procedures for road evaluation and remote sensing methodologies by creating a comprehensive reference for geotechnical engineers and remote sensing experts. Results showed the use of remote sensing techniques offers new potential for pavement managers to assess large areas, often in little time. Based on the results, they found that remote sensing techniques do provide an opportunity to reduce the number or size of areas requiring site visits or manual methods.

González-Jorge et al. (17) evaluated and parameterized the influence of the precision of LiDAR data for runoff estimation. In their study, aerial and terrestrial MLSs are combined for surveying roads and their surroundings to provide a complete point cloud. They introduced Gaussian noise with different standard deviation values in the point cloud to determine its influence in evaluation of water runoff direction. The surface drainage pattern of the road and its surroundings were determined by using the D8 algorithm under different conditions of LiDAR precision. Results indicated an increase in the differences of flow direction with the decrease of cell size of the raster dataset and with the increase of Gaussian noise.

Accuracy of MLS and Other Mobile Data Collection Methods

Alberto et al. tried to extract road geometric parameters through automatic processing of MLS point clouds. Their methodology was carried out in different steps. First, data capturing, then segmentation, which simplifies the point cloud to extract the road platform. Second, applying principal component analysis (PCA) based on orthogonal regression to fit the best plane on the points. The final step was extracting vertical and cross section geometric parameters and analysis. The study's method proposed an alternative automated development of an as-built plan. Study results validated the method within relative accuracies under 3.5% (18).

Baffour (19) discussed the need for numeric geometry of exiting roadways in many transportation projects. The paper discusses the use of an attitudinal GPS system that has four antennas synchronized with a single GPS receiver to determine the three-dimensional orientation of the moving vehicle. Cross slopes were collected using conventional surveying at 50-ft. intervals and were compared with the attitudinal GPS cross slopes. The accuracy, found to be 0.5%, indicated that attitudinal GPS has exceptional promise as a tool for collecting this data.

White et al. (20) tested the accuracy of forest road characteristics mapped using LiDAR in the Santa Cruz Mountains, CA. They accurately extracted the position, gradient, and total length of a forest haul road using a 1-meter digital elevation model (DEM). The result indicated that the LiDAR-derived road exhibited a positional accuracy of 1.5 m, road profile grade measurements within 0.53% mean absolute difference, and total road length within 0.2% of the field-surveyed length in comparison to a field-surveyed centerline.

Surface Analysis with LiDAR Data

A mobile LiDAR scanner mounted on a car can provide a dense point cloud depicting highways, their surroundings, and the road surface very accurately. Jaakkola et al. (21) discussed that because of the density of data produced by laser-based mobile mapping, new algorithms are needed for data extraction. Using data collected with the Finnish Geodetic Institute (FGI) Roamer mobile mapping system (MMS), the authors classified points on the roadway painted markings. Then, they found curbstones from the height of the image. Finally, they modeled the pavement as a TIN and generated a raster image. They showed that the raster image was more efficient to process than the raw point cloud. The proposed method was able to find most curbstones, parking spaces, and zebra crossing.

Grafe (22) provides examples of a roadway digital surface model, cross sections, and a highway interchange that have all been surveyed using MLS. Additionally, Grafe demonstrates how a controlled and guided roadway milling machine can be set to automatically cut the road using the digital surface model. Olsen et al., show an example of how a vehicular model derived from a static scan can be used to evaluate its ability to navigate through a highway system that has been digitally captured through MLS, prior to travel.

Zhang and Frey (23) tried to model roadway grade using LiDAR to estimate vehicle emissions. The LiDAR based method was used to model grade for a road between North Carolina State University and Research Triangle Park which includes Interstate Highways such as I-40, I-540 and major arterials such as Capital Boulevard. LiDAR data has been used to fit a plane using regression techniques. The pilot case study was divided into different segments having a constant slope. One consideration in defining segments was to include adequate data, due to residuals following the natural distribution, resulting in a plane fit of the roadway surface on each roadway section using bivariate linear regression.

Volume Extraction from LiDAR data

Laser scanning is recognized as a fast, accurate, and cost-effective tool to gather geo-referenced 3D information of the shape of roadway surfaces. Contreras et al. (24) developed a model to accurately estimate earthwork volumes for proposed forest roads by using a high-resolution digital elevation model (DEM). They applied their model to three hypothetical forest road layouts with different ground slopes and terrain roughness conditions. They examined the effect of various cross-section spacing on the accuracy of earthwork volume estimation. They assumed that 1-meter spacing provides the true earthwork volume. They also compared their model results with those obtained from the traditional end-area method. The results depicted that as cross-section spacing increases, the accuracy of earthwork volume estimation decreases. They concluded that short cross-section spacing should be applied to improve accuracy in earthwork volume estimation when roads are planned and located on hilly and rugged terrain.

Cost Estimating Obstacles

Cost overruns have been identified as a common obstacle to developing quality estimates, and poor estimation of pavement construction costs have become a major concern for DOTs and contractors alike (25, 26). If a DOT overestimates the cost of a project, it could prevent the project from being approved. On the other hand, if a pavement is underestimated, the result could include cost overruns, project delay, or even cancellation of the project. If a contractor overestimates the cost of a project, there is a risk of overbidding and not being awarded the project and underestimating the project costs could result in financial losses (26). Turochy et al. explained that funds spent on cost overruns must come out of funds allocated to another project, or potentially cancellation or delay of other projects on the planning horizon (25).

Research Methodology

The methodology for this research involved a two-phased approach including 1) raster surface generation for five mobile scanning systems and an additional raster surface from traditional surveying data; and 2) comparison between the surfaces based on the volume extraction. Typically, volumes are calculated between a finished ground surface and an existing ground surface. In our comparison, one of the vendor's raster surfaces was treated as existing ground and another vendor was treated as finished ground. If the two surfaces compare favorably, the volume of cut, volume of fill, and the net difference in cut and fill should be close to 0 cubic yards. Our approach used square surface cell sizes of 0.1 ft, 1 ft, and 10 ft.

Study Area and Data Collection

A 2.9-mile urban section (153 stations) in Anderson, South Carolina was chosen for this research to evaluate multiple mobile scanning systems regarding accuracy and precision of collected surfaces and the procedures needed to calibrate, collect and process data (see Figure 1). The study section is the entirety of East-West Pkwy, which originates at US-76 (Clemson Boulevard) and terminates at SC-81 (E Greenville St). East-West Pkwy is a limited access four-lane two-way mostly divided highway. It has a variety of geometric design elements including 15-vertical curves, 7-horizontal curves (all superelevated), one-bridge, two-intersections, traversable and non-traversable medians, and two-lanes per direction with an additional turning lane at intersections. There are no other access points (driveways). To improve accuracy for this research, a ground control survey was conducted that identified 3 primary and 13 secondary geodetic control point (GCP) locations throughout the corridor. At least two primary GCPs were used by vendors as base station locations for GPS differential correction and all of the GCPs (both primary and secondary) were used for post-processing adjustment. Figure 1 shows the GCP locations along the study corridor.

