Cross Slope Verification Using Mobile Scanning on SCDOT Highways

Final Report

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16. Abstract

Ensuring adequate cross slopes on South Carolina highways and interstates is an important safety practice. When cross slopes are too flat, too steep, or vary across the travel lanes, a number of safety issues can occur (i.e., hydroplaning, loss of control, and run-off-road crashes). South Carolina Department of Transportation (SCDOT) is seeking to evaluate the use of Mobile Terrestrial LiDAR Scanning (MTLS) to collect accurate cross slope data on South Carolina highways and interstates. This study provides a wide-ranging technical and economic evaluation of multiple mobile scanning systems in terms of accuracy and precision of collected cross slope data and procedures to calibrate, collect, and process data. The research approach covered various work elements including detailed profile, alignment and cross section comparisons, and ground proofing using conventional survey methods. This study included an examination of current and historical data collection methods, specifications, and standard practices used by other transportation agencies with regard to cross slopes. Results of this research proved the feasibility of MTLS in comparison to manual data collection methods to obtain cross slope and estimate pavement material quantities. Beyond feasibility, the study proved that MTLS is safer than conventional surveying because it does not require personnel to be located in or near the travel lanes, and it also increases productivity by significantly reducing the time needed to collect the data. Further, the MTLS data uses are many and can be beneficial to virtually all state highway agency employees who work with spatial data for asset collection, design, planning, estimating, and many other applications.

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EXECUTIVE SUMMARY

Mobile Terrestrial LiDAR Scanning (MTLS) provides a cost-effective method of scanning roads for pavement cross slope data, and other roadway measurements. Conventional approaches for planimetric and topographic roadway surveys are labor intensive, expensive, and time consuming. Traditional survey methods often require personnel to work in close proximity to traffic, necessitate short term lane closures, expose personnel to safety concerns, and disrupt traffic flow potentially resulting in congestion. Surveying data collection difficulties are especially prevalent when obtaining measurements to determine an accurate depiction of pavement surfaces. Vehicle hydroplaning can result from problematic roadway cross slope and longitudinal grade issues, which can be systematically addressed through effective resurfacing and rehabilitation programs. For beneficial roadway safety outcomes to occur it is crucially important to provide critically needed pavement surface data for project design so cost effective adjustments and improvements can be provided through construction contract implementation. MTLS provides an efficient means to collect 3D imagery quickly, safely, and cost effectively. This technology-based approach can potentially accelerate pre-construction tasks required to prepare design and contract documents for successful repaving and rehabilitation projects. Furthermore, MTLS data can provide additional maintenance, asset management, and operational benefits further fulfilling South Carolina Department of Transportation (SCDOT) data needs. Lastly, establishing standardized test procedures to verify MTLS data collected by private companies for state procurement contracts that is reliable for intended purposes is another crucially important issue addressed through this research project.

Research findings were based on an extensive literature review and from data provided by vendors who participated in an MTLS rodeo. The rodeo was comprised of three test sections which are summarized below:

- Test Section 1: US 76 (Clemson Blvd.), Anderson, SC, 2,000-foot 4-lane urban arterial, beginning at Forest Hill Drive and ending at the intersection with East West Parkway
- Test Section 2: East West Parkway, Anderson, SC, 2.9-mile 4-lane divided parkway beginning at US 76 (Clemson Blvd.) and ending at SC 81 extending along a rolling vertical profile and aesthetically flowing curvilinear horizontal geometric alignment
- Test Section 3: Business 85, Spartanburg, SC, 3.5-mile limited access freeway between I-585 and I-85, including two travel lanes in each direction, paved shoulders, grass medians, and interchange ramps, along a relatively flat and straight alignment

Results of this research project are summarized with respect to each research objective, as identified in the original SCDOT research problem statement, including specific findings and recommendations as follows:

Research Objective	Statement, Findings, and Recommendations
1) MTLS Cross Slope Verification	To perform technical and economic comparisons of mobile scanning technologies with conventional survey methods for cross slope verification

Research Objective	Statement, Findings, and Recommendations
Findings	Research results indicate that MTLS can measure cross slope to within +/-0.14% grade for a single lane and to within +/-0.2% if 2 lanes are measured in one pass. These values are based on post-process survey adjustments using ground control points. Analysis of data collected on US 123 indicated that MTLS can measure cross slope to within +/-0.18% based on an unadjusted point cloud.
Recommendations	Construction: When using MTLS to determine construction adherence, average slope should be measured from generated breaklines along longitudinal pavement markings at even 100-ft stations in tangents, and even 50-ft stations in curves. These average slopes should meet Level 1 or Level 2 tolerances as per SCDOT cross slope specifications. Safety: To minimize the possibility of hydroplaning, mean MTLS cross slope measurements should average greater than 1.84% for a single pass for each lane and 1.99% for a single pass for two lanes to ensure that minimum slopes will meet or exceed 1.5% at a 95% confidence level. Cost: MTLS provides a cost-effective method for continuously measuring roadway cross slope and researchers recommend MTLS be used as standard for SCDOT's cross slope verification program. An even greater return on investment could be achieved by using MTLS data to meet additional asset management needs.
2) MTLS Validation Site: prequalifying	To establish a representative validation site that contains tangent and curve sections using traditional survey methods that may then be used to qualify mobile scanning vendors
3) MTLS Validation Site: guidelines	To develop SCDOT guidelines for mobile scanning testing procedures and data delivery that are ultimately applicable to statewide data collection
Findings	Three representative test sites were established and used effectively to evaluate MTLS data submitted by four vendors. Test section 2 (East West Parkway in Anderson, SC) was chosen as an ideal pre-qualification site because it has relatively new pavement and has varying geometric characteristics and roadway design elements. In-place survey ground control points (primary, secondary, and cross sectional at 100 ft. station intervals) will help facilitate evaluation of data collection capabilities and quality of any potential MTLS vendor.
Recommendations	MTLS vendor prequalification is recommended due to the potential for error and wide-ranging differences in data collection equipment capabilities. Measurements can be extremely variable and can include systematic errors due to insufficient Quality Assurance/Quality Control. Qualified vendors will have quality equipment and staff that will be able to conduct careful calibration procedures to provide useful data at a high degree of accuracy free of systematic errors.

Research Objective	**Statement, Findings, and Recommendations**
4) MTLS Benefits	To evaluate MTLS costs, potential benefits, application efficiencies, and comparison with conventional and existing SCDOT maintenance and construction practices
Findings	Safety Benefits: MTLS provides improved safety in work zones by greatly reducing work hours surveyors and other personnel are exposed to traffic hazards Product Benefits: Time needed for data collection is greatly reduced compared with conventional surveying. Multipurpose, continuous data collection in excess of 50-miles of highway per day is achievable--even with multiple passes for both directions. Point density virtually eliminates interpolation between points. MTLS can meet numerous other SCDOT data needs including: clear zone, roadside safety audits, asset management, cross sectional measurements, flood plain delineation, traffic control devices, bridge structures, driveways, sidewalks, building locations, drainage inlets, and more. Quality Benefits: MTLS provides differing levels of positional accuracy due to error sources in sensors including Global Positioning System (GPS), Inertial Measurement Unit (IMU), Distance Measuring Instrument (DMI), and Light Detection and Ranging (LiDAR) scanning devices. Accuracy can be improved with Global Positioning System (GPS) post/real-time processing using base stations occupying project control throughout the project area. To minimize error, MTLS systems should be carefully calibrated prior to data collection. Limitations: LiDAR scanning devices can only collect data within line of sight. Point density (and accuracy) diminishes as distance increases from the MTLS travel path in either direction. However, improved accuracy can be achieved by traveling in every lane. Heavy vegetation adjacent to the travel way can make collection of shoulder, fore slope, ditch, and back slope sections inaccurate. Mowing is advisable prior to an MTLS run to create uniform surfaces for accurate cross slope estimates. Lastly, processing MTLS point clouds to create useful Computer Aided Design (CAD) drawings, Triangulated Irregular Network (TIN) surfaces, and other useful products is time consuming unless some or most processes are automated.
Recommendations	MTLS provides a cost-effective method for continuously measuring roadway cross slope and researchers recommend MTLS be used for SCDOT's cross slope verification program. An even greater return on investment could be achieved by using MTLS data to meet additional asset management needs.

List of Acronyms

AASHTO – AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS

AC – ASPHALT CONCRETE

AHMCT – ADVANCED HIGHWAY MAINTENANCE & CONSTRUCTION TECHNOLOGY

CALTRANS – THE CALIFORNIA DEPARTMENT OF TRANSPORTATION

CEER – THE CENTER FOR EARTHWORK ENGINEERING

DEM – DIGITAL ELEVATION MODEL

DMI – DISTANCE MEASURING INSTRUMENT

DOT – DEPARTMENT OF TRANSPORTATION

FHWA – FEDERAL HIGHWAY ADMINISTRATION

GPS – GLOBAL POSITIONING SYSTEM

GNSS – GLOBAL NAVIGATION SATELLITE SYSTEM

IMU – INTERTIAL MEASUREMENT UNIT

IRI – INTERNATIONAL ROUGHNESS INDEX

LiDAR – LIGHT DETECTION AND RANGING

MTLS – MOBILE TERRESTRIAL LIDAR SCANNING

PEMS – PORTABLE EMISSIONS MONITORING SYSTEM

RMSE – ROOT MEAN SQUARE ERROR

SCDOT – SOUTH CAROLINA DEPARTMENT OF TRANSPORTATION

TIN – TRIANGULATED IRREGULAR NETWORK

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CHAPTER 1 : INTRODUCTION

1.1 Introduction and Problem Statement

Ensuring adequate cross slopes on South Carolina highways and interstates is an important safety practice. Cross slopes are intended to drain water from the roadway laterally so that water will run off the surface to a drainage system, such as a street gutter or ditch. When cross slopes are too steep, vehicles may drift to lower lanes, skid laterally when braking, and/or become unstable when crossing over the crown to change lanes. When cross slopes are too flat, ponding may occur, and vehicles in curves may tend to run off the road to the outside of the curve. Interstate routes with inadequate cross slopes are especially susceptible to hydroplaning due to higher design speeds and longer transverse drainage path lengths. As a result, problematic pavement cross slope sections should be identified by transportation agencies and corrective maintenance should be performed in a timely manner (Tsai, Ai, Wang, & Pitts, 2013). A primary objective of resurfacing and rehabilitation projects is to resolve pavement cross slope problems, requiring additional leveling and surface course material. Knowing the limits and extents of existing cross slope problems prior to obtaining contractor construction bids for a project is crucial for accurate material quantity estimates, and cost effective repaving projects, with minimal change orders.

The South Carolina Department of Transportation (SCDOT) would benefit in addressing hydroplaning, resurfacing, and contracting issues by having an efficient method for collecting highway cross slope data and providing an accurate and comprehensive pavement surface database. Ensuring that adequate cross slopes are provided, and existing problems are efficiently addressed, is highly desirable in administering roadway repaving and rehabilitation projects. SCDOT is seeking to evaluate the use of Mobile Terrestrial LiDAR Scanning (MTLS) to collect accurate cross slope data on South Carolina highways and interstates. By adopting MTLS technology, the Department could potentially experience significant savings on the cost on cross slope verification, and possibly reduce contract time for commonly administered pavement rehabilitation projects by four to six months.

This study provides a wide-ranging technical and economic evaluation of multiple mobile scanning systems covering aspects of accuracy and precision of collected cross slope data and procedures to calibrate, collect, and process data. The research approach assesses various work elements including detailed profile, alignment and cross section comparisons, and ground proofing using conventional survey methods. This study included an examination of current and historical practices, guidelines, and standard operating procedures used by other transportation agencies with regard to cross slopes. Conventional surveying methods were used to establish a representative validation site that provides a robust comparison for potential vendors' equipment used for collecting pavement cross slope and other roadway surface data.

1.2 Research Objectives

Project objectives were identified and outlined in the original SCDOT research problem statement and include:

- Perform technical and economic comparisons of the alternative mobile scanning technologies and conventional survey methods for cross slope verification;
- Establish a representative validation site that contains tangent and curve sections using traditional survey methods that may then be used to qualify mobile scanning vendors;

- Develop SCDOT guidelines for mobile scanning testing procedures and data delivery, ultimately applicable to statewide data collection, from results and feedback from the research team administered vendor rodeo;
- Evaluation of mobile scanning costs, potential benefits, application efficiencies, and comparison with conventional and existing SCDOT maintenance and construction practices.

1.3 Background and Significance of Work

Conventional roadway profile and cross section surveys are expensive and time consuming to perform. In addition, these types of traditional survey methods are labor intensive and require personnel to work in close proximity to vehicular traffic and/or may require short term lane closures disrupting traffic flow that results in congestion. Furthermore, this labor-intensive approach to survey data collection frequently places personnel in harm's way from balancing the need to measure existing roadway features while avoiding traffic. This problem is especially prevalent in determining an accurate depiction of the pavement surface. Mobile data collection and LiDAR scanning technology provides an optimal solution to the difficulties encountered with conventional surveying collection within roadway environments (Chang, 2014).

Vehicles hydroplaning while traveling at high speeds is a considerable safety issue. Cross slope of the pavement surface is a crucial component in providing adequate roadway surface drainage to reduce hydroplaning risks during wet pavement conditions. During higher intensity rainfall events, provision of positive drainage through roadway cross slopes becomes an even more important factor in protecting drivers from hydroplaning (Guven, 1999). Hydroplaning crashes constitute a considerable risk to drivers with 25,298 dynamic and viscous hydroplaning crashes occurring in Florida from 2006 to 2011 (Jayasorriya, 2014).

Repaving and rehabilitation projects are a key focus of all state Departments of Transportation (DOTs) and are commonly implemented in a systematic program based on need. Effective competitive bidding by highway contractors is an important tool used by transportation agencies to obtain cost effective pricing for construction projects conducted by private sector companies. Providing prospective contractors with accurate material quantiles for use in the bidding process is crucially important to obtaining competitively priced contracts (Jalili, 2016). If anticipated material quantities are inaccurate and contractors are justified in obtaining a change order after the original contract is secured, the competitive advantage of bidding is negated, and project costs are typically adversely effected (Sanchez, 2015).

Roadway geometry is a critical element of designing and planning for all types of roadway projects (Baffour, 2002). Horizontal curves, cross slope or amount of superelevation, and the longitudinal profile or grade are major characteristics of the roadway geometry (Baffour, 2002). Grade and cross slope are used in a number of transportation applications, such as stopping and passing sight distance, roadway capacity, and modeling drainage patterns (Souleyrette, 2003). Roadway pavement cross slopes can be reliably and efficiently measured using LiDAR technology along considerable lengths of roadway and data can be collected at highway speeds (Tsai, 2013). Maintaining better roadway pavement cross slope data can be used to improve the safety of existing roadway designs, identify areas with drainage problems, and provide more accurate reconstruction information (Santido-Chaparro, 2015). The following research provides a basis for obtaining proper pavement cross slope data and evaluates the effectiveness of MTLS technology and equipment for addressing maintenance, safety, and reconstruction issues in network based roadway improvement programs. Additionally, testing procedures are identified for application in ensuring LiDAR data reliability provides accuracies and quality control needed for intended purposes.

1.4 Importance of Research

MTLS has been shown to be a cost-effective method of scanning roads for pavement cross slope and other roadway measurements, that would otherwise have to be collected through more labor-intensive and time-consuming means. Vehicle hydroplaning, resulting from problematic roadway cross slope and longitudinal grade, is an issue that can be readily addressed through systematic repaving and rehabilitation programs. For beneficial roadway safety outcomes to occur, it is crucially important to provide critically needed pavement surface data for project design. Thus, effective adjustments and improvements can be addressed through construction contracts. MTLS can be used to collect 3D imagery quickly, safely and cost effectively without placing the safety of employees in harms way by conducting traditional surveys in and adjacent to vehicular traffic or using expensive aerial imagery methods. This technology-based approach potentially accelerates the pre-construction process required to prepare for successful repaving and rehabilitation projects, and can produce additional maintenance, asset management, and operational benefits as well. Furthermore, this research addresses the important topic of test procedure development to ensure MTLS data collected by private companies through state procurement contracts is reliable for intended purposes.

1.5 Report Organization

This report is organized into seven chapters. Chapter 2 provides a review of relevant literature and the results of a survey of states. Chapter 3 provides a preliminary evaluation of MTLS data for all restricted access highways in South Carolina. Chapter 4 discusses vendor rodeo planning. Chapter 5 provides vendor rodeo results. Chapter 6 discusses MTLS validation site test procedures. Chapter 7 gives recommendations and conclusions.

CHAPTER 2 : LITERATURE REVIEW AND SURVEY OF STATES

The following sections will cover a number of topics that are important in the design, construction, maintenance, and evaluation of pavement cross slope. These topics include definition of cross slope and safety impacts, cross slope measurement procedures, cross slope data collection, evaluations of automated data collection systems, and mobile mapping applications. In addition to the review of literature, a survey of states is reported to provide information on specifications, measurement, and archiving of cross slope data nationally.

2.1 Cross Slope Definition

Cross slope is a geometric feature of pavement surfaces. It is the transverse slope with respect to the horizon. On straight sections of normal two-lane roads, the pavement cross section is usually highest in the center and drops off to either side (see Figure 2-1). The cross slope is intended to drain water from the roadway laterally so that water will run off the surface to a drainage system, such as a street gutter or ditch. This feature helps minimize ponding of water on the travel surface, which also prevents maintenance problems and enhances driver safety by minimizing the risk of hydroplaning and formation of ice during cold weather. Cross slope is usually expressed as a percentage [cross slope = (rise/run) * 100%].

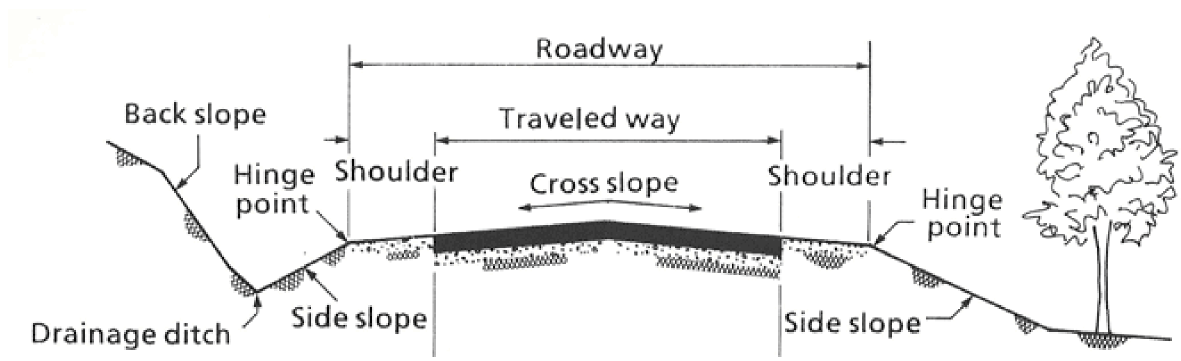

Figure 2-1 Example Cross Section Detail for Two-Lane Roadway

In horizontal curves, the cross slope may be banked into superelevation to reduce steering effort and lateral force required to go around the curve. Under superelevated conditions, all water drains to the inside of the curve.

2.1.1 Cross Slope Design

Cross slope criteria apply to typical tangent alignments. On high-speed roadways with speed limits of 50 mph or greater, normal cross slope is typically between 1.5–2.0 percent. Figure 2-2 shows a cross-section for a typical four lane divided freeway in South Carolina. It shows a typical cross slope of 2.08% based on the 48H:1V slope specification (SCDOT, 2003). Further, the cross slope break (the algebraic difference in slopes between the lanes) at the centerline should not exceed five percent. In areas of intense rainfall and where there are three or more lanes in each direction, additional cross slope is required for adequate drainage.

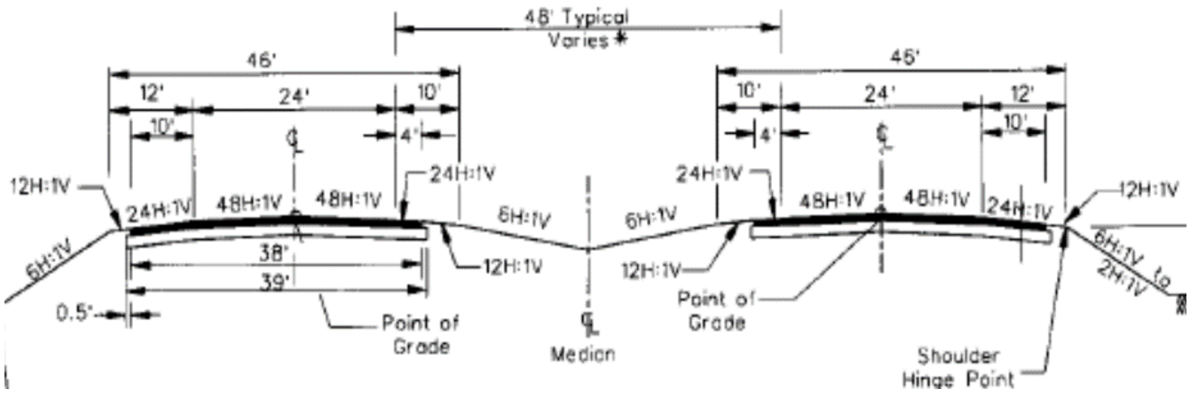

Figure 2-2 Typical Rural /Urban Four Lane Divided Freeway Cross-section (SCDOT 2003)

Accomplishing other design features (e.g., superelevation transitions, pavement warping at intersections) will inevitably require removal of cross slope in spot locations (see level section in Figure 2-3). These cases are routine and necessary in design and a design exception is not required. In addition to the cross slope of the lanes, the cross slope break on the high side of superelevated curves should not exceed 8 percent. A formal design exception is required when this condition is not met. A design exception is not needed for rollover if the break occurs at the outside edge of shoulder.

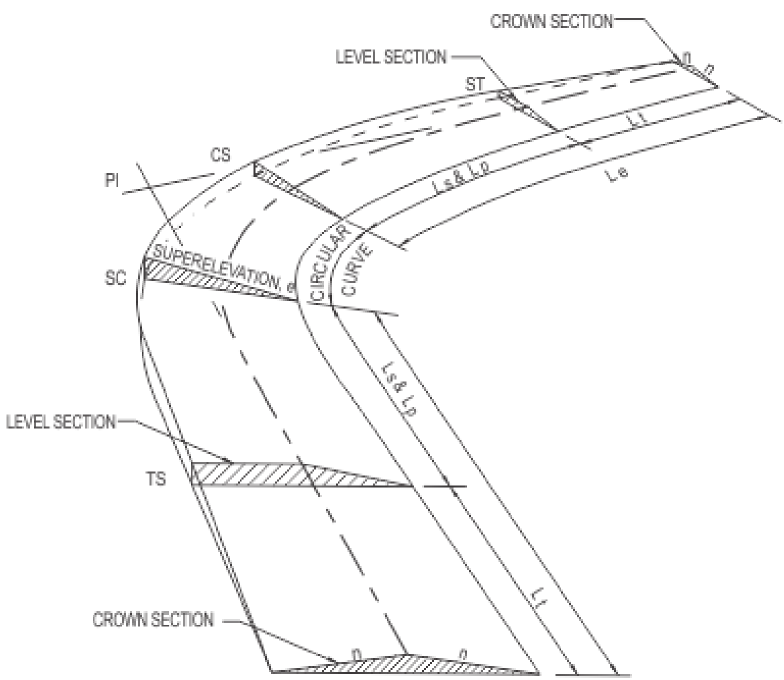

Figure 2-3 Example of Cross Slope Removal during Superelevation (Bilbao, 2014)

2.1.2 Cross Slope Safety and Operational Issues

Cross slope is an important safety feature to help vehicles maintain their lane position in superelevated sections, as well as drain water to keep vehicles from hydroplaning. While a cross slope should be close to uniform across individual lanes, the transverse profile of a lane may vary. This may occur after repaving or it may be due to pavement distress (e.g., rutting) over time.

Deformation such as rutting may allow pooling of water in the travel lanes, and variances in construction may also cause cross slopes to be higher or lower than the design levels.

Hydroplaning is a phenomenon that occurs when a vehicle traveling at a high speed essentially floats on a film of water covering the roadway. When the tires lose contact with the road surface, the vehicle cannot be controlled by the driver. Roadway factors affecting water depth accumulation on the road surface include depth of compacted wheel tracks, pavement microtexture, pavement macrotexture, pavement cross slope, grade, width of pavement, roadway curvature, and longitudinal depressions. Lack of quality control for pavement construction and overlays is cited as causing numerous paving projects to be built with less than one percent cross slope grade. Minimum pavement cross slopes of less than one percent are prone to creating unacceptable water depths susceptible to hydroplaning and resulting in potential safety and litigation risks. When paving contractors are awarded overlay contacts, it is common practice to apply the overlays without any regard for existing deficiencies in the roadway cross slope. Specifications often do not cover this issue and provide methods for paving contractors to correct. (Glennon, 2006)

A water depth of 0.15 inches can lead to hydroplaning for a passenger vehicle. Florida DOT used a laser-scanning vehicle to collect and analyze cross section data related to drainage surface runoff and potential for hydroplaning. A relationship between cross slope, longitudinal grade and pavement drainage width was used to calculate drainage path length, which was determined at discrete station locations. Based on these values a continuous plot of potential water sheering was calculated along roadways using laser-scanning data. The dominant factor affecting this analysis is cross slope, which requires use of an Inertial Measurement Unit (IMU) to account for the roll axis of the vehicle body. (Mraz, 2008)

Parametric curves were created to assist in correlation of optimal values for pavement cross slope based on rainfall intensity and corresponding variables of water depth at the edge of pavement, surface texture depth, pavement width, and longitudinal grade. Intensity rates ranged from 0.5 -2.0 inches per hour, with corresponding cross slopes up to 2.5 percent. (Guven, 1999)

When cross slopes are too steep, vehicles may drift to lower lanes, skid laterally when braking, and/or become unstable when crossing over the crown to change lanes. When cross slopes are too flat, ponding may occur, and vehicles in curves may tend to run off the road to the outside of the curve. All of these safety and operational issues are highlighted by common roadway types in Table 2-1.

Table 2-1 Common Safety and Operational Issues Related to Roadway Cross Slope

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

There are a number of resources that contain guidance for managing all of these safety and operational issues including:

- A Policy on Design Standards Interstate System, AASHTO, 2005
- A Policy on Geometric Design of Highways and Streets, AASHTO, 2001.
- A Guide for Reducing Collisions on Horizontal Curves, NCHRP Report 500, Volume 7, Transportation Research Board, 2004
- A Guide for Reducing Collisions Involving Heavy Trucks, NCHRP Report 500, Volume 13, Transportation Research Board, 2004
- A Guide for Addressing Run-Off-Road Collisions, NCHRP Report 500, Volume 6, Transportation Research Board, 2003
- Guidelines for Geometric Design of Very Low-Volume Local Roads (ADT $\leq$ 400), AASHTO, 2001
- Highway Drainage Guidelines, AASHTO, 2000

2.2 Cross Slope Standards and Specs

2.2.1 Standards for Transverse Profile Measurement and Cross Slope Determination

In 2010, American Association of State Highway and Transportation Officials (AASHTO) published a provisional standard of practice for measuring the transverse profile of a pavement (AASHTO, 2010a). This standard outlines a method for collecting the transverse profile, which can then be used to determine the cross slope as well as certain pavement distresses (e.g., rutting, edge drop-off, water entrapment, and transverse deformation). The data collection standard, however, does not specify particular equipment to be used to collect the profile data.

The guidelines for data collection included in AASHTO PP70-14 (AASHTO, 2010a) recommend the following minimums to provide a usable database and for uniformity in the long-term:

- The interval between transverse profiles should not exceed 10-ft for network-level collection and 1.5-ft for project-level collection.
- The transverse profile should have a width of at least 13-ft for distress detection and 14-ft if edge drop-off is desired.
- The data points in the transverse profile are to be no more than 0.4-in apart.
- The resolution of the vertical measurements is to be no greater than 0.04-in with an accuracy of 0.12-in or less relative to the average elevation of the same profile or 0.2-in relative to the true horizontal reference.

This measured data must then be processed to determine the cross slope and deformation parameters (e.g., rutting) using the procedures outlined in AASHTO PP69-14 (AASHTO, 2014b).

2.2.2 SHRP2 Pavement Performance Specification

One of the products of the Strategic Highway Research Program Two (SHRP2) R07 project was a guide pavement performance specification for pavement construction (26). These guide specifications provide a template that can be adopted by state DOTs when developing or modifying their pavement performance specification documents. The SHRP2 guide specification covers all aspects of pavement construction quality management. With respect to cross slope, the SHRP2 guide specification includes a target value of ± 0.2% of the design value for the final measurement after project completion. This reference also requires that the contractor submit final pavement details and drawings (as-built) for the completed work.

2.2.3 South Carolina Cross Slope Verification Specification

The SCDOT's cross slope verification specification is included in the Supplemental Specification updated on November 16, 2009 (SCDOT, 2009). The specification states that the contractor is responsible for obtaining the existing cross slope data by collecting elevation data for the edge of each travel lane at even 100-ft stations in tangents and 50-ft stations in curves. Elevation data shall be recorded in accordance with the *SCDOT Preconstruction Survey Manual* (SCDOT, 2012) to the nearest 0.01 ft.

During the construction process, the contractor is responsible for submitting progress measurements verifying the cross slope after the completion of initial corrective action (i.e., milling and/or build-up) and after each uniform lift of pavement prior to the final surface course. For these progress measurements, the elevation data shall be collected at the edge of each travel lane at (1) minimum of one random location every 300 ft. in tangent sections; (2) beginning and end of superelevation, flat cross slopes within the superelevation transition, and beginning and end of maximum superelevation; and (3) cross slopes at beginning and end of bridges.

The final cross slope measurement used for final payment shall be performed after placing the final surface course (prior to open graded friction course if applicable). As with the initial conditions, these measurements shall be collected at 100-ft stations in tangents and 50-ft stations in curves; beginning and end of superelevation, flat cross slopes within superelevation transition, and beginning and end of maximum superelevation, and at the beginning and end of bridges.
The SCDOT has two acceptable tolerance levels for cross slopes:

- **Tolerance Level 1**: ± 0.00174 ft/ft (± ¼ in over 12 ft or ± 0.174%) of design cross slope
- **Tolerance Level 2**: ± 0.00348 ft/ft (± ½ in over 12 ft or ± 0.348%) of design cross slope

The different tolerance levels come into play when considering final payment for the work completed. For final measurements within Tolerance Level 1, there will be no pay adjustments for the work. When final measurements are outside of Tolerance Level 1, either corrective measures may be required at the contractor's expense or a pay reduction will be assessed to the work. For final measurements outside of Tolerance Level 2, the work will either be corrected at the contractor's expense or work will be subject to a pay reduction (greater than work outside of Tolerance Level 1).

The final deliverable from the contractor at the completion of the project is the final as-built plan sheets of the pavement cross sections. These plan sheets include a significant amount of information including:

- Control points, horizontal alignment, and stationing used to construct the project
- Superelevation with horizontal curve data
- Cross sections at 100-ft stations in tangents and 50-ft stations in curves
- Cross sections at beginning and end of superelevation, flat cross slopes within superelevation transition, beginning and end of maximum superelevation, and cross slopes at the beginning and end of bridges

2.3 Cross Slope Data Collection

Many techniques are used for acquiring road way cross slope including as-built plans, photogrammetry using high-resolution ortho images, conventional surveying, Global Positioning System (GPS), remote sensing data such as USGS Digital Elevation Models (DEMs), measuring with digital Gyroscope, advanced electronic surveying (Souleyrette, 2003; Baffour, 2002). Factors such as accuracy, safety, cost, and time play important roles in the selection of the method over another (Baffour, 2002).

Surveying gives accurate results but is time consuming and poses a safety risk to surveyors while they are on-road during the collection process (Souleyrette, 2003). Photogrammetry is an accurate method, which takes less time because after collecting the control points, most of the work can be conducted in office. However, collecting high resolution ortho-rectification of aerial imagery is expensive (Souleyrette, 2003). Mobile mapping method is vital since vehicle based laser scanners allow fast processing of long corridors. Such information is needed in road 3D modeling, 2D and 3D navigation data (Jakkolla, 2008)**.**

2.3.1 Automated Mobile Transverse Profile Data Collection Methods

Based on these data collection requirements set forth by AASHTO, the manual methods would be extremely labor intensive and time consuming. Therefore, the need to evaluate automated methods to collect transverse profile data makes sense due to the speed, accuracy, and precision of the data collection. The following summarizes the specifics for some of the available automated scanning technologies.

2.3.1.1 Multi-Point Rut Measurement System

System contains up to 37 ultrasonic sensors that measure transverse profile elevation to an accuracy of 0.04-in spaced at 4-in centers. The transverse profile can be measured at variable traffic speeds. The pavement cross slope can be measured from the data collected for the transverse profile at rod and level accuracy.

2.3.1.2 Laser Transverse Profiling System

Vehicle mounted subsystem of dual synchronized scanning lasers that can measure the transverse profile of a 13-ft lane width with a lateral resolution of approximately 1,280 points and an accuracy of 0.04-in. The system has two operation frequencies that essentially allows the user to adjust the longitudinal distance between the 40-point transverse profile. The higher frequency option allows for a distance of approximately 8-in at a collection speed of 67 mph compared to a distance of approximately 19-in at a speed of 33 mph. When the transverse profile is combined with other data available from the system, such as vehicle pitch and roll, the pavement cross slope can be easily determined (AASHTO, 2010a).

2.3.1.3 Gyroscope System

Vehicle mounted subsystem that utilizes a combination of gyroscopes that record vehicle pitch, roll, and heading at traffic speeds. The data collected from the gyroscopes can be interpreted by accompanying software to determine pavement cross slope at approximately 13-ft intervals.

Other systems combine sensitive gyroscopes and accelerometers to collect precise vehicle roll data. When this data is coupled with GPS and a supplemental distance measurement system, the transverse profile data can be used to determine the pavement cross slope at rod and level accuracy. Through a case study testing of static LiDAR it was observed that collected data demonstrated better relative elevation results based on control and checkpoints established than real-time kinematic global positioning system (Johnson, 2012).

2.3.2 Mobile Terrestrial LiDAR Scanning (MTLS)

MTLS strengths also 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 (Olsen, 2013). 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 (Olsen, 2013; NCHRP, 2013).

A primary benefit of a mobile mapping system that uses a rotating laser(s) is that it can collect a point cloud for multiple travel lanes with a single pass. The problem is that cross slope data will only be accurate if the system adequately accounts for the roll angle of the vehicle. Further, very accurate ground control points are needed to adjust and calibrate MTLS data for applications that require a high level of accuracy. Integrating LiDAR with Global Navigation Satellite System and Inertial Measurement Unit (GNSS/IMU/LiDAR) can produce more accurate results through post processing, see Table 2-2 (Yen, 2011).