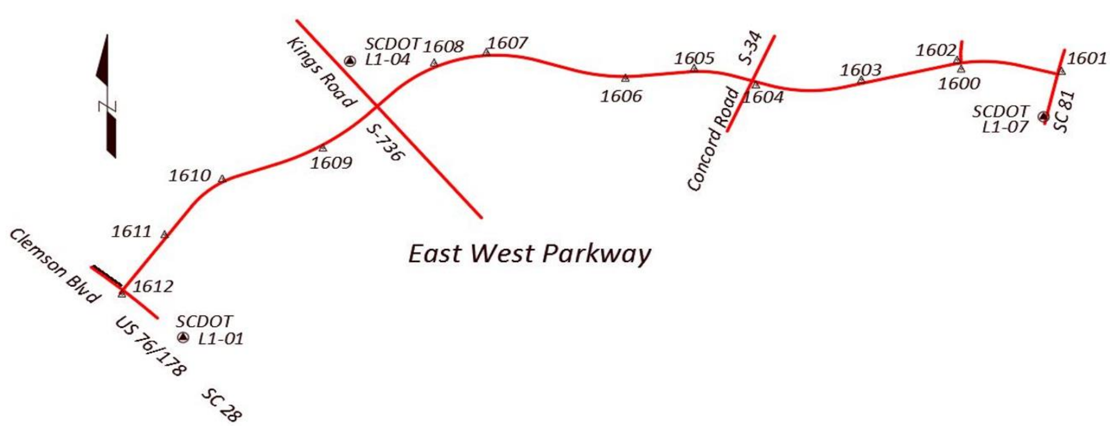

Figure 3-1 Case study location (East-We0-1st Parkway, Anderson, SC)

The vendors had the opportunity to calibrate their systems and set up GPS base stations at selected primary GCPs prior to making their runs. The vendors were allowed to make a single pass in each direction through the test section. To make results more comparable, the vendors followed the same trajectory and were expected to travel at the posted speed limit. Vendor vehicles were always in the rightmost lane except when making a U-turn at the end of the East-West Parkway section and also when making a left turn from East-West Parkway to US-76 on the return trip. Traffic control was provided by two trailing SCDOT vehicles driving side by side so that no cars could pass vendor data collection vehicles. For practical purposes, there was no traffic control for the opposing travel direction. Data collection runs could be repeated if a data collector experienced technical difficulty but only data from one run could be used when submitting results. Table 1 summarizes equipment specifications for four of the vendors that participated. The fifth vendor did not submit specifications.

Surveying nails and reflective tape were established at 100-ft station intervals. Identifying precise locations of station panel points in the LiDAR data was at times difficult to distinguish due to surveying nails being located in the middle of the white edge line. It was also a challenge for vendors to distinguish the white edge line from the reflective tape. In retrospect, it was concluded that placing station locations on the white edge lines was not a good idea. It was assumed intensity attributes would allow differentiation between pavement markings and the pavement tape used. To facilitate locating the surveying nails, the taper of the reflective tape began on the pavement section so that the point could be distinguishable leading to the nails' location.

Table 3-1 Mobile Scanning Equipment Specifications

	Variable	Vendor A	Vendor C	Vendor B	Vendor D
LiDAR	Brand	Riegl	Teledyne Optech	Teledyne Optech	ZF Scanner
	Model	VMX450	M1	SG1	9012
	Single Laser or Dual	Dual	Dual	Dual	Single
	Measurement rate	1100 kHz	500 kHz / sensor	0.6 kHz (each Laser)	1000 kHz

**Vendor E did not submit their MLS specifications*

Traditional surveying (auto leveling combined with taping and total station measurements) was used to develop the comparison survey surface. Pavement cross sections were collected at 100-ft station intervals throughout the entire study corridor. Each cross section was leveled using two different instrument setups to eliminate mistakes and adjust for random error.

Processing

Figure 2 represents the workflow for the research. Raw and adjusted LiDAR point cloud data was rasterized by overlapping a horizontal grid and recording the average point in each cell. Based on the research conducted by Hengl (27), the choice of grid cell size must be observant to the LiDAR scanning density, aiming to capture sufficient detail, and at the same time avoiding raster gaps. In this study, three raster cell sizes of 10 ft, 1ft, and 0.1ft were used to examine sensitivity of the results regarding raster size. To avoid excessive noise with capturing the vertical information, the space was divided into a predefined number of height levels.

Even with careful selection of the pixel size and the number of height levels, the raster is bound to have noise (28). Although cars were not allowed to pass during data collection, existing cars in turn lanes and in the opposite direction were found as one of the sources of noise in the study. To mitigate this problem, the image was convoluted with a 3 × 3 Gaussian kernel that approximates the Gaussian blob. The Gaussian filter (see Equation 1) has a smoothing effect on the raster.

$$G_{2D}(x,y;\sigma)=\frac{1}{2\pi\sigma^2}e^{-\frac{x^2+y^2}{2\sigma^2}} \qquad (1)$$

Where σ determines the width of the Gaussian kernel and acts as a magnitude parameter.

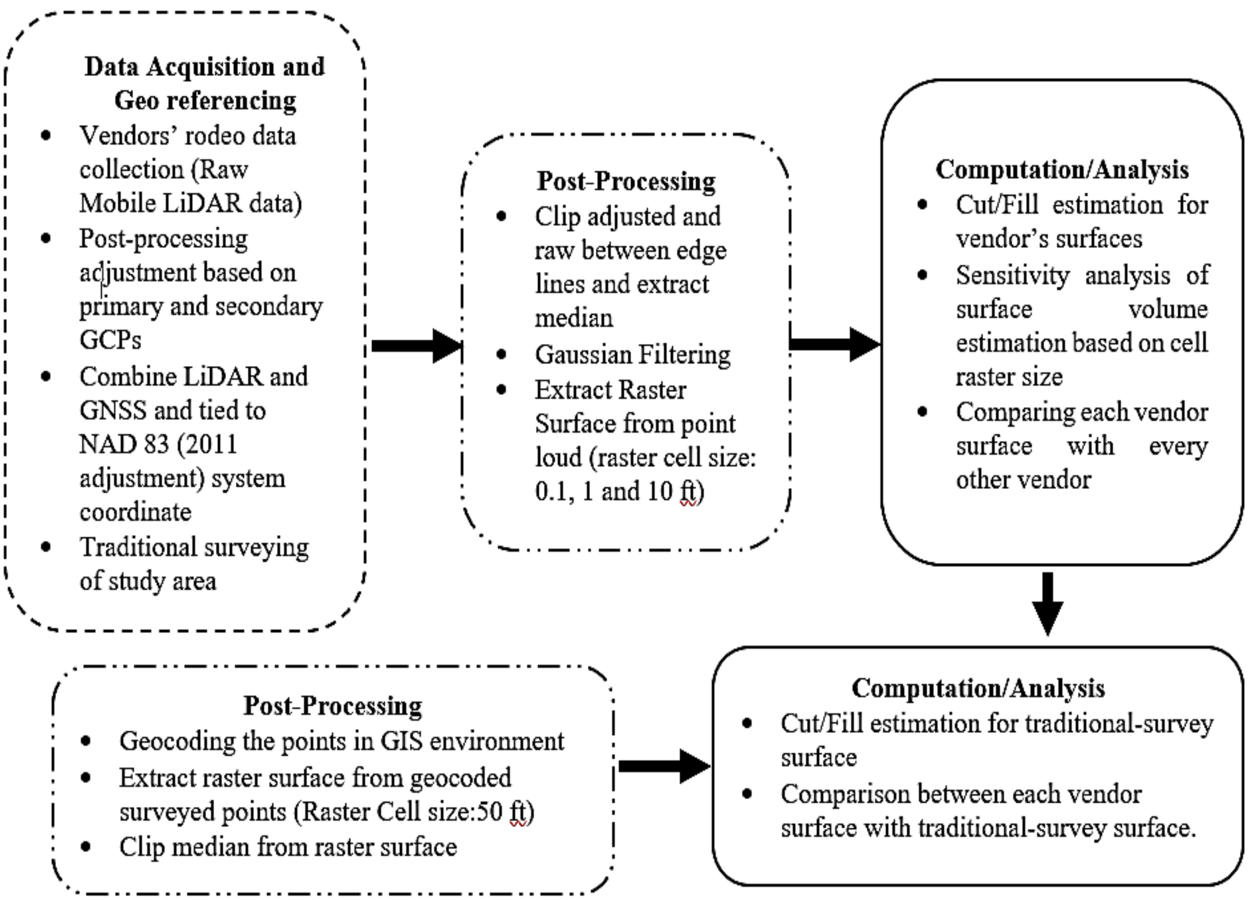

Figure3-2 Research method

The operation used for volume extraction was a procedure in which the elevation of a landform surface is modified by removal or addition of surface material. The Cut & Fill tool in ArcMap summarizes areas and volumes of change from a cut-and-fill operation. By taking surfaces of a given location at two different time periods, the method identifies regions of surface material removal, surface material addition, and areas where the surface has not changed. Equation 2 represents the volume calculated for each single cell.

$$Vol = (cell\_area) * (Z_2 - Z_1) \tag{2}$$

Where Zi represents the average elevation calculated for each cell. The cell areas used in this study were 0.01, 1 and 10 ft. The study used this method to compare the raster surfaces generated from the point clouds collected by the MLS vendors. Each vendor was compared with every other vendor and with the raster surface created using the traditional surveying data.