Table 2-2 LiDAR performance with GNSS/IMU and post-processing (Yen, 2011)

	Accuracy without GPS outage			Accuracy with 1 km or 1 min GPS outage		
Applanix POS LV Model	420	510 / 520	610	420	510 / 520	610
X, Y Position (m)	0.02	0.02	0.02	0.12	0.1	0.1
Z Position (m)	0.05	0.05	0.05	0.1	0.07	0.07
Roll & Pitch (degree)	0.015	0.005	0.005	0.02	0.005	0.005
Heading (Degree)	0.02	0.015	0.015	0.02	0.015	0.015

The accuracy and repeatability of vehicle-mounted MTLS has been determined to be effective for measuring cross slope for drainage on highways. Results show that vehicle-mounted MTLS can achieve accuracies with an average measurement difference of 0.08 degrees and standard deviation of less than 0.03 degrees. (Tsai, 2013)

Collection of digital images or video, simultaneously with MTLS can be synchronized with the GNSS/IMU clock. This allows images to be geocoded and often used to overlay/colorize LiDAR points in the point cloud. Orientation of the vehicle-mounted camera is different depending on application use of the final data. A forward-looking camera is best for capturing road signs, a side-looking camera is better for attaining features such as drainage, sound wall, median barriers, etc. Typical image spacing is between 25 to 50 feet and must be paired with vehicle speed. Use of digital cameras can drastically increase data storage requirements, as digital images often comprise 2 to 10 times more data than LiDAR point clouds collected along the same runs. (Yen, 2011)

2.4 Benefits of MTLS Mapping

MTLS technology presents several benefits to transportation agencies, including safety, efficiency, accuracy, and cost. (Yen et al, 2011)

2.4.1 Safety

Compared to traditional survey techniques, MTLS has increased safety benefits. Nearly all work for MTLS technology is performed from within the vehicle. There are various reasons why this technology is beneficial:

- Drivers become distracted by survey instruments, often observing the equipment and not paying attention to the actual surveyor
- Surveyors may have no other option but to place themselves in precarious situations to acquire the necessary measurements, whereas mobile mapping requires little or no need for surveyor and vehicular interaction
- The MTLS vehicle generally can move with the flow of traffic, eliminating the need to divert traffic or close roadways

2.4.2 Efficiency

A study conducted by Zampa and Conforti shows that MTLS can be significantly more efficient than static terrestrial LiDAR scanning (TLS). According their study, in 2007, an 80 km stretch of highway was scanned using TLS, and in 2008, 60 km of similar highway was scanned using MTLS. The field time required to collect the TLS was 120 working days, while the MTLS was able to capture all the data in three hours. (Zampa, 2009)

2.4.3 Accuracy

Some of the first research on using LiDAR for collecting geometric design data began in the early 2000's. 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) triangulated 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 (3).

In 2008, AASHTO, Federal Highway Administration (FHWA), North Carolina Department of Transportation (NCDOT), and North Carolina State University (NCSU) sponsored a national workshop on Highway Asset Inventory and Data Collection. While the core data emphasis areas were limited to pavements, bridges, roadside elements, and geotechnical features, there were some roadway inventory elements included in the tests. As part of the horizontal curvature information, the cross slope was obtained to the nearest 1%. At this point, many vendors found errors of multiple percent on the cross slope element. While there was little to no record from an accuracy standpoint, there were several observations on best-practices for performing vendor rodeo tests.

During Task 2 of the SHRP2 research program (Hunt, 2011), researchers developed a prioritized listing of roadway safety data elements and suggested accuracy levels that were necessary for evaluation of the safety of the participants in the Naturalistic Driving Study (NDS). Under Task 3, the research team developed and implemented a plan to evaluate numerous automated data collection firms including:

- Data Transfer Solutions (DTS)
- eRoadInfo
- FHWA
- Fugro/Roadware, Inc.
- GeoSpan
- Mandli Communications, Inc.
- Michael Baker, Jr., Inc.
- Pathway Services, Inc.
- Sanborn
- Tele Atlas
- Yotta

The SHRP2 vendors were provided six unmarked test sites in Northern Virginia along two rodeo routes covering approximately 43 centerline miles. Each route was surveyed three times in both directions. Each of the six test sites was 2500 feet long and included most of the asset types identified in the prioritized list of roadway safety data elements. A variety of land use, cover types, and roadway types were included.

For the cross slope data elements, only five teams reported information. Of those, 3 teams did not have any matches, and 2 teams successfully provided data. The cross slope of the roadway was measured between the wheel paths using automated equipment. Originally, researchers had chosen a +/- 0.10% accuracy level; but after testing, settled on a recommended accuracy of +/- 0.20% (see Table 2-3). During the rodeo to select vendors for the SHRP 2 research contracts, the best achieved accuracy for cross slope was -0.2045%. However, the research team did indicate that using an Applanix POS LV 320 or 420 system with laser reference sensors enables measurement of cross slope to achieve an average absolute error of 0.13% over 200-300 readings compared to manual measurements. Still, the best achievable cross slope measurement accuracy was set to +/- 0.20%. (Hunt, 2011).

While superelevation was defined as a separate data collection element, it was actually collected as part of the cross slope data. For this to be reported separately, vendors must know start and end points of horizontal curvature, and/or an acceptable range of cross slope values for straight tangent sections.

Table 2-3 SHRP2 Roadway Inventory Data Collection Targets and Recommended Accuracies (Hunt, et al, 2011)

Feature	Data Element	Definition	Rodeo Target Accuracy	CTRE Desired Accuracy	Best Achieved Accuracy	Recommended Accuracy
		Roadway Inventory				
Rail Crossings (continued)	Grade of approach side of crossing	Direction ("+" uphill in direction of travel, or "-" downhill in direction of travel) and Percent of Slope	±0.5%	±0.5%	N/A	±0.5%
	Grade of leave side of crossing	Direction ("+" uphill in direction of travel, or "-" downhill in direction of travel) and Percent of Slope	±0.5%	±0.5%	N/A	±0.5%
Ramps	Ramp location	GPS coordinates of point of ramp gore area	±3 ft	±3 ft	> 4 m	sub-1 m
	Type of ramp terminal	Entry or exit (for roadway on which the vehicle is traveling)	100%	100%	100%	100%
	Type of section	Acceleration lane, deceleration lane, weaving section	100%	100%	100%	100%
Shoulder	Shoulder type	Paved, unpaved, composite (part paved, part unpaved) and curb	100%	N/A	100%	100%
	Shoulder paved width	Width of paved portion of shoulder. Reported from edge line to edge of paved surface to the nearest foot.	±0.5 ft	±0.5 ft (0.15 m)	-0.03 ft	±0.5 ft (0.15 m)
	Shoulder total width	Total width of shoulder (composite only), including paved and unpaved parts. Measured to the first obstacle, or the break in slope.	±0.5 ft	±0.5 ft (0.15 m)	-0.29 ft	±0.5 ft (0.15 m)
	Location of measurement	GPS coordinates of reported data. Reported when the shoulder type changes, or the width changes more than 1 foot, but not in transition areas.	±3 ft	±3 ft	±3 ft	sub-1 m
		Geometric Features				
Grade	Grade in direction of travel	Direction ("+" uphill in direction of travel, or "-" downhill in direction of travel) and percent of slope	±0.5%	±0.5%	-0.164%	±0.5%
	Location of measurement	GPS coordinates of reported data	±3 ft	±3 ft	N/A	sub-1 m
Cross Slope	Location of measurement	GPS coordinates of reported data	±3 ft	±3 ft	N/A	sub-1 m
	Roadway cross-slope	Cross-slope of lane being driven. Direction ("+" slopes toward side of road or "-" slopes towards center of road) and percent of slope.	±0.01%	±0.10%	-0.2045%	±0.2%
Curvature	Horizontal curve PC (point of curvature)	GPS coordinates where curve begins	±3 ft	±3 ft	-154.97 ft	sub-1 m
	Horizontal curve-length		±2 ft	±25 ft (7.62 m)	-17.5 ft	±25 ft (7.62 m)
	Horizontal curve-radius		±25 ft	±25 ft (7.62 m)	128.48 ft	±25 ft (7.62 m)

2.5 Application of MTLS

Several applications have been developed for data obtained from MTLS including extraction of roadway geometric features (i.e., grades, curvature, cross slope, and superelevation), pavement maintenance, and surface analysis.

2.5.1 Geometric Feature Extraction

In 2013, Tsai et al. proposed a mobile cross slope measurement method, which used emerging mobile LiDAR technology. The instruments included: an emerging mobile LiDAR system, a high-resolution video camera, 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. The acceptable accuracy level is typically 0.2% (or 0.1°) during construction quality control. Repeatability results showed standard deviations within 0.05% (0.03°) at 15 benchmarked locations in three runs. The case study also demonstrated the proposed method could efficiently conduct the network-level analysis. The GIS-based cross slope measurement map of the 3-mile section was derived in fewer than two person hours with use of the collected raw LiDAR data.

Another group (Holgado-Barco, 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%.

Research by Cook et al. (2015) developed a horizontal curve detection algorithm, referred to as the horizontal alignment finder (HAF), that can be used to identify and classify curve segments of highways as well as to propose guidelines for best practices in curve detection algorithms. Part of the process used in this research involved dividing roadways into segments classified as either curves or tangents. However, the authors removed from the analysis any segments that were too small to be considered a true curve. In addition, this method used LiDAR point cloud data that were preprocessed before being used as the input for the study. The authors found that the curve identification and classification success rate of this method, depending on calibration, ranged from 84.4% to 92.9% accuracy. Curve geometries accuracy rate varied between 78.7% and 89.9%. The primary challenge of curve detection and classification using HAF, as described by the authors, is in the actual classification of each segment as a curve, a partial curve, or a tangent.

Holgado-Barco et al. (2015) presented a methodology for the automated extraction of topographical parameters of road axes using a dataset acquired through MTLS. The authors have justified the use of an MTLS for being an accurate and time-saving technology that increases productivity in capturing road networks. This methodology has been divided into three parts; (1) segmentation, (2) filtering, and (3) parameterization of the collected point cloud data. Thus, the point cloud data collected by the MTLS were segmented semi-automatically using intensity and scan angle thresholds. Road pavement marking lines were segmented using the intensity values captured by the LiDAR system while taking into consideration their higher reflectivity. An antialiasing filter was used to simplify the relatively large centerline point cloud data due to the presence of random errors. This method has been employed in a software package developed using MATLAB©. Tests were performed and validated using both simulated and real-world data.

Most recently, Gargoum et al. (2018) proposed a method to be used on highways scanned using mobile LiDAR to automatically extract and measure attributes of horizontal curves. The methodology makes use of the high point density of LiDAR to measure horizontal curve attributes on LiDAR segments to a high degree of accuracy. In addition, the authors have asserted that LiDAR datasets facilitate the assessment of sight distance on curves to measure the allowable horizontal offset. The extraction method used in this study was implemented as follows. First, the set of position vectors tracing the path of the data collection truck were filtered from the Lidar point cloud using MATLAB. Next, changes in azimuth between consecutive vectors were normalized across the entire segment. In addition, locations where the change in azimuth exceeded a predefined threshold were flagged as location where horizontal curves existed.

White et al. (2010) 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 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.

2.5.2 Pavement Maintenance

The California Department of Transportation (CalTrans) 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 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 including highly demanding pavement surveys to produce DTMs. 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. (Yen, 2010)

The Center for Earthworks Engineering Research (CEER) investigated the potential for using dense 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. It was concluded that these technologies would enable capturing large amounts of data, which allows modeling the elevation of the full surface (Alhasan, 2015).

Schnebele et al. (2015) 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.

2.5.3 Surface analysis

MTLS 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. A mobile LiDAR scanner mounted on a car can provide a dense point cloud depicting roadway features, the surrounding terrain, and the road surface very accurately. Jaakkola et al. (2008) indicated that the density of data produced by laser-based mobile mapping required new algorithms for data extraction. Using data collected in Finland with the Finnish Geodetic Institute (FGI) Roamer mobile mapping system (MMS), the authors classified points on the roadway pavement 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 locate most curbstones, parking spaces, and zebra crossings.

Grafe (2008) provides examples of a roadway digital surface model, cross sections, and a highway interchange that have all been surveyed using MTLS. 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. (2013) showed 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 MTLS, prior to travel.

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 RMSE 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.

MTLS is recognized as a fast, accurate and cost-effective tool to gather geo-referenced 3D information of the shape of the roadway surfaces. Contreras et al. (2012) developed a model to accurately estimate earthwork volumes for the proposed forest roads by using high resolution 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 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.

González-Jorge et al. (2015) evaluated and parameterized the influence of the precision of LiDAR data for runoff estimation. In their study, aerial and terrestrial MTLSs 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.

2.5.4 Cost Estimating and Volume Extraction

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 (Turochy, 2001; Peng, 2006). 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 (Peng, 2006). Turochy et al. (2001) 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.

2.6 Survey of States

Many states are still using traditional surveying methods, which provide accurate results, but are time consuming to perform. They also pose safety risks because they require data collectors to be located on or near travel lanes, and there are additional concerns with traffic interference (Yen et al, 2011). In an attempt to better understand uses of MTLS, specifically for cross slope data collection, the research team deployed a survey to all state department of transportation research offices. The complete survey form can be found in Appendix A, and the results with personal contact info redacted can be found in Appendix B. The following sections provide summaries of some of the key findings from the survey. Not all question responses are summarized, but can be found in the appendix.

2.6.1 Q1 – Contact Information

In total, 20 responses were received and represent 16 different states (i.e., AK, CA, CO, FL, GA, IL, IN, KS, MT, NC, NJ, NV, OR, TX, and VT). A few states had duplicate responses from the perspectives of different offices within the state agency. Typical responding offices included Surveying, Design, Pavements, Safety, Preconstruction, Research, and Asset Management.

2.6.2 Q2 - Does your agency currently collect cross slope data for any purpose?

The respondents indicated that over 70% of the agencies collect cross slope data for some purpose. For those that did not, two have not identified a need for the data and one indicated that they have LiDAR data but have experienced storage issues and post processing costs.

2.6.3 Q3 - For what purpose/application do you collect cross slope data?

The responses for this question varied with roughly a quarter of respondents checking for cross slope compliance, along with a few responses for material quantity take offs and pavement distress. However, the most responses were for other and text responses indicate that collection is typically in response to high accident site investigations, drainage issues/hydroplaning, and pavement failures.

2.6.4 Q4 - Does your agency have any plans to collect cross slope data in the future?

For those that responded no to Q2 (see section 2.6.2), roughly half had plans to collect data in the future whereas the others did not. One respondent indicated other data priorities were of higher concern.

2.6.5 Q5 - For what purpose/application do you wish to collect cross slope data?

A follow on to Q4 (section 2.6.4), one responded indicated desire to collect cross slope as a design aid, and the other indicated all of the answer choices were of interest.

2.6.6 Q6 - On what type of roads does your agency perform cross slope data collection?

For those states that collect cross slope data, few collect cross slope on secondary routes, but most collect it on primary routes (See Figure 2-4).

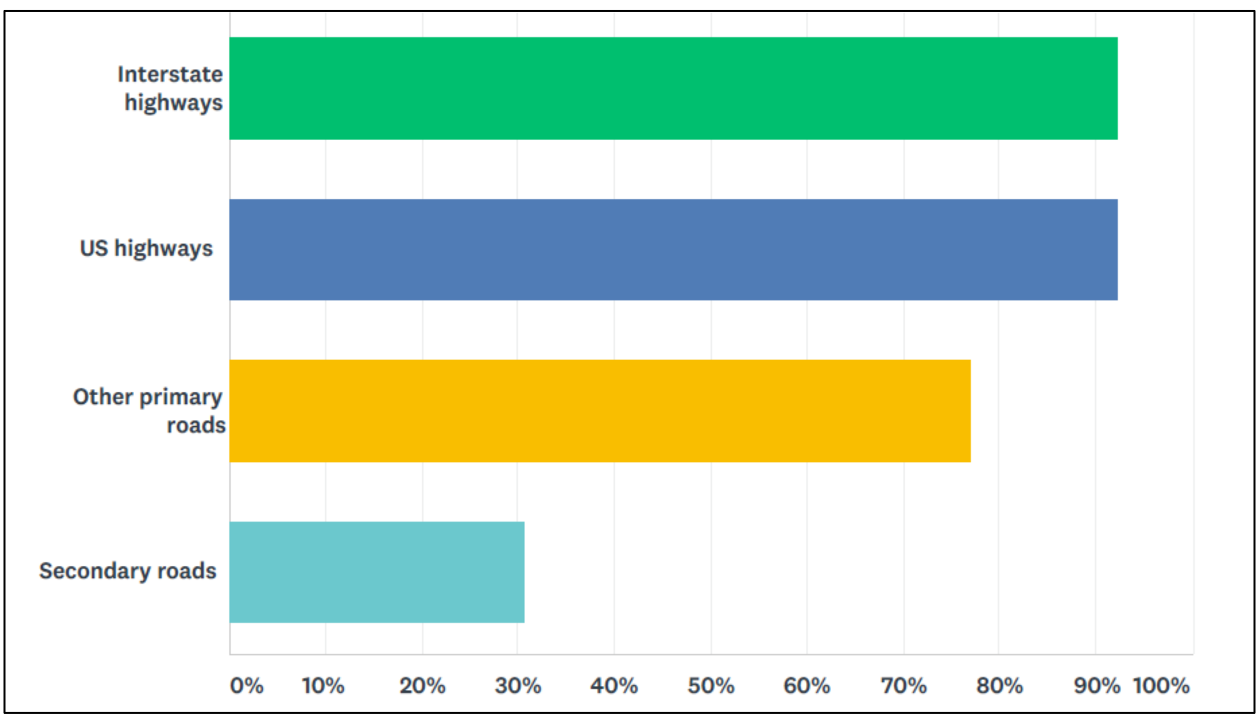

Figure 2-4 Responses to Q6 – (type of roads for cross slope data collection)

2.6.7 Q7 - How is cross slope data collected?

The majority of respondents indicated using mobile methods such as MTLS for collecting cross slope data. Almost 40% indicated using traditional surveying techniques, and other techniques most commonly referred to laser profiling.

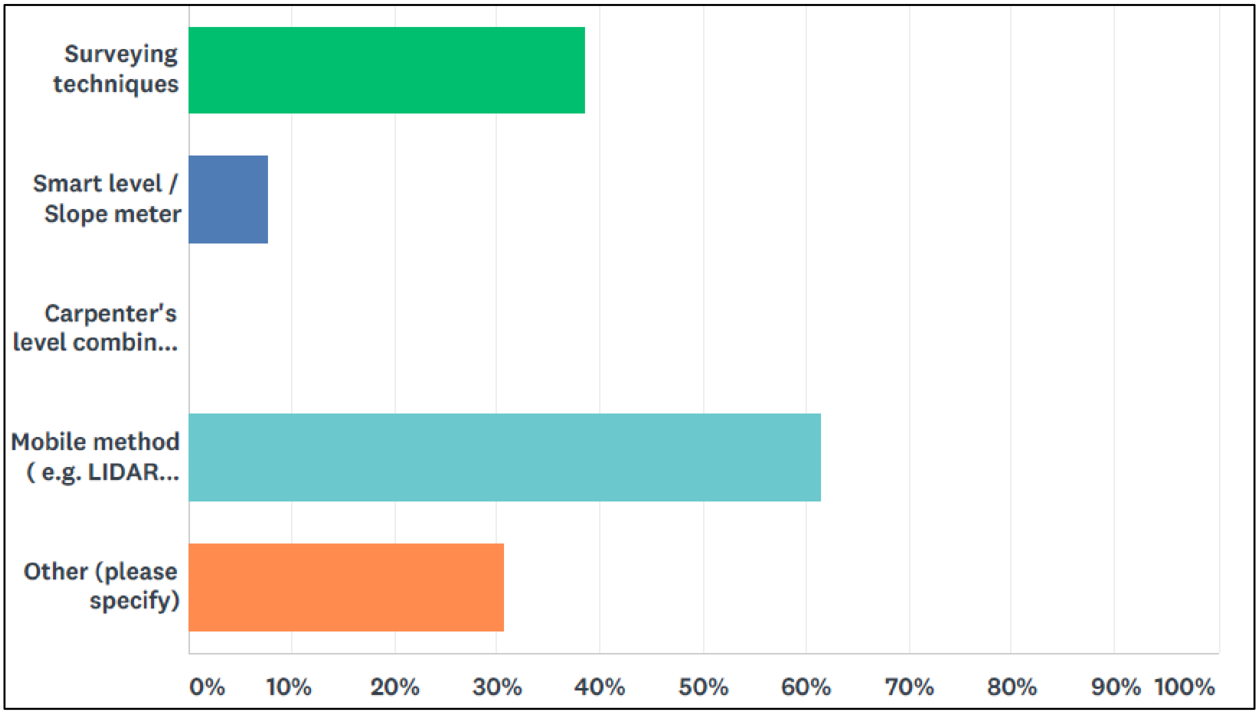

Figure 2-5 Responses to Question 7 – (methods of cross slope data collection)

2.6.8 Q9 - When does your agency collect cross slope data?

Over half of the respondents reported collecting cross slope data for inspections after new construction, as well as prior to maintenance or rehabilitation activities. About 15% indicated collecting cross slope inspection data after maintenance and rehabilitation or for general road inventory attribute data collection. Almost half of the respondents indicated other occasions for collecting cross slope data with the most common being in conjunction with accident investigations or special evaluation requests.

2.6.9 Q10 – At what interval is cross slope data collected?

There were no clear differences in the responses to this question. Nearly equal numbers of respondents chose each of the following responses:

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

For other responses, there were no common answers. Responses indicated that the interval was determined by the resident engineer, determined by the survey request, or random points are collected.

2.6.10 Q11 – What guideline does your agency follow to measure cross slope?

The majority of respondents indicated having in-house construction manuals. Several provided links to their methods or manuals including:

- California
  http://www.dot.ca.gov/design/manuals/hdm/chp0300.pdf
- Florida
  http://www.fdot.gov/materials/administration/resources/library/publications/fstm/methods/fm5-611.pdf
- Montana
  http://www.mdt.mt.gov/other/webdata/external/photosurvey/survey/manual_guides_forms/survey_manual/sm_entire_manual.pdf

2.6.11 Q12 - What level of cross slope tolerance is accepted for construction specification?

The majority of respondents indicated 0.2%, with others indicating variable or not applicable.

2.6.12 Q13 – Does your agency use mobile LiDAR data collection?

Only a quarter of the total respondents indicated collecting data via mobile LiDAR. Follow up question number 14 indicated that the majority use MTLS and one uses aerial LiDAR, and one uses both terrestrial and aerial.

2.6.13 Q21 – Does your agency use a laser transverse profiler?

Over 60% of the respondents indicated using laser transverse profiling.

2.6.14 Q22 - What is the purpose of using a laser transverse profiler?

By far, the most use of laser transverse profiling is for determining depth of roadway rutting and crack detection (See Figure 2-6). Other uses include collection of cross slope data, pavement texture, and ride quality.

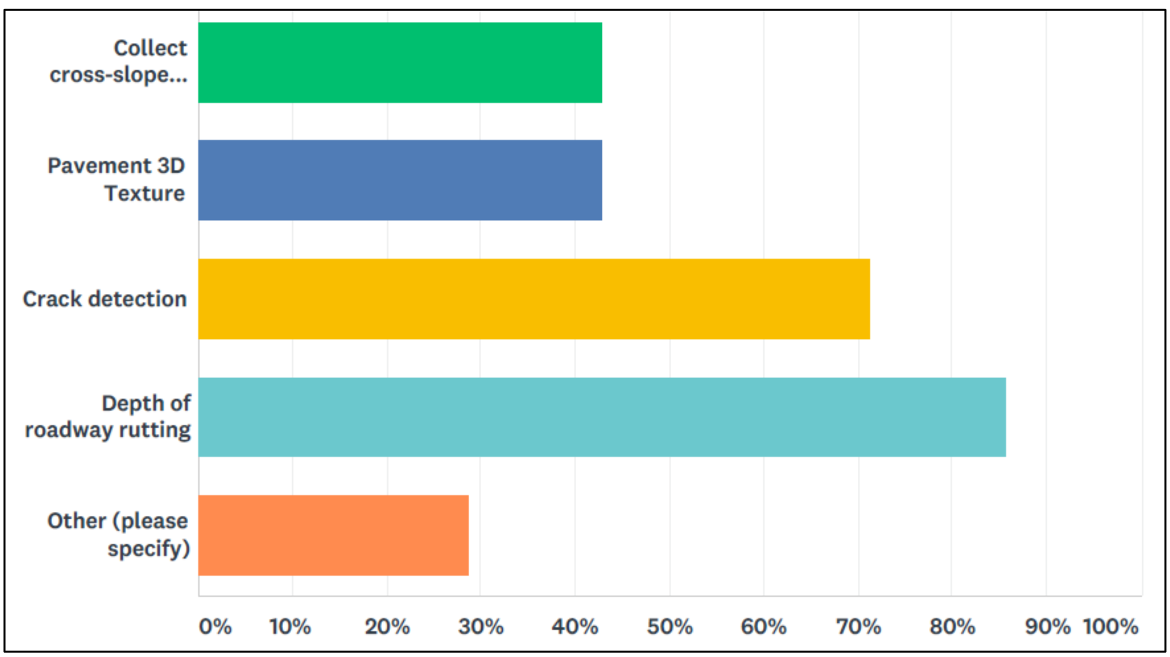

Figure 2-6 Responses to Q22 (uses of laser transverse profiling)

2.6.15 Q24 - Which guideline does your agency follow for transverse profiling?

California and Florida both indicated having their own manuals for transverse profiling while most other responses indicate the latest federal standard practice documents (AASHTO PP 69-14 and AASHTO PP 70-14).

CHAPTER 3 : PRELIMINARY EVALUATION OF MTLS TO COLLECT CROSS SLOPE DATA

3.1 Introduction

Early in the research a Mobile Terrestrial Laser Scanning (MTLS) firm contacted SCDOT indicating that they had collected MTLS data for all restricted access highways in South Carolina. Their purpose for doing this was for an autonomous vehicle application. The researchers made a request to the firm for a small sample of the data for use on this project and this request was granted. The researchers thought that this would be a good opportunity to work with MTLS data to help plan the rodeo. Another benefit of this data is the manner of which it was collected. A high accuracy MTLS survey requires extensive ground control for post-process least-squares adjustment to ensure absolute accuracy of the point cloud data. For this research, absolute accuracy may not be required to receive a high degree of accuracy for cross slopes. Relative accuracy between points is what is most important. The researchers saw this as an opportunity to evaluate an unadjusted point cloud. The term "unadjusted" is actually a misnomer. In reality, the LiDAR range measurements are combined with high accuracy GPS and IMU measurements to create a point cloud. GPS positions are differential corrected in real-time using a Virtual Reference System (VRS). A positional accuracy of one foot or better can be achieved with an unadjusted point cloud which is suitable for a number of applications including asset management and autonomous vehicles.

3.2 US-123 Corridor Description

The MTLS data sample provided by the vendor was for a one mile corridor US 123 just west of Easley, SC. This section of US 123 is a restricted access 4-lane 2-way divided highway. The researchers decided to evaluate cross slopes extracted from the MTLS data at locations where highway signs are present. The signs would delineate where we would need to do a conventional survey to collect cross slopes. These locations would be easy to find in the MTLS point cloud because the signs locations are distinctive. Figure 3-1 identifies station locations of the signs where conventional surveying would be done.

Figure 3-1 US 123 Test Section Sign Locations

3.3 Field Surveying Using Auto Level

Conventional surveying (auto leveling combined with taping and total station measurements) was used to develop ground truth cross slopes on US 123 at the six stations. Each of the cross section stations was leveled using two different instrument setups on either side of the highway to ensure accuracy and adjust for random error. The cross slope at each station was computed for each lane from the elevation difference between lane lines, along with horizontal distances in between, which were measured using a survey tape.

Figure 3-2 Field Surveying at the Six Stations (Sign Locations)

3.4 LiDAR Data

For US123, the vendor's LiDAR system was a Reigl VMX 450. This is a relatively new dual laser system that is very popular among MTLS vendors. Data was collected using one pass in each direction.   Figure 3-2 (a) shows the LiDAR point cloud of the corridor that was provided in a single digital file in ASPRS LAS format. Figure 3-2 (b) shows an aerial view of the corridor from a similar perspective. The point cloud has a resolution of roughly 20 points per square foot.

3.5 Comparison of LiDAR and Conventional Survey Data

The use of LiDAR to extract pavement cross slope on US123 was compared against cross slope measurements collected using conventional surveying for the six sign locations. The comparison is shown in Table 3-1.

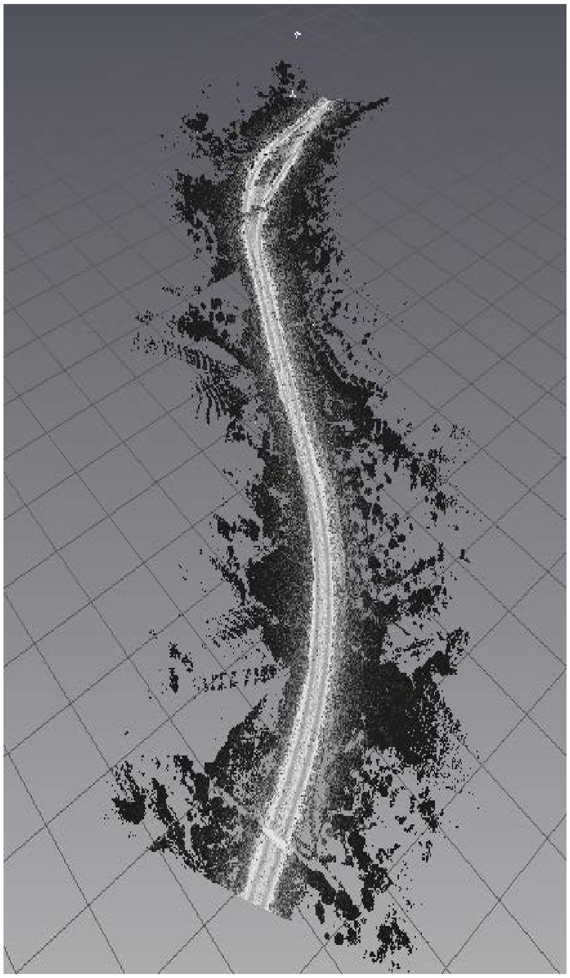

Figure 3-2 a) Lidar Point Cloud of the Corridor That Was Provided in a Single Digital File in ASPRS LAS Format

Figure 3-2 b) Aerial View of the Corridor from a Similar Perspective

Table 3-1 Cross Slope Comparison between Surveyed Data and LiDAR Derived Cross Slope – Us 123

Station	Lane	Lane width (ft)	Surveyed Data	MTLS Vendor	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%

3.6 Evaluation of Results

In evaluating cross sectional data at reference station locations, cross slope estimates from the unadjusted LiDAR differed from field surveyed measurements ranging from 0% to 0.24%, as shown in Table 3-2. The LiDAR derived point clouds on this section point cloud was adjusted only with the integrated IMU data. The one sided t-test for unadjusted LiDAR indicates at a 95 % confidence level the difference of the LiDAR derived slopes and field surveying was less than 0.18% (Table 3-2). This meets the SHRP2 slope tolerance specification of ± 0.2% for MTLS (SHRP2, 2013). It is noteworthy that the MTLS level of error of this specification without doing a survey adjustment of the MTLS data using GCPs. Additional discussion on the implications of this level of error is discussed in Chapter 7.

Table 3-2 Summary of Cross Slope Comparison

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

CHAPTER 4 : VENDOR RODEO PLANNING AND DESIGN

4.1 Introduction

Clemson University, in cooperation with The Citadel, planned, promoted, and coordinated a Mobile Terrestrial Laser Scanning (MTLS) vendor rodeo, which occurred throughout the summer of 2016. The rodeo took place in the upstate of South Carolina along 3 roadway test sections: 1) a 4-lane urban arterial section; 2) a 4-lane parkway; and 3) a section of urban freeway. MTLS combines precise ranging, with high accuracy GPS and additional parameters to obtain a very dense point cloud for the pavement surface and along the road right of way. The point cloud is adjusted based on roll, pitch, and heading data collected from an integrated inertial unit. The resulting "GIS accuracy" point cloud can be useful for many GIS applications such as asset data collection (e.g., lane widths, presence of median and guardrail) or navigation, however may not be accurate enough for surveying or some engineering applications such as geometric alignment and cross slope extraction, or calculation of quantity take-offs for pavement rehabilitation projects. One of the objectives of this research is to evaluate if the GIS accuracy MTLS data provides is suitable for pavement cross slope data collection. To improve accuracy for engineering applications, adjustment techniques can be administered using ground control survey data. For adjustment purposes for this research project, Ground Control Points (GCPs) were collected using static Differential Global Positioning System (DGPS) (Figure 4 -1).

Figure 4-1 Primary and Secondary GCPs and Using Dual Frequency Topcon GPS on Section 2

4.2 Test Sections

The location of rodeo Test Sections are provided in Figure 4-2. The first Test Section is a 2,000 foot long 4-lane urban arterial section on US 76 (Clemson Blvd.) in Anderson, SC. Test Section 1 begins at Forest Hill Drive and ends at the intersection of Clemson Blvd. with East West Parkway

(Figure 4-5). The second Test Section is 2.9 miles of East West Parkway that starts at the end of the urban Test Section 1 and ends at SR 81 (Figure 4-7). The third Test Section is 3.5 miles along a limited access freeway known as Business 85 in Spartanburg (Figure 4-7) extending between Interstate 585 and Interstate 85.

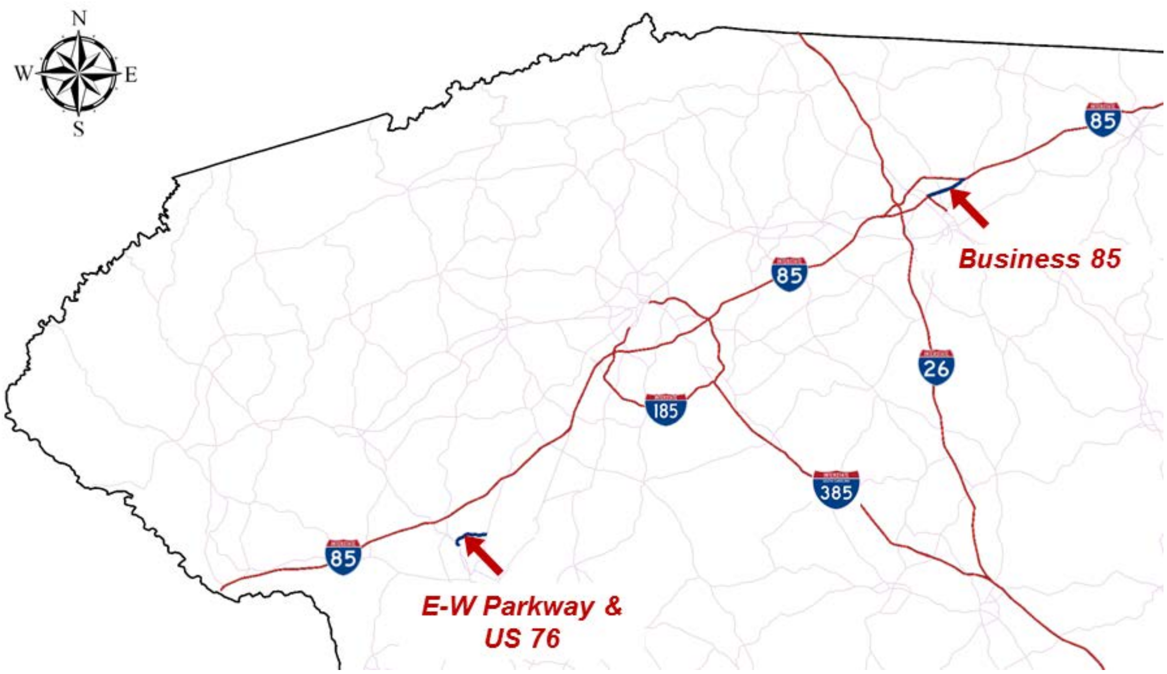

Figure 4-2 Overview Map of Rodeo Sections

East West Parkway is a relatively new road that opened to traffic in the fall of 2013. It is an urban multilane highway that is largely divided with a number of horizontal and vertical curves, a few intermediate intersections, and one bridge over a watercourse. The comparative rodeo plan was for vendor systems to be evaluated on Test Section 2 based upon several criteria including 3D coordinate accuracy of predetermined reflective pavement tape locations at 100 in. station intervals (Figure 4-3) and preestablished secondary survey control locations that are delineated with range poles (Figure 4-4), as well as a comparison of mobile system cross sections with the surveyed cross sections. Cross slope deviations from

Figure 4-3 Sample Station Location

surveyed data were calculated for each lane of each cross section collected. One of the goals of this research was to determine reasonable allowable measurement deviations for SCDOT construction and pavement rehabilitation projects. The locations for desired cross section comparisons were established at whole stations and included stations 110, 124, 128, 149, 203, 208, 227, and 232. Results were tabulated and included deviations and accuracy levels (between mobile measured and survey measured cross slopes). Tolerance levels were noted in relation to South Carolina current cross slope specifications. One of the cross slope sections was surveyed at 2 ft. spacing to provide an even more detailed transverse profile. The location for this evaluation occurred at station 107+83 and was marked with cones and transverse yellow pavement marking tape during the rodeo. The section was chosen due to its surface irregularity. Vendor systems were evaluated on how well their system can replicate the surveyed 2 ft. spacing transverse profile.