Results and discussion

The portion of the vendor LiDAR point clouds that fell outside of the white edge lines were clipped before the raster surfaces were generated in ARCGIS. The clip boundary was defined from CAD lines drawn in Microstation using survey data and the LiDAR points along the pavement white edge lines. These points were easily identified because of their higher intensity values. The boundaries were also compared with breaklines that were provided by some of the vendors that were generated from their LiDAR. For the purpose of minimizing the amount of noise (especially noise from scanning vegetation in the median), the median was extracted from the model.

Nearly 1000 points on the inside and outside edge lines for 153 stations (100 ft space interval) in both directions were surveyed twice and geocoded in ARCGIS. These points were used to generate the comparison surface to the LiDAR raster surfaces. Two automatic levels were used to measure the elevation difference between the pavement edge (surveying nail locations placed at 100-ft stations), the crown of the roadway located along the dashed pavement markings, and the median yellow line. Surveying instruments were placed out of the shoulder and the elevation along section L1, Center and R1 were measured as shown in Figure 3-3.

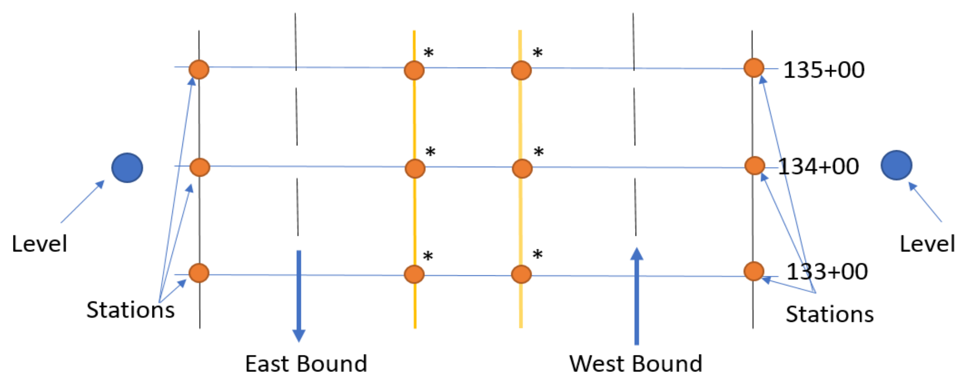

Figure 3-3 Data collection points for ground survey (*represent survey nail locations)

Geocoded points were rasterized by overlaying a horizontal grid and recording the average point in each cell. A comparison of the results from MLS datasets is given in Table 3-2. The results in Table 3-2 are given in terms of the average difference in elevation between two raster surfaces. The results show that the average difference in surface elevation ranges from 0.01 inches to 0.63 inches when comparing vendors B, C, D, and E depending on the raster resolution. Vendor A has a much higher average difference when compared to the other vendors. Taking a closer look at the surfaces shows that vendor A's raster surface is more than 1.5 inches lower than the other vendor surfaces which indicates a systematic error with vendor A's LiDAR data. A comparison of selected secondary control points with the corresponding vendor A LiDAR points reaffirms a systematic error. Furthermore, the raw and calibrated surfaces for vendor A and vendor D were compared and the results are shown in Table 3. The table shows that vendor A's surface had very little adjustment based on GCPS in comparison to vendor D. Because of the apparent systematic error in vendor A's LiDAR data, it has been omitted from further comparison.

Table 3-2 MLS Surface Comparisons (the numbers are in inches)

Vendors	Vendor A	Vendor B	Vendor C	Vendor D	Vendor E
Vendor A					
Vendor B	1.799* 1.862** 1.890***				
Vendor C	1.575* 2.110** 2.043***	0.026* 0.199** 0.155***			
Vendor D	1.663 * 1.763** 1.716***	0.484* 0.137 ** 0.163***	0.630* 0.336** 0.322***		
Vendor E	2.059* 2.035** 2.047***	0.262* 0.127** 0.160***	0.156* 0.047 0.009	0.124* 0.263** 0.332***	

, ** and * Indicate use of 10×10, 1×1 and 0.1×0.1 ft raster size (72,474, 724,742 and 74,247,423 raster pixels, respectively)*

Table3-3 Comparison between Raw and Adjusted Surfaces

Vendors	Raw vs. Adjusted Raster cell size: 10×10 ft (Cubic Yards)	Raw vs. Adjusted Raster cell size: 1×1 ft (Inches)
Vendor A	52.0	0.024
Vendor D	992.8	0.447

In looking at the surface differences between vendors B, C, D, and E, it is noteworthy that the quality of the bare-earth surface LiDAR model and its suitability for mapping terrain features is highly dependent on the density of returns representing the true ground surface. The average surface differences for vendors B, C, D, and E are 0.2808, 0.1854, and 0.1907 inches for the 10-ft, 1-ft, and 0.1-ft raster cell sizes, respectively. A sensitivity analysis for the raster cell sizes shows that there is not a significant difference between the results for 10-ft, 1-ft, and 0.1-ft raster surface models ($F_{2,15}=0.6543$, $p=0.534$). Since the P-value from ANOVA test is greater than 0.05, the three means are statistically similar. Ideally, the optimal raster cell size should be selected based on LiDAR point spacing. While reducing the block size will decrease the effect of surface relief on the error, it might increase the effect of measurement noise and varying point densities. Recall that passing cars in turning lanes or in the opposing direction would produce noise in the LiDAR data. While the vendors were asked to collect data by direction, there were not specifically asked to provide the data by direction. While vendor C provided the LiDAR data by direction in two separate sets of tiles, Vendors B and D provided LiDAR tiles that had both directions combined. A closer look at the LiDAR data from Vendors B and D shows a clear indication of vehicle "blobs" in both roadway directions. For vendor C, there were only vehicle blobs in the direction opposite of the direction the LiDAR was collected. To evaluate the amount of noise caused by cars, Vendor C's raster surface was compared to the other's surfaces by direction. Table 4 presents the results of the comparison in the eastbound direction for a 1-ft raster cell size. Based on the results, there is an increase in the average elevation difference when comparing only the EB data of Vendor C (no cars) with the combined LiDAR data from Vendor B or Vendor D (both with cars). The addition of cars by combining Vendor C's directions shows a reduced average elevation difference. This is because having the presence of cars in Vendors C's data counteracts, to some extent, the presence of cars in Vendors B and D data. This is especially the case for comparing Vendor C and B because they collected data simultaneously (one vehicle following the other) and thus scanned the same vehicles in the opposing direction to their direction of travel. Not coincidentally, the smallest difference in average elevation shown in Table 3-2 discussed previously occurs when comparing Vendor B to Vendor C. The average surface elevation difference was less than ¼ inch for all raster sizes (closer to 1/40 inch for the 10-ft cell size).

Table3-4 MLS Surface Comparisons (the numbers are in inches)

	Vendor C (data provided by direction)	**Vendor C (Combined)**
Vendor D (Combined directions)	0.3367	0.0998
Vendor B (Combined directions)	0.1997	0.0168

The results of the comparison of the raster surface created from the surveyed cross sections with the raster surfaces of the vendors is shown in Table 3-5. The average of the differences in the surface elevations between the surveyed raster surface and the vendor raster surfaces using a 10-ft cell size is 3.12 inches. The average difference in net volume is 6981.0 cubic yards for the 2.9-mile section. This equates to 601.8 cubic yards per lane mile. This difference is due to the interpolation between the 100 ft cross sections and the inability to capture terrain variation. This type of variation could include the presence of pavement rutting, which would not have been captured with traditional surveying that does not consider the surface profile (e.g., rutting) across the entire lane. The accuracy that can be achieved using a mobile LiDAR raster surface to calculate materials volume will result in more accurate materials and cost estimates and a significant per lane-mile cost savings.

Table 3-5 MLS surface comparisons with surveyed data

Vendors	Surface Difference (Cubic Yards)	Surface Difference (Inches)
Vendor B	8182	3.65
Vendor C	5731	2.56
Vendor D	6405	2.86
Vendor E	7603	3.39

Conclusions

The study provided a detailed technical evaluation of multiple mobile scanning systems in terms of the accuracy and precision of collected pavement surfaces. The use of LiDAR data to extract surface models along a roadway test section was evaluated and compared to a surface model created from collected points using an automatic level and traditional cross section surveying approach along a 2.9-mile section of East-West Parkway in Anderson, SC. Comparisons were made between the surface collected by traditional surfaces and those collected by five MLS vendors. The average of differences in raster cell height were determined to be statistically significant, which can result in inaccurate pavement volume estimates. Comparison of LiDAR data between compliant MLS vendors (Vendors B, C, D, and E) yielded raster cell height differences ranging from 0.01 to 0.63 inches with an average of 0.21 inches. These results indicate that LiDAR data has considerable potential for creating accurate pavement material volume estimates. Due to limitations in capturing terrain variation, traditional surface data collected using traditional survey methods did not provide similarly accurate pavement material quantities needed for resurfacing. Based on this determination, application of LiDAR for collecting pavement surface data provides a considerable potential for use in pavement rehabilitation and resurfacing projects.

Further research is needed to determine an optimal raster cell size. In this paper, blocks of size 10×10, 1×1 and 0.1×0.1 feet are used. Reducing block size will decrease the effect of surface relief on the error, however this will increase the effect of measurement noise and increase variation in point densities.

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CHAPTER THREE

PAPER III: Application of Mobile Terrestrial LiDAR Scanning Systems in Identifying Potential Pavement Rutting Locations

Abstract

Periodic measurement of pavement rutting is vital for state transportation agencies. Vehicle-based mobile light detection and ranging (LiDAR) systems can be used as a versatile tool to extract pavement transverse profiles at selected stations. This study provides a detailed evaluation of multiple mobile terrestrial Lidar scanning (MTLS) systems regarding the accuracy of collected transverse profiles. For this purpose, 2-inch interval pavement transverse profiles have been collected using traditional surveying techniques. Transverse profiles captured from MTLS systems have been compared using partial curve mapping (PCM), Frechet distance, area, curve length, and Dynamic Time Warping (DTW) techniques. The resultant pavement transverse profiles were compared between vendors and with a profile created from traditional surveying. The results show potential for MTLS systems for use in creating an accurate transverse profile for potential identification of pavement rut areas. Curvature surfaces have been extracted from MTLS elevation raster surfaces. Using three grid cell sizes for the elevation raster surface, an optimal value of 1*1 foot was found to create a better result of the curvature surface. Continuous concave areas of the curvature surface on wheel path trajectory need to be highlighted for further investigation for potential pavement rut areas.

Keywords*: Mobile terrestrial Lidar scanning transverse profile, curvature surface*

INTRODUCTION

Pavement rutting is not only responsible for the functional and structural degradation of pavement structure integrity, but also can potentially contribute to driver safety hazards such as hydroplaning [1, 2]. Different ranges of values of rut depth identify the rutting severity magnitude, which can be small, medium, and high. Studies have shown that this magnitude has a direct relationship with crash frequency and severity [1, 3]. Periodic measurement of rut depth is necessary for state department of transportation (DOT) road maintenance plans and for identifying unacceptable increases in the amount or severity of rutting [4, 5]. Table 1 summarizes information about the most common manual and automated rut measurement equipment methods and technologies used nationally and worldwide. One common disadvantage of manual rut measurement is that isolated rutting spots might not be recorded in pavement management systems (PMSs). That is because it is difficult for agencies to manually collect such detailed levels of information. Table 4-2 summarizes rutting measurement methods by agency. The table shows that the intervals of 0.01 to 1 mi are common for collecting and aggregating data. Pierce et al. [6] recommended having less than a mile pavement condition interval for pavement assessment purposes by transportation agencies. As recent technology has enabled the collection and processing of data points for calculating rut depth at very close longitudinal spacing (less than 2 inches), pavement condition assessment summary reports have become more practical and useful to transportation agencies.

Mobile terrestrial LiDAR scanning (MTLS) systems have been used as an efficient spatial data acquisition method, which can provide point clouds with thousands of points per square foot representing the three-dimensional road pavement surface and surrounding area with high spatial resolution. These point clouds have become popular for the collection of detailed geospatial information (e.g. assets, sidewalks, and geometric design) in a convenient, flexible, and rapid manner [7]. These systems have the potential to greatly improve existing DOT geospatial data collection practices [8, 9]. Metadata collected from this method can produce high-resolution rutting measurements and provide an opportunity to detect isolated ruts [10]. Another MTLS advantage is the data collection can be done while driving at normal highway speeds and without any extensive traffic control. The significant volume of data can be challenging for state DOTs to processes and store. In 2013, the National Cooperative Highway Research Program (NCHRP) project resulted in published MTLS guideline [11] with the following objectives:

- Promoting and improving MTLS usage in transportation agencies
- Assisting transportation agencies to adopt MTLS technology
- Improving communication between data users and transportation agencies
- Assisting transportation agencies with data management, storage, and compatibility of gathered MTLS datasets
- Establishing data providers to deliver adequate meta-data

Based on the report [11], the transportation agencies can handle the volume of data without issues if they have experience with centralized data management. They also need to develop a data management plan to maximize the benefits of MTLS applications. The guideline also recommends that before selecting a specific target accuracy and resolution, agencies should take into consideration all potential applications and resulting benefits of MTLS output [11]. The guideline indicates that MTLS systems vary and that accuracy of a system needs to be evaluated for a particular application.

Pavement profilers are specialized MTLS systems designed specifically for collecting pavement distress information including rutting. They use downward pointing sensors to collect pavement surface point data for a single lane in a single pass. There have been a number of studies that have evaluated the use of pavement profilers to collect pavement surface distress information [12, 13, 14]. Overhead mounted MTLS systems that include one or more lasers are designed to collect an entire cross section of roadway related information in a single pass. They are capable of collecting not only pavement profile information but also a multitude of data about roadway assets including signs, pavement markings, safety devices such a guardrail, and foreslope and backslope information adjacent to the travel lanes. The literature indicated that the use of overhead mounted MTLS systems to collect pavement rutting information has not been thoroughly evaluated. In this paper, we focus on the ability of overhead mounted MTLS to collect pavement rutting data. MTLS systems are extremely expensive and being able to collect accurate pavement distress information such as rutting may from an overhead mounted MTLS can make these systems more versatile.

Table 4-1 Most common manual and automated methods for pavement rut measurement

Method	Method Type	Pros	Cons
Straightedge	Manual	Acceptable in ASTM Standard E1703M-10 (Standard Test Method for Measuring Rut Depth of Pavement Surfaces Using a Straight Edge)	• Does not specify the gage type. • Does not specify the location of reference markings. • No specifics are provided in the standard to clarify which side of the gage is considered the "width" or whether the specified dimensions apply to both sides of the rectangular shape [4].
Transverse Profile Beam (TPB) reference profiler	Manual	capable of collecting multiple points of the profile using sensors with high accuracy and resolution	• slow operation • Designed for research or forensic level applications and not suitable for network-level data collection
Dipstick	Manual	Capable of collecting a series of sequential readings typically at 1-ft intervals (Adequate data collection for transverse profile)	• Require extensive traffic control [15] • The possibility of missing the point of maximum rut depth [15] • Slow operation
Tripod	Manual	• Easy to operate • Less technical training needed	• Require extensive traffic control [15] • Only collect one point (Maximum rut depth) • Less accuracy in comparison to other methods
INO LRMS and LCMS	Automated	capable of collecting up to 4,160 points per transverse profile at normal driving speeds	• Technical training needed • More costly than manual methods • Needs data processing after data collection
Optical system	Automated	capable of calculating the shape of the pavement surface	• The accuracy of the measurements can be affected by environmental factors [4] • Sunlight can influence the line image quality (Post-processing cannot filter the complete effects of sunlight)
Ultrasonic and laser point-based "discrete" systems	Automated	capable of measuring transverse profiles every 10 mm in the traveled direction,	• Typically require correction of the distance measurements from the sensor to the pavement surface considering temperature, humidity, and wind speed [4, 16] • The error increases with vehicle speed and as the longitudinal profile segment locations spacing increases [4, 16] • Variations in lateral placement (wheel path wander) of the survey vehicle during data collection [17]
Pavement profilers using scanning laser system	Automated	• Data can be used to calculate rut measurement, IRI (International Rough Index) (RI) and Ride Number (RN) • Precision up to 0.4 inches inappropriate weather condition	• Need post-processing of data • Technical training needed • light scanners generally need more time to calibrate and compute when processing data [18]