Figure 4-4 Range Pole Location

Finally, vendors were asked to voluntarily provide multiple levels of data extraction from the LiDAR data. Data extraction included cross slopes, breaklines, attributes, and horizontal and vertical curve elements. An evaluation criterion was the ease at which cross slope data and other elements could be extracted from the LiDAR point cloud. The adjacent lane/direction accuracy was also evaluated as well as the ability to extract shoulder, median, and clear-zone slopes. Horizontal and vertical alignment comparisons of extracted data were planned along the centerline on tangents and on curves, and at the beginning of tangent runout (remove crown), at the beginning and end of superelevation runoff, at PC’s and PT’s, and at the beginning and end of the bridge. While vendors were encouraged to do this extraction, they could elect to qualitatively discuss how this can be accomplished using their collected data and provide associated costs for each level. These levels included fully automated, semi-automated, or manual data extraction. The Vendor Rodeo Data Collection Plan (Appendix C) and the Quick Reference for Submitting Results (Appendix D) identify desirable asset attributes for Test Section 2 and the submittal format and requests details on how attributes could be extracted. If a vendor preferred not to provide a particular attribute they could elect to answer questions associated with “attribute not collected.”

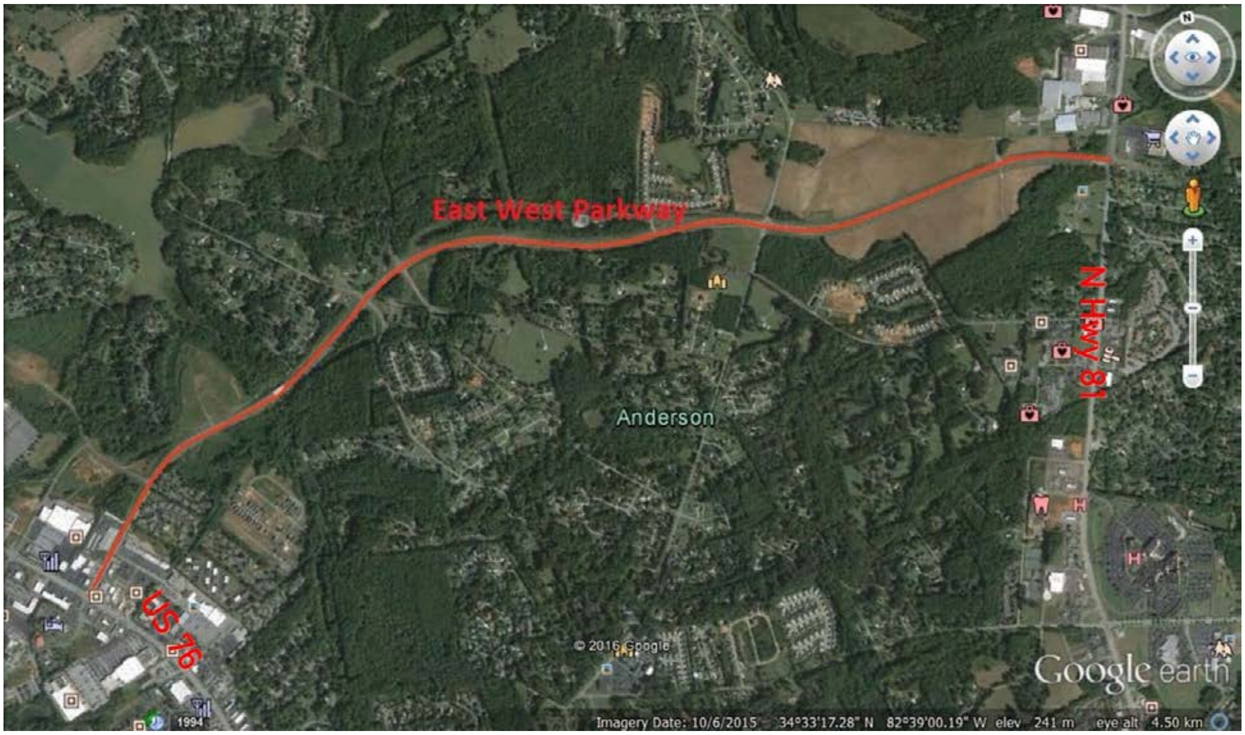

Figure 4-5 Section 2 - East West Parkway in Anderson, SC

<u>Test Section 3 (Interstate Freeway Section, Business 85 in Spartanburg)</u>

This section is a rural freeway that was recently surveyed by a SCDOT contractor. The surveyed data, which includes panel point locations for aerial sensing, was provided to the researchers for use on this project. The researchers measured cross slopes at selected locations in preparation for the vendor rodeo. These locations corresponded with panel points P78, P91, P98, P103, P126, and P127 (note that P103, P126 and P127 are located on ramps). All panel points were marked with a painted chevron, yellow reflective pavement marking tape, and a PK nail. See Figure 4-6 for an example. Detailed surveying of horizontal/vertical elements was not performed for the freeway, however, primary, and secondary geodetic control was established along the shoulder.

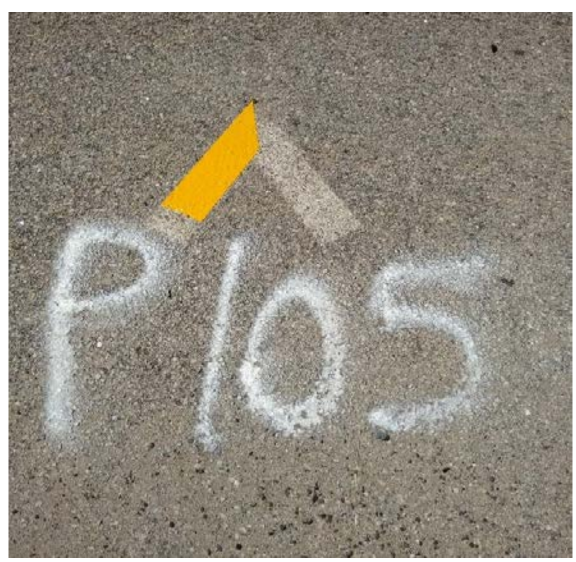

Figure 4-6 Section 3 Panel Point Example

Vendor mobile mapping data was evaluated through comparisons with RTK GPS surveyed data labeled CU 1, CU 2, CU 3, and CU 4. The approximate map locations of these points are:

- CU 1 - Between P92 and P93
- CU 2 - Between P97 and P98
- CU 3 - Between P73 and P74
- CU 4 - Between P77 and P78

SCDOT is interested in the comparative accuracy of mobile and aerial LiDAR. Comparisons of the vendor collected mobile LiDAR data with the surveyed data was planned for the selected cross section locations and the CU survey point locations.

The evaluation for Test Section 3 cross slope and other MTLS data was conducted in a manner similar to Test Section 2. Appendix C and D identify desirable asset attributes for Test Section 3 and the submittal format and request for vendor software details on how asset attributes were extracted.

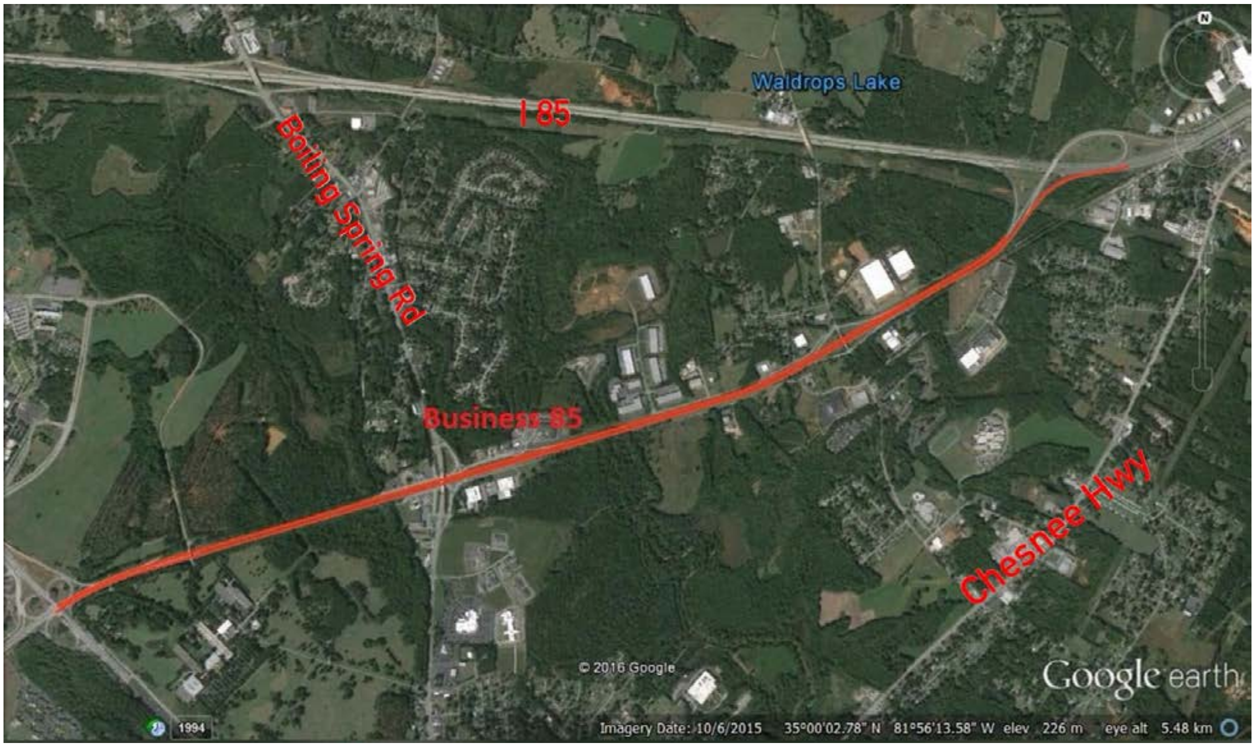

Figure 4-7 Section 3 - Business 85 in Spartanburg, SC

4.3 Test Procedure

Each vendor was allowed an opportunity to calibrate their systems and make a single pass in each direction through the Test Sections. Vendors followed the same trajectory and were expected to travel at the posted speed limit. Both directions of Test Sections 1 and 2 were collected in one continuous trip. Beginning at the staging area on US 76, vendor vehicles traveled northbound until making a right-turn on East West Parkway and traveling eastbound until they reached SR 81. At this point, the vehicles made a U-turn and returned to the staging area along the same route but in the opposite direction of travel. The vehicles traveled in the right most lane except when making the 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. The researchers understood that accuracy would be influenced by functions of distance and incidence angle relative to the data collection vehicle. Since each vendor followed the same trajectory, fair and objective comparisons could be performed. Data collection runs could be repeated in the event a vendor experienced technical difficulty, however, only data from one run was allowed to be used when submitting results.

Vendors could elect to set up a GPS base station prior to making their data collection runs. Base stations could be set up at available control point locations along the corridors. Alternatively, a

VRS could be used at the Vendor's discretion. Primary and secondary survey control locations and selected panel locations for Test Sections 1 and 2 were provided in separate PDF files to all Vendors. Hard copies were available at the rodeo. Figure 4-9 provides a map of the primary and secondary survey control locations for Test Sections 1 and 2. Coordinates for these locations are shown in Table 4 -1 for control points and in Table 4-2 for edge line station locations at even 500' intervals for Test Section 2. Figure 4-10 provides a map of the primary and secondary (panel points) survey control locations for Test Section 3. Coordinates for the primary control point locations for Test Section 3 panel points are shown in Table 4-3. Primary and Secondary control point accuracy met SCDOT standards for pre-construction. These standards can be found in the SCDOT Survey manual posted on the SCDOT website at:
(http://www.scdot.org/business/pdf/publicationsManuals/Survey_Manual.pdf)

Painted Station Centerline target coordinates near the beginning and end of Test Sections 1 and 2 are shown below. The station targets used PK Nails to identify precise locations of the coordinates. Painted Station Centerline target coordinates near the beginning and end of Sections 1 and 2 are indicated below. The station targets used PK Nails to identify precise locations of the coordinates.

Figure 4-8 Painted Target with PK Nail in center

<u>Clemson Blvd (US 76)</u>:

N 991,090.49'
E 1,497,072.82'
Elev = 770.99'
(Assigned Station 0+00 Near Logan's Steakhouse)

N 992,252.71'
E 1,495,965.30'
Elev = 773.06'
(Assigned Station 16+05.415 Station Near Grady's Outfitters)

<u>East West Parkway:</u>

N 992,432.67'
E 1,495,960.48'
Elev = 774.50'
(Station 102+00)

N 995,853.50'
E 1,509,784.45'
Elev = 857.14'
(Station 255+00)

Table 4-1 Primary and Secondary Survey Control Coordinates for Sections 1 and 2

Mon.	North Coord	East Coord	Elev	
L1-01	999,551.32	1,496,784.55	777.83	
L1-04	996,019.10	1,499,301.22	718.12	
L1-06	992, 188.42	1,503,672.15	788.7*	GPS derived elevation
L1-07	995,120.48	1,509,736.71	847.97	
1600	Range Pole Location			
1601	995,850.92	1,510,006.75	860.88	
1602	996,033.49	1,508,435.07	848.58	
1603	Range Pole Location			
1604	995,632.27	1,505,410.54	807.34	
1605	995,897.74	1,504,481.75	805.84	
1606	995,737.19	1,503,449.34	799.47	
1607	996,156.02	1,501,354.22	762.81	
1608	Range Pole Location			
1609	Range Pole Location			
1610	994,110.57	1,497,380.39	758.04	
1611	993,205.82	1,496,515.47	789.73	
1612	992,245.82	1,495,872.81	773.65	

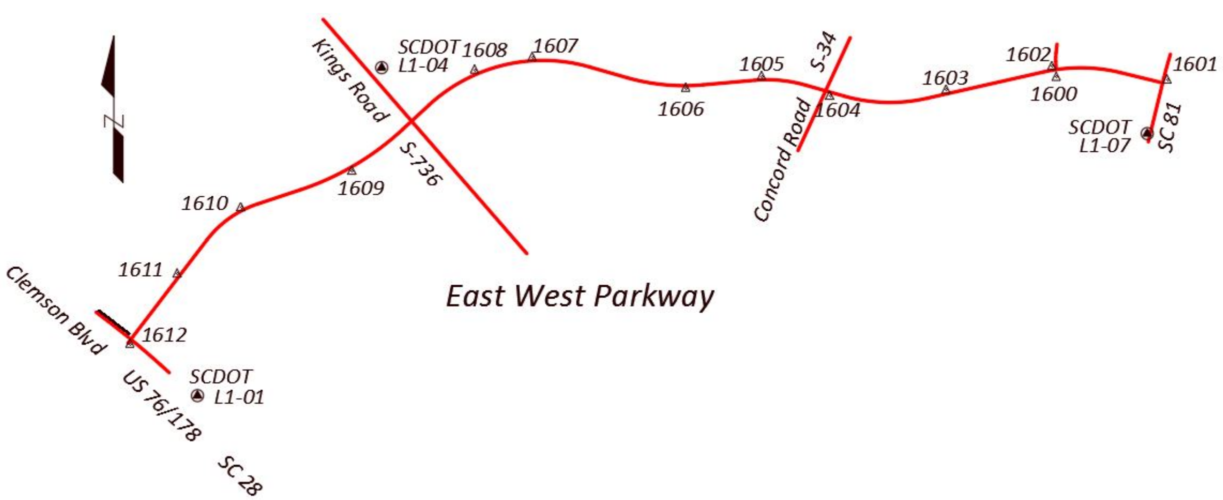

Figure 4-9 Control Points along Clemson Boulevard and East West Parkway

Table 4-2 Edge line Station Locations at 500' Intervals for Section 2

	LEFT			RIGHT		
Station	**North**	**East**	**Elevation**	**North**	**East**	**Elevation**
105+00	992,688.30	1,496,120.26	778.98	992,652.53	1,496,167.07	779.29
110+00	993,079.03	1,496,432.41	789.39	993,049.73	1,496,470.67	789.40
115+00	993,480.67	1,496,730.31	781.80	993,442.36	1,496,780.38	781.55
120+00	993,869.38	1,497,051.63	765.83	993,823.53	1,497,094.85	763.00
125+00	994,148.16	1,497,476.63	755.92	994,090.33	1,497,501.49	752.95
130+00	994,311.54	1,497,951.90	737.10	994,251.36	1,497,971.82	737.21
135+00	994,476.08	1,498,421.62	712.65	994,417.46	1,498,445.55	714.26
140+00	994,693.17	1,498,867.29	695.03	994,638.12	1,498,898.44	696.57
145+00	994,965.85	1,499,281.08	694.06	994,916.36	1,499,318.43	695.55
150+00	995,289.97	1,499,657.60	709.43	995,244.15	1,499,699.85	709.97
155+00	995,628.91	1,500,027.64	733.28	995,579.40	1,500,068.11	731.18
160+00	995,903.83	1,500,452.33	754.10	995,847.20	1,500,480.96	751.91
165+00	996,080.81	1,500,926.15	764.43	996,020.52	1,500,941.55	762.16
170+00	996,151.68	1,501,426.87	761.96	996,089.42	1,501,428.82	759.72
175+00	996,112.78	1,501,931.12	752.70	996,051.50	1,501,919.55	750.43
180+00	995,984.44	1,502,417.24	756.37	995,923.71	1,502,399.88	756.44
185+00	995,858.69	1,502,898.60	777.61	995,797.40	1,502,886.99	779.36
190+00	995,809.07	1,503,389.94	796.48	995,746.79	1,503,389.19	798.26
195+00	995,838.06	1,503,885.66	805.91	995,776.82	1,503,891.07	806.04
200+00	995,882.23	1,504,383.78	806.91	995,820.88	1,504,389.13	805.15
205+00	995,860.08	1,504,889.95	806.77	995,798.90	1,504,879.13	804.21
210+00	995,734.10	1,505,376.84	808.22	995,671.68	1,505,359.11	808.61
215+00	995,610.71	1,505,857.26	799.94	995,548.85	1,505,847.04	801.98
220+00	995,583.49	1,506,348.81	799.14	995,521.48	1,506,352.17	801.24
225+00	995,661.27	1,506,836.63	805.12	995,600.61	1,506,850.34	805.88
230+00	995,771.56	1,507,324.26	815.78	995,710.64	1,507,338.04	815.72
235+00	995,881.59	1,507,812.10	833.99	995.820.54	1,507,825.91	833.97
240+00	995,991.86	1,508,299.80	846,86	995,931.13	1,508,313.49	845.57
245+00	996,052.30	1,508,801.70	851.06	995,989.77	1,508,802.39	848.79
250+00	996,001.98	1,509,305.02	850.09	995,941.02	1,509,292.15	847.92
255+00	995,884.73	1,509,792.07	856.55	995,824.13	1,506,777.24	856.40