Table 4-2 Rutting measurement methods by state agencies

Agency	Method	Aggregation Interval	Sample Interval	Data Aggregation
NCDOT [19]	Manual (6-foot Straight edge)	1 mile	-	The deepest average for each calculation method is recorded. (if the average rut depth for the right wheel path is greater, that value is recorded)
GDOT [20]	Manual (Straight edge)	1 mile	-	Representative rut depth for each wheel path
SCDOT [21, 22]	• Sonar • Sonar/Laser • Laser • Scanning Laser • Other/Manual	0.1 mi	-	Based on AASHTO R48 or LTPP Protocol
PennDOT [23]	ARAN Profiler	0.5 mile	<30 ft	Length for each severity level for each wheel path
ODOT [24]	5-point	0.1 mile	6 in.	Average rut depth and standard deviation for each wheel path
KDOT [10]	3-point	0.1 mile	1 ft.	Average rut depth for each wheel path
TxDOT [4, 25]	5-point	0.1 mile	-	Based on TxDOT PMIS data collection protocol

MATERIALS AND METHODS

Study Area

The research team planned, promoted, and coordinated an MTLS vendor rodeo throughout the summer of 2016. The study took place along a short (0.5 mile) 4-lane urban principal highway and a 3-mile section of 4 lane divided parkway in upstate South Carolina. Four vendors (data collectors) contributed to the research study. Prior to the MTLS data collection, the research team conducted a conventional survey and identified three primary and thirteen secondary geodesic control points (GCP) throughout the study corridor. For GPS differential correction, at least two primary GCPs were used by vendors as base station locations and all the GCPs were used for post-processing adjustment. Figure 1 shows the GCP locations along the study corridor. The urban arterial section is US 75 shown at the bottom of the figure. For more detail on the data collection used in the present study, refer to [26]. Equipment specifications of vendors have been summarized in Table 4-3.

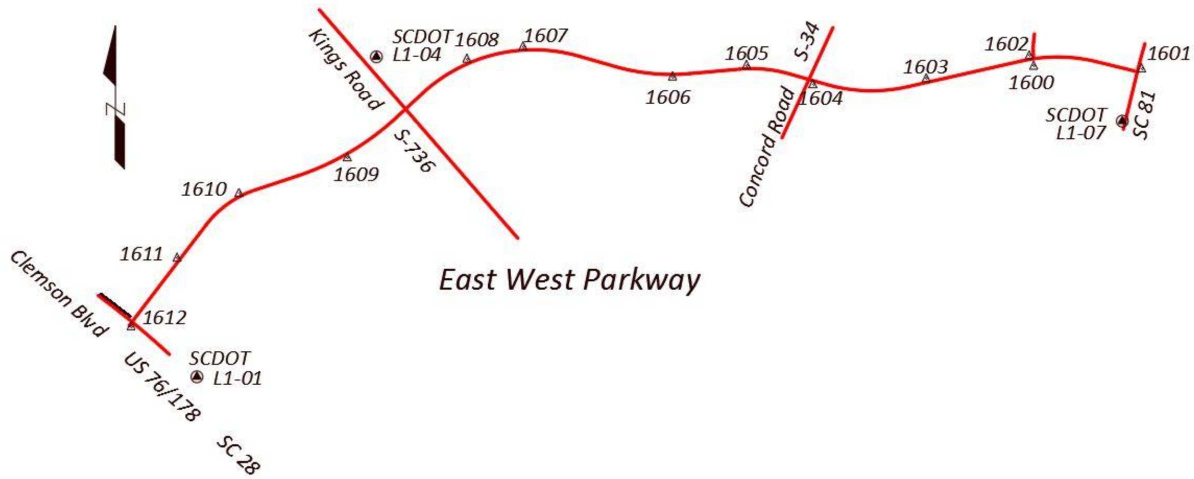

FIGURE 4-1 Case study location (East-West Parkway, Anderson, SC)

TABLE 4-3 Mobile Scanning Equipment Specifications

Data Collector	Brand	Model	Laser Type	Measurement Rate (KHZ)
Vendor A	RIEGL	VMX450	Dual	550 / sensor
Vendor B	Teledyne Optech	M1	Dual	500 / sensor
Vendor D	Teledyne Optech	SG1	Dual	600 / sensor
Vendor E	ZF Scanner	9012	Single	1000

Evaluating the Accuracy of a Profile Captured by Overhead Mounted MTLS Systems

Five different techniques have been applied to evaluate the accuracy of transverse profile MTLS data collection. To check the accuracy of each vendor's data collection, the extracted transverse profile from elevation raster surfaces was compared individually to the survey data curve. The following sections briefly describe these methods:

Partial Curve Mapping (PCM) method

The PCM method maps the experiment curve onto a computed curve based on survey data and then a curve mismatch is calculated. To measure the curve mismatch, the PCM method uses the volume between the test curve and the computed curve section. This method addresses the major disadvantage of using the original mean square error (MSE) technique for mapping the curves. A major difficulty with ordinate-MSE curve matching is that steep parts of the curve are difficult to incorporate in the matching. For more information about failure models in MSE curve methods, refer to [34]. Figure 4-2 illustrates how the algorithm maps the test curve to the computed curve.

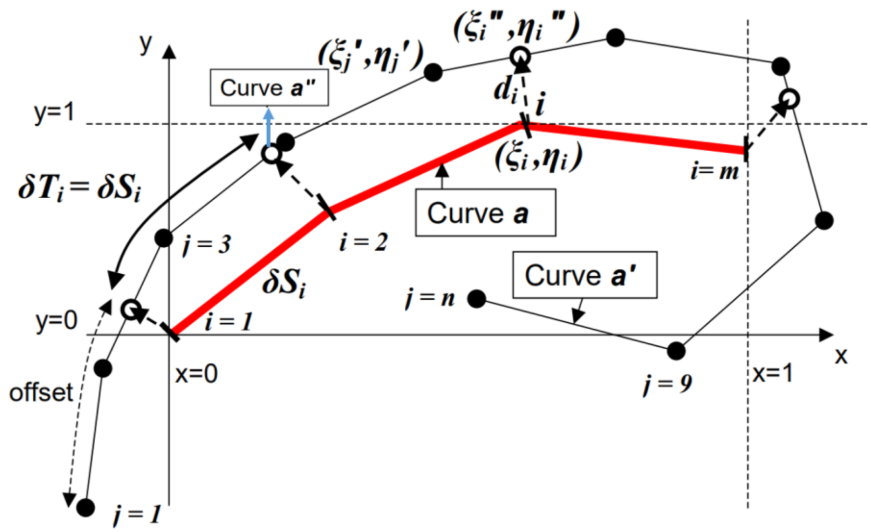

FIGURE 4-2 PCM mapping technique [34]

The red curve in figure 4-1 (curve a) represents a test curve mapped on to a computed curve. Curve a' represents the curve on which the test curve is being mapped. The final is curve-a", which shows the complete mapped curve. Curve a' is normalized based on the axis x limits of the curve a (in figure 4-1 the x-axis was limited to 0 to 1). For more information about this technique, refer to [37].