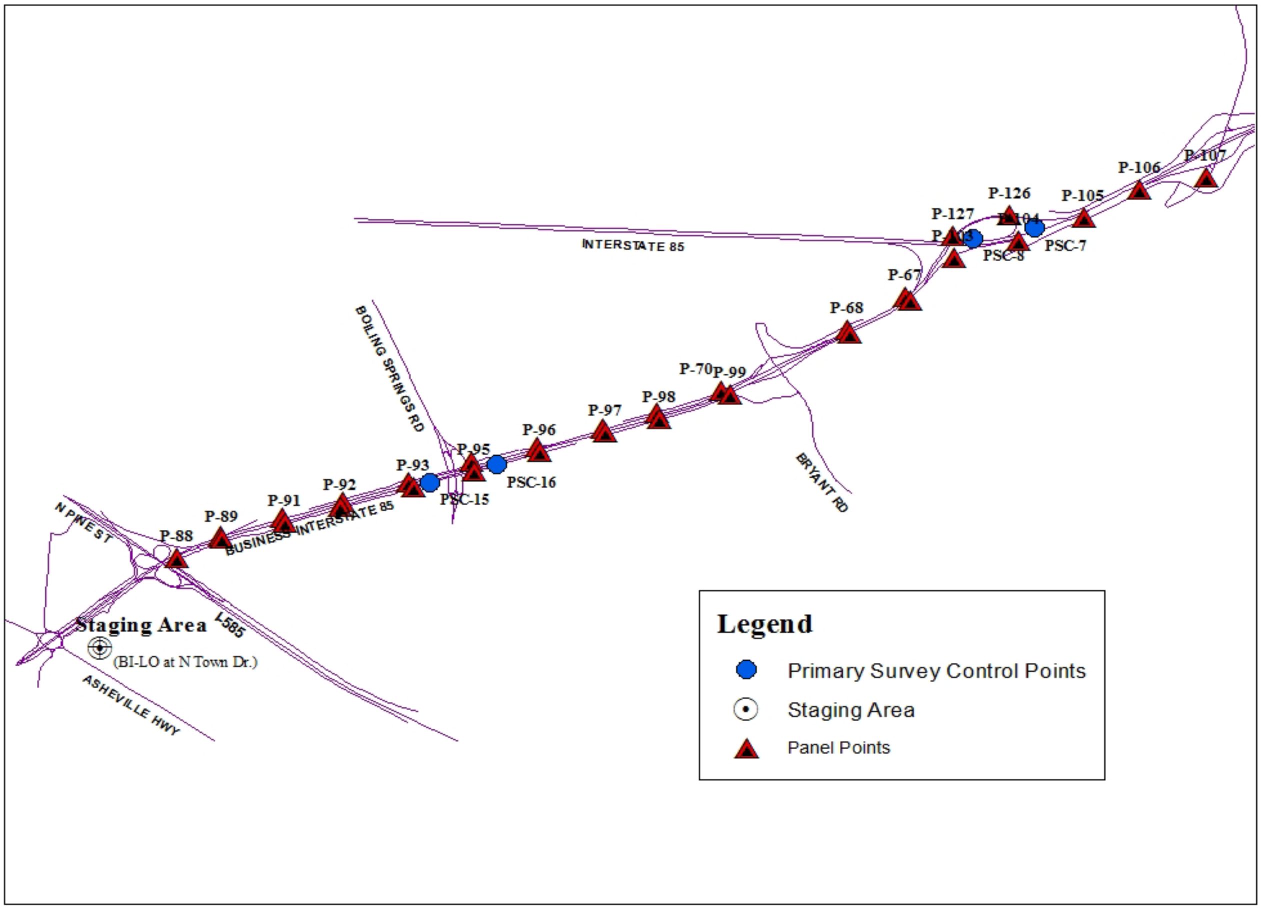

Figure 4-10 Survey Control Point Locations for Section 3 (Business 85)

Table 4-3 Primary Survey Control Coordinates for Section 3, Business 85

Horizontal Datum/Coordinate System: NAD 83 (2011) SC State Plane, Vertical Datum: NAVD 88

PSC	Grid Easting (iFT)	Grid Northing (iFT)	Project Elevation
7	1727798.57	1157849.73	860.39
8	1726604.13	1157597.35	831.73
15	1716026.30	1151632.87	790.26
16	1717325.42	1152057.34	774.90

On Business 85, Primary Control Points, were located with rebar and aluminum caps with nearby wooden stakes. They were easily identified from painted labels marked on the nearby pavement. PCPs could be used by vendors for base station setups if desired. Note that the pavement label "GPS 16" corresponds to PSC 16. Panel points were marked with painted white chevrons and yellow retroreflective tape. A PK nail was located at the tip of the tape.

4.4 Submitting Results

As a minimum, vendors were asked to provide equipment specifications and "raw" and adjusted/rectified point cloud with attributes (e.g., elevation, amplitude/intensity) in ASPRS LAS format. The term "raw" point cloud was used in this report to refer to LiDAR measurements that were combined with high accuracy GPS and IMU measurements. An adjusted point cloud was provided via post-processing using least-squares adjustment and control points provided. It was 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. The researchers chose to evaluate both raw and adjusted point clouds for comparative purposes. It was hypothesized that raw point cloud data could be accurate enough for cross slope and material quantity purposes because relative accuracy of LiDAR points could be sufficient for these applications compared with absolute accuracy.

Equipment specifications requested to be provided by vendors included: information about GPS positioning, the inertial measurement unit, the LiDAR units, and cameras. If a vendor vehicle included a pavement profiler, those specifications were also requested to be provided. Manufacturers and models for all equipment was required to be specified.

The researchers completely understood that extraction of asset attributes could be a very time-consuming process. While the Test Sections may have a significant number of planimetric features, only a limited number of items were requested. Requested information varied by Test Section (See Appendices C and D).

While pavement condition data was not required, vendors were told it would be beneficial if they had the capability to collect pavement condition data. The researchers were aware that equipment specifications could vary considerably for vehicles that are outfitted with this type data collection capability. Ideally pavement condition data requested should have included International Roughness Index (IRI), rutting depth, fatigue cracking, longitudinal cracking, and transverse cracking. Raveling, patching percentage, and/or any other commonly collected asphalt distresses were additional attributes vendors could provide voluntarily. The data summary interval should be 0.1 miles. Any downward images (especially with distresses marked) were also of great interest, if available.

CHAPTER 5 : VENDOR RODEO RESULTS

5.0 Introduction

Clemson University, in cooperation with The Citadel, conducted a Mobile LiDAR vendor rodeo during the summer of 2016. The rodeo occurred over multiple dates to maximize participation. Rainy weather also played a role in having to conduct the rodeo on three different dates. Vendors were not compensated for their participation in the rodeo. There were seven vendors who participated in the rodeo data collection; however, only five vendors submitted data and therefore those are the Vendors identified herein. Vendors who submitted LiDAR data for the rodeo test site locations are: IMC Mapping, Michael Baker, Quantum Spatial, Rice, and McKim and Creed. Vendors, vendor equipment, and data collection capabilities are summarized in Table 5-1. For the evaluation of vendor results covered in much of this chapter, vendor names are anonymous, identified as Vendor A, B, C, D, and E, randomly assigned.

Table 5-1 Mobile Lidar Vendor Rodeo Date

IMC	McKim and Creed	Michael Baker	Rice	Quantum Spatial
June 30, 2016	June 30, 2016	August 23, 2016	August 23, 2016	August 30, 2016

The Vendor Rodeo Data Collection Plan was sent to the vendors in advance of their rodeo participation. The data collection plan is provided in Appendix C. All vendors who submitted data drove all 3 rodeo Test Sections, described and discussed in Chapter 4. After vendors completed acquiring their data, they were able to ask questions about post processing and submitting data. Detailed instructions for submitting are included in the data collection plan. A quick reference form for data submittal was also sent to all vendors after the rodeo. The quick reference is provided in Appendix D. Additionally, rodeo participants were provided Microsoft Excel templates to submit equipment specification information, asset attributes, and other information extracted from the Mobile Terrestrial LiDAR Scaning (MTLS) data. Four vendors (Michael Baker, Rice Associates, IMC Mapping, and McKim and Creed) provided equipment specification requested. These specifications are summarized in Table 5-2.

Table 5-2 Comparison of Vendors' Equipment Specification

Equipment		Michael Baker	Rice Associates	IMC Mapping Associates	McKim and Creed
LiDAR	Brand	Teledyne Optech	Leica	Riegl	Optech
	Model	SG1	9012	VMX450	M1
	Single laser or Dual	Dual	Single	Dual	Dual
	Measurement Rate	1.2 MhZ	1 MhZ	1.1 MhZ	1 MhZ
	Additional Info:	500 lines/sec	119 m range	400 lines/sec	
DMI	Brand	Applanix	N/A	Applanix	Applanix
	Model	HS35F	N/A	BEI HH5	LV
	Measurement Accuracy	1 mm	N/A	N/A	N/A
	Additional Info:				
IMU	Brand	N/A	NovAtel	Applanix	Northrop Grumman
	Model	FMU P301	SPAN IMU-FSAS	AP50	LN 200
	Roll/pitch accuracy (degrees)	0.005 degrees	0.008 degrees	0.005 degrees	0.25°, 1σ
	Heading Accuracy (degrees)	0.015 degrees	0.023 degrees	0.015 degrees	0.50°, 1σ
	Additional Info:				N/A
Camera	Type	Point Grey 360 degree camera	Leica	NIKON/RIEGL	Optech
	Number of Cameras	6	7	4	4
	Focal Points of Cameras (front, etc)	N/A	2 front, 2 side, 2 rear, 1 above	2 front, 2 rear	2 front, 2 rear
	Frame Rate	3 fps	8 fps	15 fps	2 fps
	Resolution per Camera	5 MP	4 MP	5 MP	5 MP
	Additional Info:	Also includes 4 - JAI 5 mp frame cameras	360 degrees x 270 degree coverage	N/A	N/A
Vehicle Mounted GPS/GNSS	Brand	Trimble	NovAtel	Trimble	Trimble
	Model	AT1675-540TS	GPS-702-GG	Zepher model 2	Zephyr Model 2
	Accuracy	0.02' H; 0.04' V - NSSDA @ 95% confidence interval with proper application of ground control	N/A	10 mm	Survey Grade
	Additional Info:	N/A	N/A	N/A	N/A
GPS Base Station	What survey control point(s) was used for Sections 1 and 2?	L1-01	1605	L1-07 (LEICA GS14)	L1-01
	What survey control point(s) was used for Section 3?	PSC 16	PSC 8	PSC 7 (LEICA GS14)	PSC 16

5.1 LiDAR Data Collection

Vendors were allowed to calibrate their systems both before and after data collection runs. A primary benefit of 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 (outside) 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 Rodeo Test Section 1 and 2, 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 Test Section 3. Figure 5-1 shows the McKim and Creed MTLS vehicle followed by the trailing SCDOT vehicles on Test Section 1.

Figure 5-1 Mckim and Creed MTLS Vehicle Being Trailed by SCDOT Traffic Control Vehicles.

5.2 Selected Point Accuracy

5.2.1 Test Section 2 Range Pole Accuracy

While absolute accuracy of selected points is not a primary objective of this research, the ability to make this comparison remains an important consideration. As mentioned in Chapter 4, 4 range poles located at Secondary Control Points (SCPs) were identified as unknown locations to be determined by the vendors (Figure 5-2). The use of range poles will add error because while range poles can point to the exact center of the SCP at the bottom, the top of the range pole has a radius of 0.045 feet (0.54 inches). This will be the minimum expected error of a LiDAR point assuming that the pole is placed perfectly vertical. Typically, the best bullseye spirit level is accurate to within plus or minus 0.005 inches/inch or 0.029 degrees. The range pole height was 8.26 feet; therefore, the horizontal error associated with the range pole being not exactly vertical is +/-0.4956 inches. Equation (1) shows that the expected horizontal error of the range pole setup accounting for the radius of the range pole and leveling error is equal to +/- 0.73 inches (+/-0.061 feet).

$$Error_{rangepole} = \sqrt{Error_{level}{}^2 + Error_{diameter}{}^2} = \sqrt{0.4956^2 + 0.54^2} = \pm 0.73\ inches = \pm 0.061\ ft \quad (1)$$

Where,

$Error_{rangepole}$ = Total error associated with range pole setup
$Error_{level}$ = Error associated with making bubble (spirit) level
$Error_{diameter}$ = Error associated with range pole diameter

The range pole location data provided by five different vendors along with the field surveyed data are presented in Table 5-3.

Figure 5-2 Range Pole Set Up at an SCP

Table 5-3 Comparison of Vendors Data Collection and Actual Coordinates

		1600	1603	1608	1609
Vendor A	N	995887.373	995708.361	995980.763	994607.016
	E	1508495.674	1506989.049	1500566.32	1498896.414
	Z	852.12	814.284	765.897	704.142
Vendor B	N	995887.25	995708.3362	995980.724	994606.7459
	E	1508495.67	1506989.065	1500566.324	1498896.48
	Z	852.17	814.304	766.053	704.304
Vendor D	N	995887.19	995708.36	995980.55	994607.18
	E	1508495.36	1506989.17	1500566.76	1498896.22
	Z	852.07	814.41	765.93	704.27

		1600	1603	1608	1609
Vendor C	N	995887.24	995708.33	995980.67	994607.11
	E	1508495.57	1506989.24	1500566.76	1498896.21
	Z	851.52	814.23	765.97	703.99
Vendor E	N	995887.44	995708.26	995980.39	994606.93
	E	1508495.51	1506989.14	1500566.78	1498896.41
	Z	851.95	814.34	765.96	704.34
field surveyed (note: Z is at the top of the range pole)	**N**	**995887.28**	**995708.37**	**995980.57**	**994606.96**
	E	**1508495.56**	**1506989.13**	**1500566.71**	**1498896.33**
	Z	**852.36**	**814.42**	**766.06**	**704.33**

The NCHRP report 748 provided different levels of accuracy for transportation applications of MTLS. The accuracy levels are as follows (Olsen, et al., 2013) :

- High level < 0.16 ft (Terrain Modeling and Engineering Applications).
- Medium Level < 0.66 ft (General Mapping).
- Low level > 0.66 ft (Asset Management).

Accounting for the horizontal error associated with the range pole diameter, the horizontal accuracy levels become:

- High level < 0.22 ft.
- Medium Level < 0.72 ft.
- Low level > 0.72 ft.

The differences between vendors' data collection and field surveying are provided in Table 5-4. Note that raw LiDAR data includes IMU and GPS differential correction but does not include post-processed survey adjustments using known Ground Control Points (GCPs).

Table 5-4 Comparison of Vendors' Data Collection and Field Surveying

Point #	**1600**		**1603**		**1608**		**1609**	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
Vendor A	0.147	0.240	0.081	0.136	0.435	0.163	0.101	0.188
Vendor B	0.114	0.190	0.073	0.116	0.415	0.007	0.261	0.026
Vendor C	0.041	0.840	0.117	0.190	0.112	0.090	0.192	0.340
Vendor D	0.219	0.290	0.041	0.010	0.054	0.130	0.246	0.060
Vendor E	0.168	0.410	0.110	0.080	0.193	0.100	0.085	0.010
Error Statistics								
Min	0.041	0.190	0.041	0.010	0.054	0.007	0.085	0.010
Max	0.219	0.840	0.117	0.190	0.435	0.163	0.261	0.340
Average	0.138	0.394	0.085	0.106	0.242	0.098	0.177	0.125
Median	0.147	0.290	0.081	0.116	0.193	0.100	0.192	0.060

Typically, a 95% confidence level is used to provide accuracy estimates however this usually requires a minimum of 20 points to get a reasonable statistic. Nevertheless, Table 5-4 shows that nearly all of the data for all of the vendors meet medium levels of accuracy or greater for even maximum error values. The mean adjusted errors are within the highest level of accuracy for MTLS data collection in all cases except for the vertical value of one of the points.

5.2.2 Test Section 3: Intestate 85 Business Loop Selected Point Accuracy

Point location data was requested from the vendors for four points that were marked with chevron reflective panels pointing to PK nails. These points were surveyed with static GPS with differential correction through OPUS post-processing. The assumption is that the field survey points are control however a static OPUS corrected survey with a 1-hour observation period has an expected error of about 2 centimeters or 0.067 ft. Accounting for this, data provided in Tables 5-5 and 5-6 falls within medium to high levels of accuracy.

Table 5-5 Coordinate Comparison of CU points, Test Section 3, Spartanburg, SC

Vendors /Points	CU1		CU2		CU3		CU4	
	Easting	Northing	Easting	Northing	Easting	Northing	Easting	Northing
A	1715033.088	1151326.938	1720068.435	1153070.865	1717564.259	1152302.425	1713893.078	1151031.401
B	1715032.98	1151326.887	1720068.615	1153070.746	1717563.726	1152302.544	1713893.24	1151031.413
C	1715033.209	1151326.998	1720068.674	1153070.804	1717563.475	1152302.347	1713891.721	1151030.979
D	1715033.386	1151326.382	1720068.557	1153070.461	1717563.974	1152302.635	1713892.757	1151031.418
E	1715032.943	1151326.808	1720068.504	1153070.579	1717564.255	1152302.651	1713893.206	1151031.328
Field survey	1715033.041	1151326.916	1720068.661	1153070.673	1717564.068	1152302.559	1713893.054	1151031.762

Table 5-6 MTLS Accuracy of CU points, Test Section 3, Spartanburg, SC

Vendors	Horizontal Difference	Horizontal Difference	Horizontal Difference	Horizontal Difference
	(CU1)	(CU2)	(CU3)	(CU4)
A	0.0516	0.2974	0.2328	0.362
B	0.0676	0.0867	0.3425	0.395
C	0.1861	0.1319	0.6298*	1.5468*
D	0.6356	0.2359	0.121	0.4546
E	0.1458	0.1832	0.2084	0.4599
Summary				
Min	0.0516	0.0867	0.121	0.362
Max	0.6356	0.2974	0.6298	1.5468
Mean	0.2173	0.187	0.3069	0.6437

* Vendor C provided adjusted las files only for the eastbound direction. Hence, these numbers were extracted from the raw Las file.

5.3 Cross Slope Analysis

A primary benefit of a mobile mapping system that uses a rotating laser(s) is that it can collect a point cloud for multiple travel lanes with a single pass. Previous research has shown that accuracy and repeatability of vehicle-mounted LiDAR scanning has been determined to be effective for measuring cross slope for drainage on highways (Tsai, 2013). For this research, cross slopes were extracted from point clouds by three vendors (A, B, and C) for one section on Test Section 1 (US 76), four vendors (A, B, C, and D) for eight test sections along Test Section 2 (East West Parkway), and three vendors (A, B, and C) for six test sections on Test Section 3 (Business 85). Vendor E did not provide cross sections for any of the test sections. Diagrams for cross sections including cross slope information is included in Appendix E. The diagrams are for all test sections and the US 123 corridor discussed in Chapter 3.

5.3.1 Cross Slope Sensitivity Analysis

The typical range for cross slopes along urban arterials is 1.5 to 3 percent (AASHTO, 2011); 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 (AASHTO, 2011). On high-speed roadways, SCDOT recommends that the normal cross slope be 2.08% on tangent sections except when a steeper cross slope is required if there are more than three lanes in one direction (SCDOT, 2003). 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 a pavement can be calculated from the following equations (Guven & Melville, 1999) (Gallaway, et al., 1979).

$$L_f = L_x \left(\left(1 + {S_g}/{S_x}\right)^2\right)^{0.5} \quad (2)$$

$$WD_0 = 0.00338\, TXD^{0.11} {L_f}^{0.43} I^{0.59}\, {S_x}^{-0.42} - TXD \quad (3)$$

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

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 (Guven & Melville, 1999). To determine how the difference in cross slope values impact the water depth, the following assumption has been made (S_g = 0%, TXD = 0.02 (design value) (Guven & Melville, 1999)). The impact of cross slope on pavement water depth accumulation by intensity are shown in Figure 5-3. South Carolina freeways are typically two 12-foot lanes in one direction with a uniform cross slope. Thus, 24 feet is the assumption for pavement width in Figure 5-3.

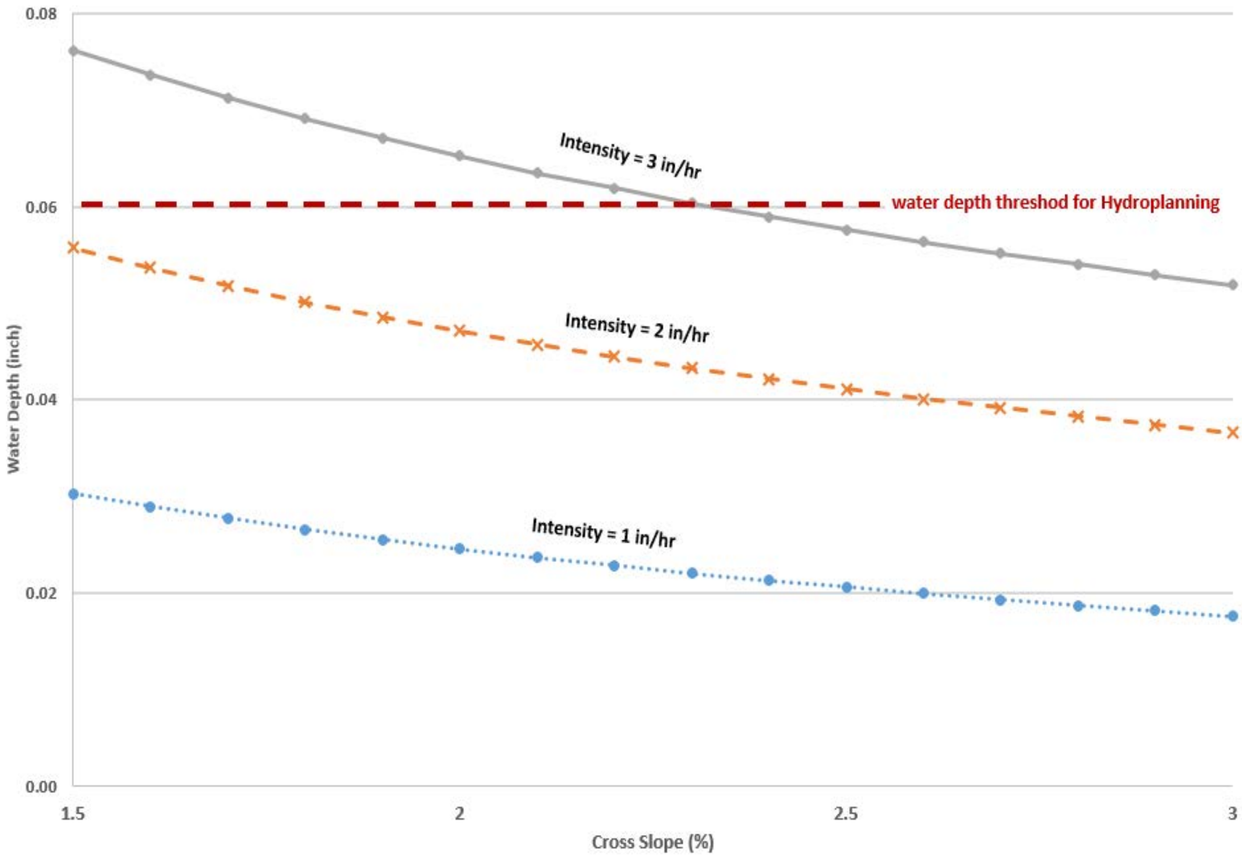

Figure 5-3 Cross Slope Sensitivity Analysis on Highway Pavement Water Depth

Research has not clearly defined a water depth at which hydroplaning occurs because this phenomenon depends on a range of vehicle speed, tire tread pattern, tire pressure, and pavement surface texture. However, there is considerable agreement on the water depth required to produce sufficient loss of tire friction to present a major driving hazard. This particular value of the allowable water depth, namely WD = 0.06 inches, is suggested as an acceptable upper limit for design purposes (Gallaway, et al., 1979) (Guven & Melville, 1999) (AASHTO, 2007). According to equations (2), (3) and (4) vehicles traveling at 60 MPH or less should not hydroplane with a water depth of 0.06 inches if their tires are fully inflated and have remaining tread life. For vehicles with nearly bare tires and low tire pressure (e.g., 24 PSI), hydroplaning can occur at speeds as little as 48 MPH if the water depth is 0.06 inches.

Figure 5-3 shows that rainfall intensity of 2 in/hr. can result in pavement water depths approaching 0.06 inches for cross slopes less than 1.5% and will exceed 0.06 inches for SCDOT standard cross slopes of 2.08% for rainfall intensities of 3 in/hr. Even though rainfall intensity of 3 in/hr can create hazardous driving conditions for virtually all vehicles traveling at the speed limit regardless of tire pressure, studies have shown that driving visibility is difficult when rainfall intensity exceeds 2 in/hr, and becomes poor when intensity exceeds 3 in/hr (Gallaway, et al., 1979). Thus, there is an expectation that vehicle operators will refrain from driving or drive very slowly during such heavy rainfall periods (Guven & Melville, 1999). Based on this expectation, the AASHTO recommended minimum cross slope of 1.5% is a safe standard even in heavy rainfall events of 2in/hr.

5.3.2 Cross slope Comparison

A cross slope comparison for Test Sections 1, 2, and 3 are shown in Tables 5-7, 5-8, and 5-9 respectively. The differences from surveyed data given in the tables are percent grade differences. The percent grade differences can be either positive or negative however only the absolute value of the difference is provided. The comparison is based on each travel lane. Vendors were asked to provide cross slopes based on the difference in lane elevations and the distance between travel lanes.

Table 5-7 Cross Section Comparison at Test Section 1

Lane	Surveyed Data (percent slope)	Difference from Surveyed Data		
		Vendor A	Vendor B	Vendor C
SB-outer	4.14%	0.57%	0.08%	0.17%
SB-middle	1.37%	0.09%	0.11%	0.01%
SB-Inner	2.04%	0.05%	0.02%	0.03%
Median(turning Lane)	-1.11%	0.34%	0.19%	0.11%
NB-Inner	-0.89%	0.18%	0.16%	0.20%
NB-outer	-5.59%	0.06%	0.11%	0.05%

Table 5-8 Cross Section Comparison Test Section 2

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%

Station	Lane	Lane width(HD)	Surveyed Data	Difference from Surveyed Data			
				Vendor A	Vendor B	Vendor C	Vendor D
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

Table 5-9 Cross Slope Comparison between Surveyed Data and Lidar Derived Cross Slope – Test Section 3

Station	Lane	Lane width (HD)	Surveyed Data	Difference from surveyed data		
				Vendor A	Vendor B	Vendor C
P78	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%
P91	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%
P98	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%
P103	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%
P126	WB Outer Lane	11.97	3.97%	*	0.14%	0.12%
	WB Inner Lane	12.09	4.47%	*	0.33%	0.24%
P127	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

5.3.3 Evaluation of Results

In evaluating cross sectional data at reference station locations, cross slope estimates from the vendors who submitted cross section data differed from field surveyed measurements ranging from 0% to 0.98% for all of the sections as shown in Table 5-10. A one sided t-test for adjusted LiDAR indicates at a 95% confidence level the difference of the LiDAR derived slopes and field surveying was less than 0.16% for Section 1, 0.18% for Section 2, and 0.19% for Section 3 (Table 5-10). These values meet the SHRP2 slope tolerance specification of ±0.2% for MTLS (SHRP2, 2013).

Table 5-10 Summary of Cross Slope Comparison

Section1, Clemson Boulevard						
	SB-Outer	SB-Middle	SB-Inner	Median (Turning Lane)	NB-Inner	NB-Outer
Min	0.08%	0.01%	0.02%	0.11%	0.16%	0.05%
Max	0.57%	0.11%	0.05%	0.34%	0.20%	0.11%
Mean	0.28%	0.07%	0.03%	0.21%	0.18%	0.07%
Median	0.17%	0.09%	0.03%	0.19%	0.18%	0.06%
One side t-test	Margin of error		N	p.value		Significant
	0.16%		18	<0.05		Yes

Section2, 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%	0.98%	0.57%
Mean	0.14%	0.19%	0.30%	0.22%	0.14%
Median	0.09%	0.11%	0.26%	0.15%	0.05%
One side t-test	Margin of error	n	p.value		Significant
	0.18%	136	<0.05		Yes

Section 3, I-85 Business Loop				
	EB-Inner Lane	EB-Outer Lane	WB-Inner Lane	WB-Outer Lane
Min	0.01%	0.02%	0.02%	0.00%
Max	0.42%	0.24%	0.8%	0.73%
Mean	0.15%	0.1%	0.34%	0.23%
Median	0.15%	0.11%	0.29%	0.12%
One side t-test	Margin of error	N	p.value	Significant
	0.19%	49	<0.05	Yes

A closer look at the summary statistics in Table 5-10 indicates that the cross slopes are more accurately measured in outside lanes than in inside lanes. This is because the vendors were required to only drive in the outside lanes. The research results indicate that MTLS can measure cross slope to within +/-0.14% grade for a single lane and to within +/-0.2% if 2 lanes are measured in one pass.

Using a +/-0.2% grade error, from a construction adherence standpoint, MTLS measurements that fall between 1.932% to 2.228% will meet the SCDOT Level 2 tolerance on average for roads with a design cross slope of 2.08%.

From a safety standpoint, cross slopes should exceed 1.5% to minimize the potential for vehicles to hydroplane. Our statistical analysis indicated that the cross slope values were normally distributed about a mean value. In a normal distribution, 50% of measurements will have +/- an average error from the mean or less. If the mean measurement and average error is known, then the proportion of measurements within any range can be calculated from the standard normal curve. Based on an average error of +/-0.14% (+/-0.21 RMSE), at a 95% level of confidence, the MTLS measured mean cross slope for the section should be at least 1.84% for a single pass for each lane. Stated another way, if the cross slope mean is 1.84%, then 95% of the measured cross slopes will be 1.5% or higher. For a single pass for two lanes which assumes an average error of +/-0.2% (+/-0.30 RMSE), the MTLS measured mean cross slope for the section should be at least 1.99% for a 95% level of confidence.

5.3.4 Transverse Profile Comparison

While it is desirable for a cross slope to be uniform across individual lanes, the actual transverse profile of a lane may vary due to seams during construction or pavement distresses that develop over time. In 2010, AASHTO published a provisional standard of practice for measuring the transverse profile of a pavement. This standard was updated in 2014 (AASHTO, PP70-14). This standard outlines a method for collecting the transverse profile, which can then be used to determine the cross slope as well as certain pavement distresses (rutting, edge drop-off, water entrapment, and transverse deformation). This standard, however, does not specify particular equipment to be used to collect the profile data.

The guidelines for data collection included in AASHTO PP70-14 recommend the following minimums to provide a usable database and for uniformity in the long-term:

- Interval between transverse profiles should not exceed 10-ft for network level collection and 1.5-ft for project-level collection.
- The transverse profile should have a width of at least 13-ft for distress detection and 14-ft if edge drop-off is desired.
- The data points in the transverse profile are to be no more than 0.4 inches apart.
- The resolution of the vertical measurements is to be no greater than 0.04 inches with an accuracy of 0.12 inches or less relative to the average elevation of the same profile or 0.2 inches relative to the true horizontal reference.

This measured data must then be processed to determine the cross slope and deformation parameters (e.g., rutting) using the procedures outlined in AASHTO PP69-14.

In order to evaluate the MTLS data collection accuracy from a transverse profile standpoint 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 yellow reflective pavement tape to make the section distinctive in the point cloud. Ground truth field surveying at this cross section was done every 2 inches using an auto level and rod. All five vendors were asked to provide a continuous transverse profile for this section, however only Vendor D actually provided the data. The researchers manually extracted transverse profiles from the LAS files for all of the vendors including Vendor D using the workflow shown in Figure 5-4. Bentley Microstation and Matlab were used in this extraction. The closest LAS point at each 2 inch interval was used in this extraction.

Figure 5-5 shows a comparison between the transverse profile provided by Vendor D and the one manually extracted from the LAS file provided by Vendor D using the workflow shown in Figure 5-4. It is pretty clear from this figure that the transverse profile provided by Vendor D has been smoothed to remove "noise" from individual points. Figure 5-6 shows a comparison of all of the transverse profiles compared with the field surveyed transverse profile. While the profiles vary slightly, they all seem to possess the same general shape. The pavement seam locations are pronounced for all of the profiles. Summary statistics for this comparison are shown in Table 5-11. The values shown in Table 5-11 are differences between vendor and surveyed data. Thus, the mean value is the average of every elevation difference between vendor elevations at 2 inch intervals and the corresponding surveyed elevation.