Application of area method

This method applies an algorithm represented by [37] to calculate the area between the curves in 2D space. For more information about this method, refer to [38].

Application of Discrete Frechet Distance method

This method applies the shortest distance between two curves. It takes the order between points along the curves into consideration [39], which makes it a better measure of similarity for MTLS curves and field survey curve than alternatives such as the Hausdorff distance or ordinary MSE method. More information about the methodology is available in [39].

Curve Length method

This method or optimization criterion assumption rests upon a correspondent computed value based on the total length of the curve to enclose all available data [41]. The concept of calculation of the curve length is based on weighted length, which is in opposition to the weighted distance proposed by Cao et al. [41]. This method considers negative values and curve length equidistant values, at which the only true independent variable of the curves is the arc-weighted length distance along the curve from the origin [41]. For more information, refer to [40].

Application of Dynamic Time Warping (DTW)

This method uses a non-metric distance between the curves. Previous literature [39, 40, 41] showed that this method can be used for a large panel of applications. For more information about the methodology, refer to [39].

Identification of Pavement Rutting Using Road Surface Curvature

Pavement surface profile, planform, and standard curvature (see Figure 4-3) can be derived from all three types of DEMs. A raster grid-based surface can potentially be the most efficient DEM structure for estimation of these topographic attributes [27]. A contour-based surface can also be used to calculate surface attributes. The surface uses a smoothed spline to construct a surface [28]. However, this method can be challenging in terms of data storage [27]. Furthermore, it has no extra advantage in calculating roadway curvature in comparison to the grid-based surface [27]. Due to the TIN surface's irregularity, it can be more difficult for users to perform visual inspection, manual manipulation, and computation of road surface attributes instead of using a raster grid-based surface [29, 30, 31]

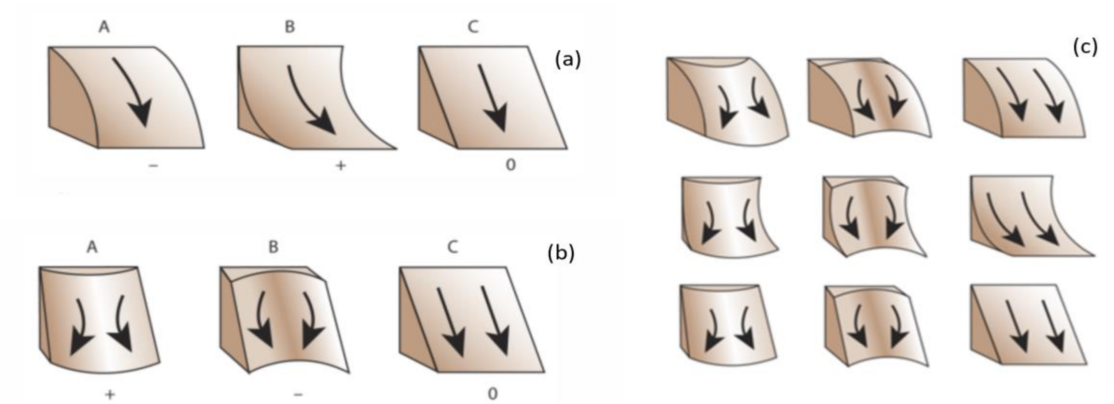

FIGURE 4-3 Profile (b) Planform (c) Standard curvatures

Zevenbergen and Thorne [32] modified the previous Evan's surface fitting method [33] by applying the following quadratic polynomial (see Eq. 1) to the interior 3*3 square grid network. The new 9-term polynomial surface can exactly fit all nine grid points of the grid network [27]. The coefficients (A, B, C, and …) can be calculated from the fitted surface. The fitted surface can be used to calculate surface features such as aspect, slope, and plan/profile curvature.

$$Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I \quad \text{(Eq. 1)}$$

Equation 2, 3 and 4 [27, 29] can be used to calculate profile (φ), plan (ω) and standard curvature (χ).

$$\varphi = -2\,\frac{DG^2+EH^2+FGH}{G^2+H^2} \quad \text{(Eq. 2)}$$

$$\omega = 2\,\frac{DH^2+EG^2-FGH}{G^2+H^2} \quad \text{(Eq. 3)}$$

$$\chi = \omega - \varphi \quad \text{(Eq. 4)}$$

RESULTS AND DISCUSSIONS

To evaluate the accuracy of transverse profile MTLS data collection, one test section was defined at station 107+83 on East-West Parkway. This location was chosen because of irregularities that were noticed during a visual inspection of the pavement. These irregularities were primarily due to noticeable seams. The station was marked on the pavement using reflective pavement tape and surveying nails to make the section more distinctive in the point cloud. Ground truth field surveying at this cross-section was done every 2 inches using an auto level and rod.

The transverse profiles were extracted from raster surfaces for vendors A, B, D, and E (see Figure 4-4). It is clear from the figure that vendor E's transverse profile contains noise from vehicles on lane 2 eastbound. This noise was filtered by defining an acceptable range of point elevations for the travel lanes in both directions. All transverse curves have been smoothed using the Savitzky-Golay filter (see Figure 4-4). Table 4-4 represents the computed curve dissimilarity values between vendor's data and survey field transverse profile using PCM, *Frechet Distance, area, curve length, and DTW* methods. Vendor A's profile was found to have systematic errors and had significant deviation in comparison with the survey field data. Frechet Distance, area, curve length, and DTW methods show good agreement among the profiles of vendors B, D, and E compared to the field data transverse profile. PCM methods show a good agreement for vendor B, D, and field data collection. Comparison of LiDAR data between three compliant MTLS vendors B, D, and E yielded area differences ranging from 0.66 to 4.69 square feet with an average of 2.25 square feet. These results indicate that LiDAR data has considerable potential for creating an accurate transverse profile along the road.

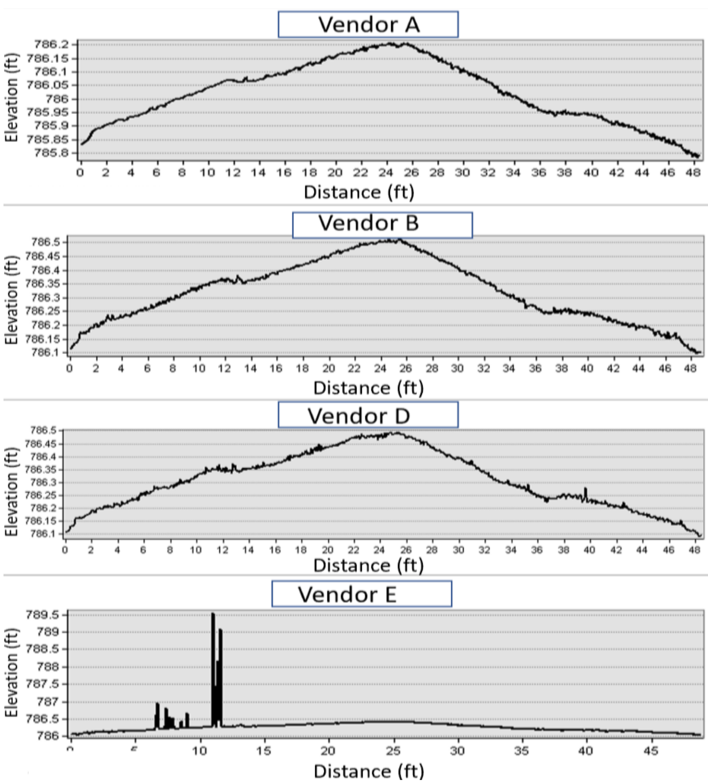

FIGURE 4-4 MTLS transverse curves by vendors A, B, C and D

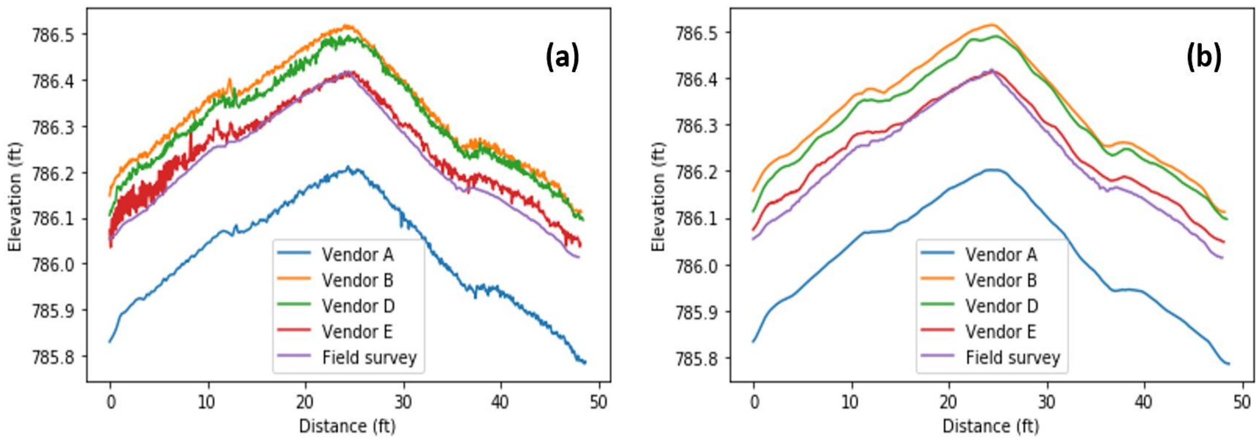

FIGURE 4-5 Raw MTLS transverse curves, (b) Smoothed MTLS transverse curves using Savitzky-Golay filter

TABLE 4-4 Comparing Profile Curve Captured By MTLS Vendors To Field Data Collection

Vendor/Method	PCM	*Frechet Distance*	Area	Curve Length	DTW
Vendor A	214.66	0.77	14.67	0.51	302.22
Vendor B	28.36	0.25	0.66	0.19	42.27
Vendor D	28.14	0.46	1.40	0.34	48.56
Vendor E	149.39	0.17	4.69	0.11	91.13

Calculated curvature (second derivative of the surface height $-\nabla 2\ h$) can be used to describe the physical characteristics of a pavement surface in an effort to detect potential rutting. The value of curvature at each elevation raster grid cell would detect whether the grid cell is flat (>-0.001 & <0.001), concave (<-0.001), or convex (>0.001). The potential rutting location of the road surface may be found in concave areas of the pavement surface. Absolute concave or convex curvature values less than 0.05 would not be of interest because these characteristics are too small to be associated with hydroplaning or any other potential pavement depression existing on the road. The optimal value to consider the curvature of travel lane normal and flat can be estimated by trial and error. Distribution of travel lane curvature values could play a vital role in categorizing the road surface curvature as flat, concave, or convex. Figure 4-5 represents the distribution of curvature values in 1/1000 ft for the edge-to-edge study section. From figure 5-a, most values fell into the -0.05 to 0.05 range. Considering these curvature values represent flat curvature on a road surface, concave and convex areas would be defined as <-0.05 and >0.05, respectively. Figure 5-b shows curvature surface extracted from the point cloud.

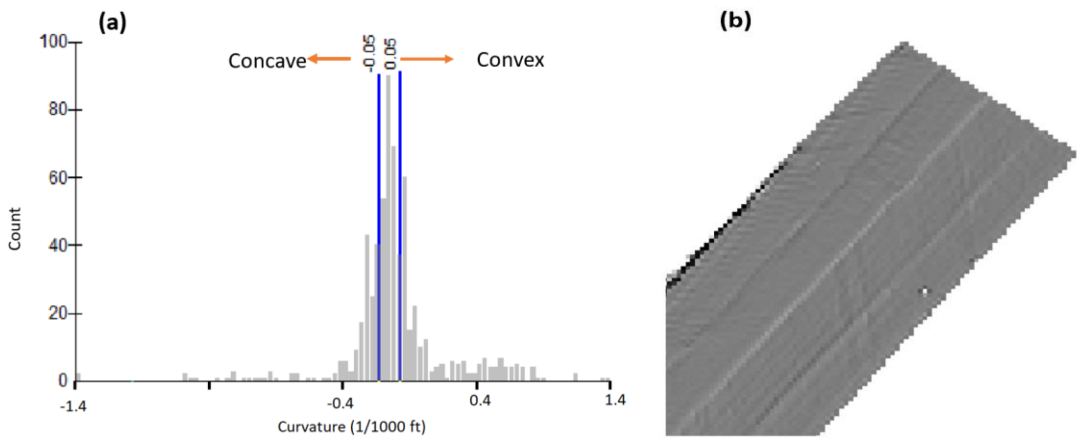

FIGURE 4-6 Distribution of curvature values in the study section (b) curvature surface of travel lane section

The edge-to-edge section of the travel lane in the study area was defined from intensity raster (see Figure 4-6). Curvature values were extracted using the methodology discussed previously from an elevation raster surface. Selecting raster cell size for raster elevation is an important factor to achieve an efficient curvature raster surface. Figure 4-8b, Figure 4-8c, and Figure 4-8d represent curvature surface obtained from raster elevation with 0.1*0.1, 1*1, and 5*5 feet as input for raster grid size respectively. Figure 4-8 clearly shows the irregular areas of the pavement surface. In addition to the area for the seam line and lane marking irregularities on the surface, the focus could be on the trajectory wheel path on each travel lane. Continuous concave values of the surface on the wheel path trajectory were highlighted in figure 4-8 because these sections represent likely rutting sections. Selecting the breakdown category for convex, concave, and flat curvature would affect the severity of pavement rutting on the surface. Since the study area has fairly new pavement, the authors chose a smaller value for this breakdown (0.05). This value could be increased (e.g. 0.1), if we are interested in identifying more severe pavement rutting locations.

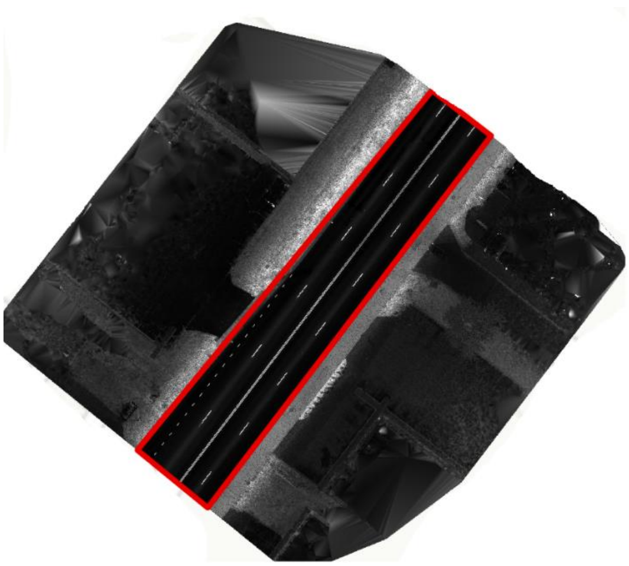

FIGURE 4-7 Edge to edge travel lane area defined from intensity raster surface

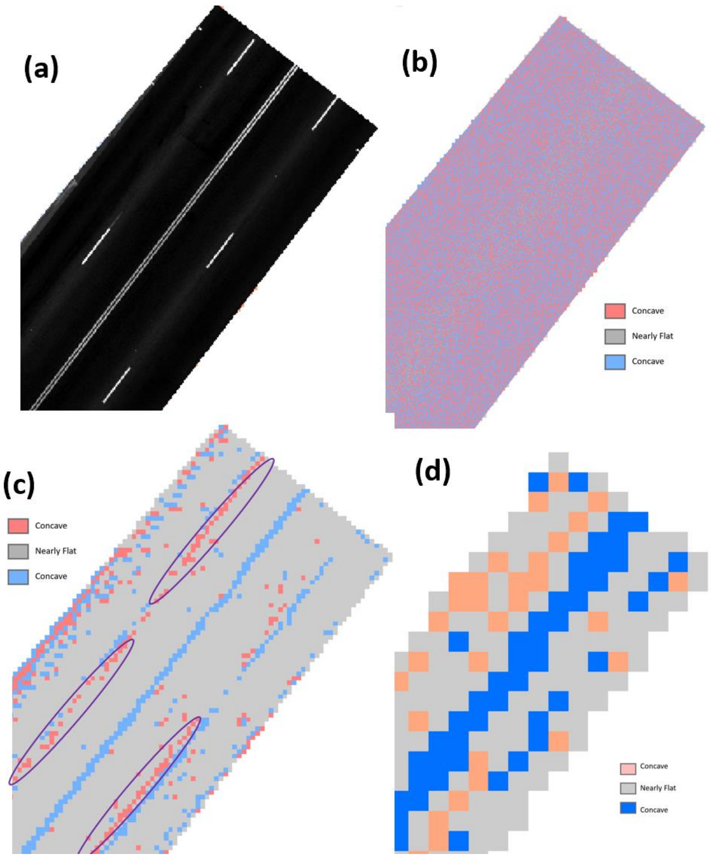

FIGURE 4-8 Intensity surface (b) (c) (d) curvature surface obtained from raster elevation with 0.1, 1 , and 5 feet raster cell size12

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CHAPTER FIVE

CONCLUSION

As stated in chapter one, the primary goal for conducting this research was to investigate if MTLS systems can be used as an efficient and effective method to create accurate digital pavement surfaces. The results can serve multiple users in the South Carolina Department of Transportation (SCDOT) and other state highway agencies across the country. There were four main objectives achieved over the three research papers in this dissertation that help to reach the goal. These objectives are listed as follows:

- Examine if accurate cross-slope measurements can be extracted from the digital pavement surface and if MTLS can be used for system-wide verification of highway cross slopes.
- Develop an efficient workflow for extracting pavement raster surfaces from MTLS point clouds.
- Conduct a comprehensive technical evaluation of multiple MTLS systems to evaluate the accuracy and precision of collected raster surfaces and required procedures to calibrate, collect, and process LiDAR data.
- Examine if accurate pavement material estimates can be made for pavement resurfacing and rehabilitation purposes.
- Examine the benefit of using MTLS in identifying potential pavement rutting locations.

Reducing control surveys can make collecting cross slope data much more affordable for state highway agencies. Paper I found that LiDAR technology can be an effective and reliable method to collect cross slope data (objective 1). The results of comparing cross slope data captured from adjusted and unadjusted MTLS pavement surfaces showed both methods can be applied to extract cross slope. Since both adjusted and unadjusted MTLS data met SCDOT standards, the finding of this research suggests that a control survey is not necessary to extract accurate cross slope data as long as the MTLS equipment is properly calibrated so that systematic errors are reduced. This is a key finding of the research because of the cost associated with control surveys. Eliminating the control survey can make it economically feasible for SCDOT (and other state agencies) to maintain a cross slope inventory of their roads. This will make it possible to identify road sections that have inadequate cross slopes in an effort to enhance safety and minimize hydroplaning potential. Unfortunately, the current approach by SCDOT to identify sections with inadequate cross slope is by analyzing crash data or answering lawsuits relating to hydroplaning.

Paper II found that MTLS systems could be an effective and reliable method to estimate material volumes needed for pavement rehabilitation and resurfacing in a cost-efficient manner. Comparing adjusted and raw MTLS point clouds showed that unadjusted point clouds might also be applied to create an accurate surface from the pavement. This finding in paper I was determined to be significant because of costs associated with ground control surveys.

Each vendor's data was evaluated regarding the accuracy and precision of the raster surfaces. Grid cell sizes used to create raster surfaces were 0.01, 1, and 10 ft. This method compared the raster surfaces generated from the point clouds collected by the MTLS vendors. Each vendor was compared with every other vendor and with the raster surface created using the traditional surveying data. In comparing LiDAR data between compliant MTLS vendors, average raster cell height differences averaged 0.21 inches, ranging from 0.01 to 0.63 inches. These results indicate that MTLS data has the potential for creating accurate pavement material volume estimates. In looking at the surface differences between vendors, the quality of the bare-earth surface LiDAR model, and its suitability for mapping terrain features is highly dependent on the density of returns representing the true ground surface. A sensitivity analysis for the raster cell sizes shows that there is not a significant difference between the results for 10-ft, 1-ft, and 0.1-ft raster surface models. The potential negative effects of noise blobs in extracted raster surfaces caused by vehicles was also examined in paper II. To evaluate the amount of noise caused by cars, one vendor's raster surface was compared to the other's surfaces by direction using 1 ft raster grid size. Based on the results, the addition of cars affects the average elevation difference when comparing only one direction data of the vendor (no cars) with the combined LiDAR data from other vendors (with cars).

By comparing the resultant surfaces from MTLS point clouds and 100-ft. cross-section data obtained from traditional surveying methods, LiDAR produced more precise surface data and pavement material estimates as compared with traditional survey data averaged linearly over 100-ft increments. Application of MTLS in pavement rehabilitation would result in potential benefits for transportation agencies since the cost of traditional field surveying is typically more than the overall cost of MTLS if used on a large scale. Reducing on-road filed surveys can make estimating pavement material for resurfacing purposes much more affordable for transportation agencies. It is noteworthy that application of this method would not eliminate control surveys, since these surveys are important to assure positional accuracy of the LiDAR point cloud.

As discussed in chapter one, because of the significant cost of both MTLS and pavement profiler systems, there is value-added potential if an MTLS can be used in place of a pavement profiler for PMS applications. Paper III focused on the evaluation of MTLS systems with overhead mounted LiDAR systems regarding the accuracy of collected transverse profiles (objectives 2 and 5). The paper examined the accuracy of the extracted profile with one test section that was defined at the selected station in the study area. Field data surveying at this cross section was conducted every 2 inches using level and rod. Five different methods including PCM, Frechet Distance, area, curve length, and DTW were applied to examine the similarity of MTLS and field data transverse curve. The transverse profile extracted from point clouds collected by three vendors shows good agreement regarding the similarity of the curves with field surveying data. The results show the potential for MTLS systems for use in creating an accurate transverse profile.

The paper applied calculated curvature (second derivative of the surface height $-\nabla 2\ h$) to describe the physical characteristics of a pavement surface. The edge to edge section of the travel lane in the study area was manually extracted from the elevation raster. The results found that selecting raster cell size for raster elevation is an important factor to achieve an efficient curvature raster surface The study used the distribution of curvature data for estimating an optimal breakdown category to list concave (<-0.05), convex (>0.05), and flat (>-0.05 & <0.05) locations of the pavement surface. The values can be increased (e.g. to 0.1) to identify more severe rut areas. The continuous concave curvature, on the pavement surface was used to highlight potential rut areas for further investigation. The finding of this research indicates that the use of MTLS systems with overhead mounted LiDAR can be used to identify even subtle rut sections. This makes these systems even more versatile in collecting roadway characteristics.

Safety Benefits

There are several other benefits regarding the use of MTLS over conventional surveying. The application of MTLS systems can potentially improve safety for survey crews, other data collectors, and road users (e.g. drivers) by considerably reducing on-road data collection. The application does not eliminate traditional surveying, since ground control surveys are required for highest accuracy. However, the majority of data collection related to ground control points are not in the proximity of travel lanes.

Value-added of MTLS

Overhead mounted MTLS systems that include one or more lasers are designed to collect an entire cross section of roadway related information in a single pass. They are capable of collecting not only pavement profile information but also a multitude of data about roadway assets including signs, pavement markings, safety devices such a guardrail, and fore slope and backslope information adjacent to the travel lanes. This research has shown that overhead mounted MTLS systems are capable of collecting accurate pavement surface information for uses that were previously intended for pavement profilers.

MTLS systems are extremely expensive and being able to collect accurate pavement distress information such as rutting from an overhead mounted MTLS can make these systems more versatile. A point cloud captured from MTLS systems can be used for multiple purposes by multiple users including roadside safety audits, asset management, flood plain delineation, lane marking, utility pole, median width and numerous others.