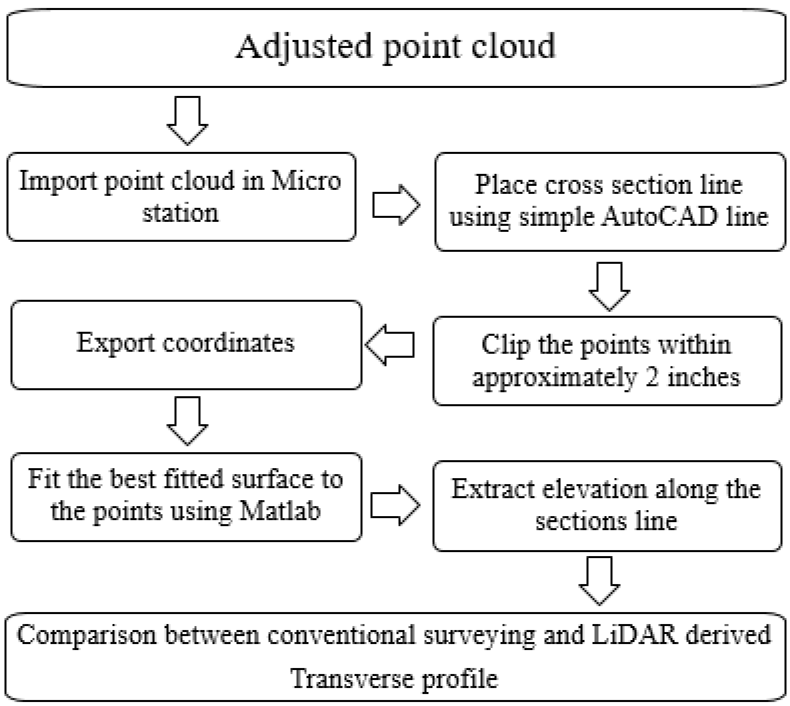

Figure 5-4 Work Flow to Extract the Transverse Profile

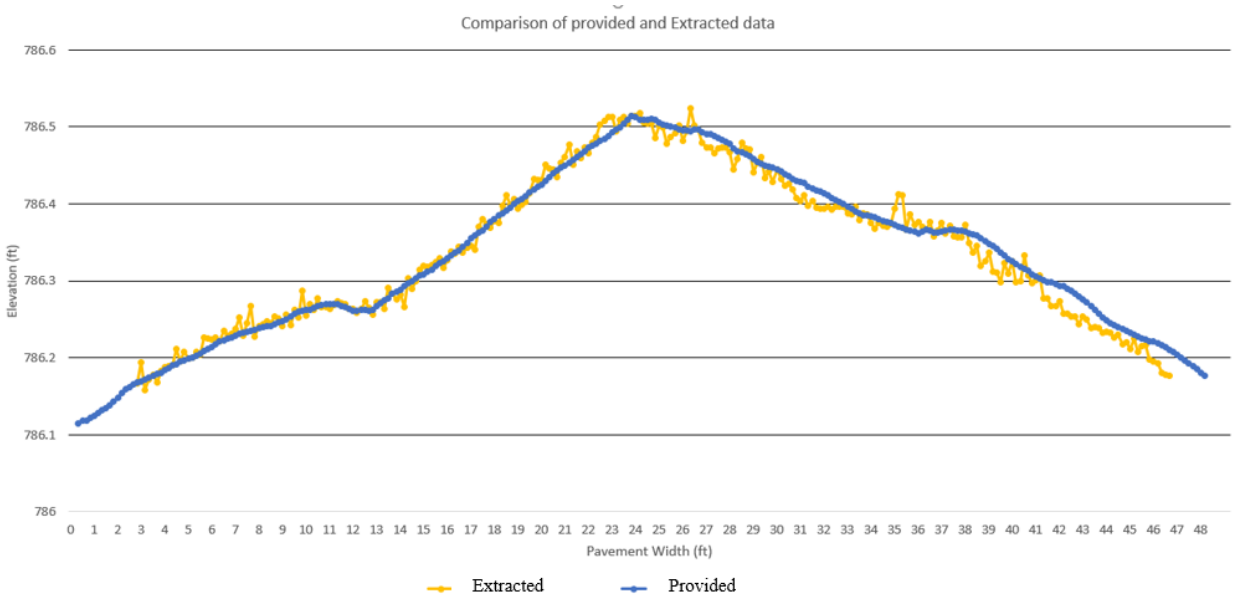

Figure 5-5 Comparison of Provided and Extracted Data Vendor D

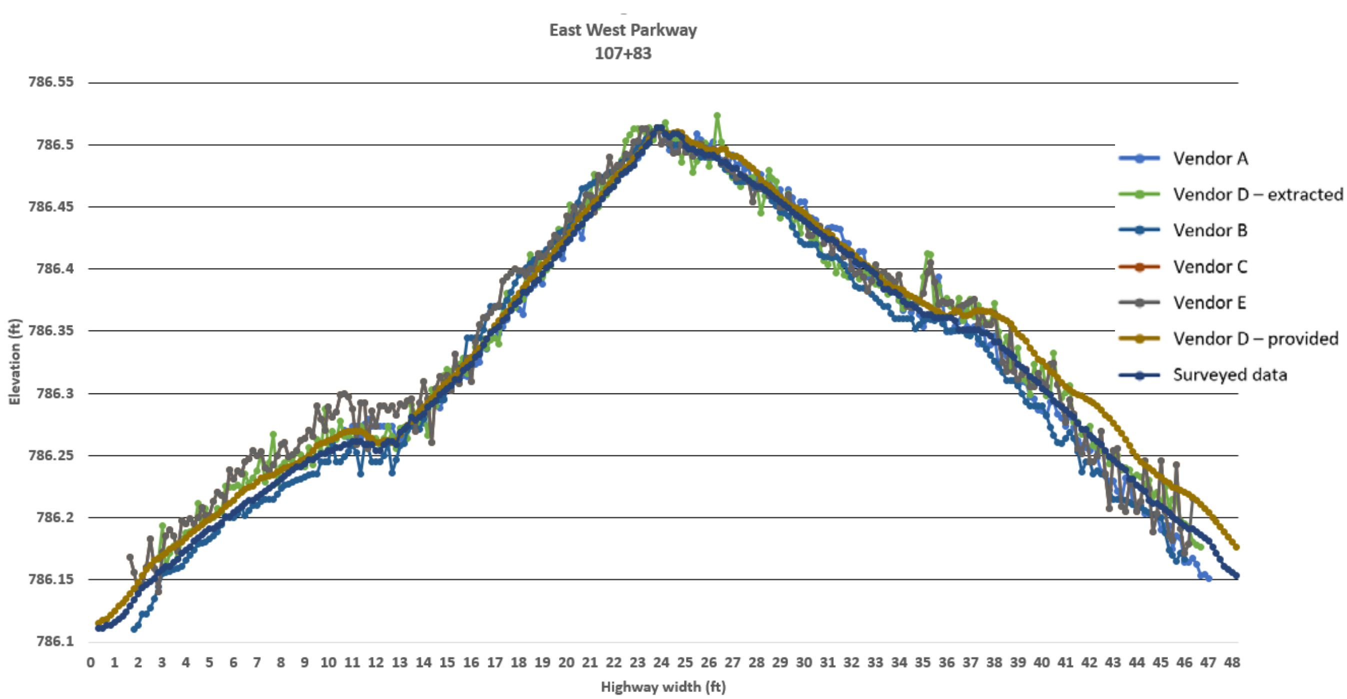

Figure 5-6 Transverse Profile Comparison

Table 5-11 Transverse Profile Comparison Between Vendors and Field Surveying (Ft)

	Vendor A	Vendor B	Vendor C	Vendor D provided	Vendor D extracted	Vendor E
MIN	0.00	0.00	0.00	0.00	0.00	0.00
MAX	0.03	0.03	0.04	0.03	0.04	0.04
MEAN	0.01	0.01	0.02	0.01	0.01	0.02
MED	0.01	0.01	0.01	0.01	0.01	0.01

5.4 Surface Analysis

Repaving, rehabilitation and pavement maintenance are routine tasks of all state and local transportation agencies including SCDOT. Compared with traditional surveying techniques, MTLS can be used to estimate material volumes needed for pavement rehabilitation and resurfacing in a cost-efficient manner and can potentially be much more accurate in pavement material volume estimates because of the resolution of the LiDAR data. In this section, we focus on the accuracy and traceability of high resolution raster surface data created from the submitted vendor LAS files. A raster surface generated from traditional survey methods (based on hundreds of points) along Section 2 is compared with raster surface data generated from the MTLS data from five vendors (based on millions/billions of points).

5.4.1 Surface Analysis Methodology

The methodology for the surface analysis involved a two-phased approach: 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 cut and fill volume differences. Typically, volumes are calculated between a finished ground surface and an existing ground surface. In our comparison, one of the vendor's raster surface was treated as existing ground and another vendor's surface was the finished ground surface. The vendor surfaces were also compared with the raster surface created using traditional surveying data. If two surfaces compared 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.

Figure 5-7 presents the workflow for the surface comparison. Raw and adjusted MTLS point cloud data were rasterized by overlapping a horizontal grid and recording the average elevation of points in each cell. The choice of grid cell size must consider LiDAR scanning density to capture sufficient detail while avoiding raster gaps (Hengl, 2006). 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 when capturing the vertical information, the space was divided into a predefined number of height levels. Points that did not fall within the target height level were ignored.

Even with careful selection of the pixel size and the number of height levels, the raster is bound to have noise (Strîmbu, 2015). 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 5) has a smoothing effect on the raster model.

$$G_{2D}(x,y;\sigma)=\frac{1}{2\pi\sigma^2}e^{-\frac{x^2+y^2}{2\sigma^2}} \quad (5)$$

In equation 5, σ determines the width of the Gaussian kernel and acts as a magnitude parameter.

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 ARCGIS 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 6 represents the volume calculated for each single cell.

$$Vol=(cell\_area)*(Z_2-Z_1) \quad (6)$$

In equation 6, Z_i represents the average elevation calculated for each cell. The cell areas used in this study were 0.01 ft., 1 ft., and 10 ft. The study used this method to compare the raster surfaces generated from the point clouds collected by the MTLS vendors. Each vendor was compared with every other vendor and also with the raster surface created using the traditional surveying data.

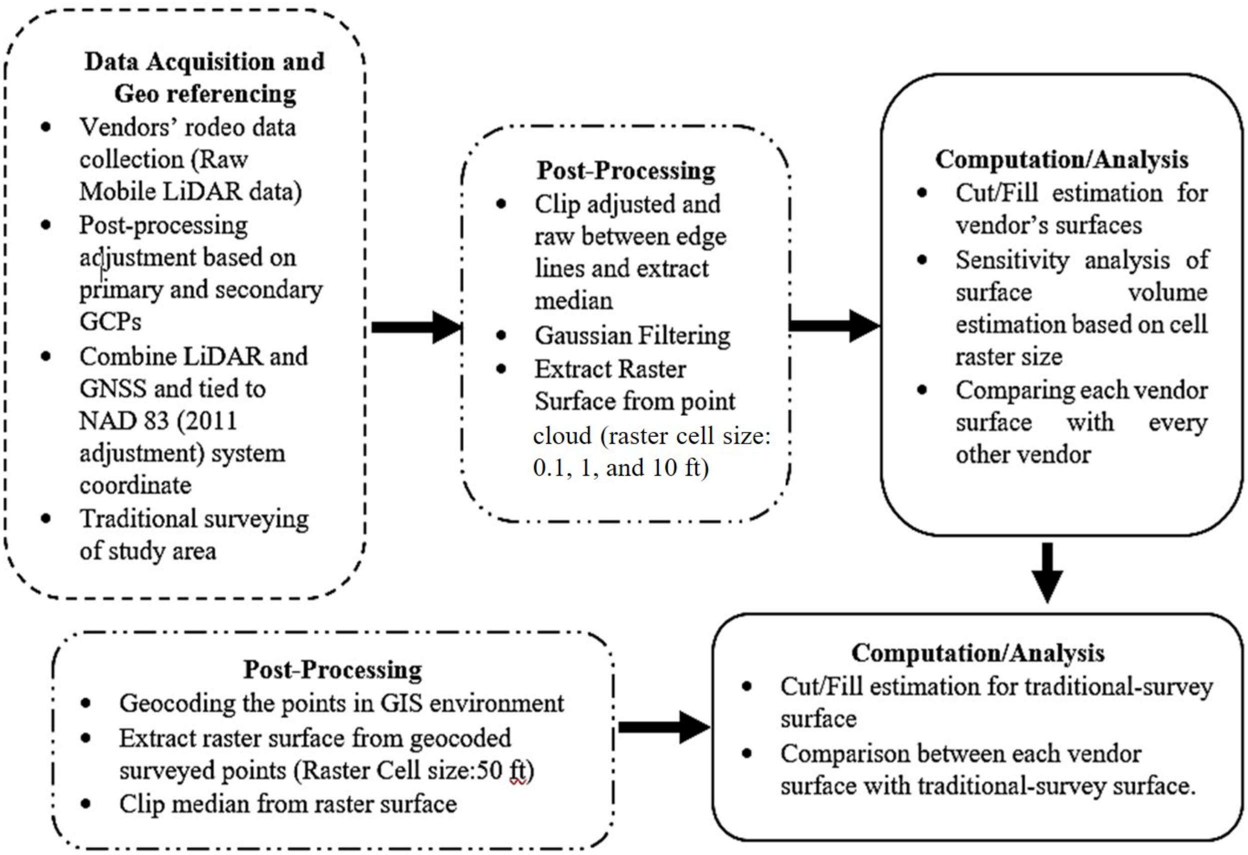

Figure 5-7 Surface Analysis Workflow

The portion of the vendor MTLS 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 the higher intensity values of pavement markings. 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. Survey instruments were placed out of the shoulder and the elevation along the white and yellow edge lines were measured as shown in Figure 5-8.

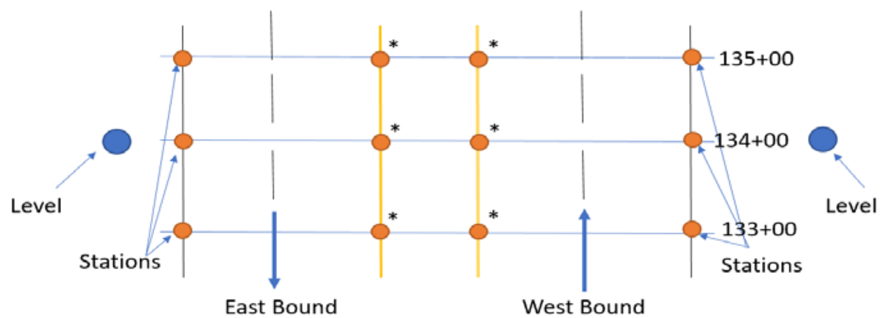

Figure 5-8 Data Collection Points for Ground Survey

5.4.2 Surface Comparison between Vendors MTLS Datasets

A comparison of the results from the vendor MTLS datasets is given in Table 5-12. The results in Table 5-12 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 0.009 inches to 0.630 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 the Vendor A 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 corresponding Vendor A LiDAR points confirmed a systematic error.

Table 5-12 MTLS Surface Comparisons-Average Surface Elevation Difference 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)*

Furthermore, the raw and calibrated surfaces for Vendor A and Vendor D were compared and the results are shown in Table 5-13. The table shows that the Vendor A 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 5-13 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 points 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 the 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 will produce noise in the MTLS data. The 1 ft. raster cell size was deemed the most suitable in terms of point density and measurement noise for use in comparing the vendor surfaces with the field surveyed surface.

While the vendors were asked to collect data by direction, they were not specifically asked to provide the data by direction. Vendor C provided the MTLS 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 MTLS 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 point cloud 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 5-14 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 eastbound 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 with 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 coincidently, the smallest difference in average elevation shown in Table 5.12 discussed previously occurs when comparing Vendor B to Vendor C. The average surface elevation difference was less than ¼ inch for all of the raster sizes (closer to 1/40 in. for the 10 ft. cell size).

Table 5-14 MTLS Surface Comparisons -Average Surface Elevation Difference 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

5.4.3 Surface Comparison between Vendors and Surveyed Data

For the comparison between vendor data and the surveyed data, only 1ft. by 1ft. raster cell sizes were used. The cell elevations for the survey data raster surface were interpolated between surveyed elevations along the white and yellow edge lines at 100 ft. station intervals. The results of the comparison between the raster surface created from the surveyed cross sections with the raster surfaces of the vendors is shown in the last column in Table 5-15. The differences between vendor surfaces are included for comparison. The results are in inches and show that the surface height differences when comparing only vendors is much closer to zero than when comparing each of the vendors surfaces to the surveyed data. The results in terms of cubic yards for the entire 2.9 miles section are shown in Table 5-16.

Table 5-15 MTLS Surface Comparisons- Average Surface Elevation Difference in Inches

	Vendor C	Vendor D	Vendor E	Surveyed Data
Vendor B	0.313 [a] 0.739 [b] 0.203 [c]	0.366 [a] 0.488 [b] 0.134 [c]	0.795 [a] 0.618 [b] 0.153 [c]	1.210 [a] 1.689 [b] 0.518 [c]
Vendor C		0.391 [a] 0.623 [b] 0.337 [c]	1.292 [a] 0.680 [b] 0.047 [c]	1.219 [a] 2.023 [b] 0.772 [c]
Vendor D			0.898 [a] 0.785 [b] 0.286 [c]	1.189 [a] 1.613 [b] 0.353 [c]
Vendor E				1.199 [a] 1.722 [b] 0.654 [c]

[a] Fill [b] Cut [c] Net

Table 5-16 MTLS Surface Comparisons-Total Volume Difference in Cubic Yards

	Vendor C	Vendor D	Vendor E	Surveyed Data
Vendor B	354.02 [a] 808.50 [b] 454.48 [c]	615.00 [a] 314.72 [b] 300.28 [c]	575.28 [a] 916.72 [b] 341.44 [c]	1068.95 [a] 2201.76 [b] 1132.81 [c]
Vendor C		240.71 [a] 994.90 [b] 754.18 [c]	1049.55 [a] 943.08 [b] 106.47 [c]	1028.35 [a] 2717.34 [b] 1688.99 [c]
Vendor D			572.10 [a] 1211.13 [b] 639.03 [c]	1169.02 [a] 1941.67 [b] 772.657 [c]
Vendor E				958.47 [a] 2389.94 [b] 1431.47 [c]

[a] Fill [b] Cut [c] Net

Table 5-17 presents the MTLS surface comparisons in pound per square yards. Although HMA density can vary based on mix design, the density rate of 145 lbs/cubic feet is assumed.

Table 5-17 MTLS Surface Comparisons (The Numbers are in PSY)

	Vendor C	**Vendor D**	**Vendor E**	**Surveyed Data**
Vendor B	17.212 [a] 39.307 [b] 22.095 [c]	29.899 [a] 15.301 [b] 14.599 [c]	27.968 [a] 44.568 [b] 16.600 [c]	51.969 [a] 107.044 [b] 55.074 [c]
Vendor C		11.702* 48.369 [b] 36.666 [c]	51.026 [a] 45.850 [b] 5.176 [c]	49.995 [a] 132.109 [b] 82.114 [c]
Vendor D			27.814* 58.882 [b] 31.068 [c]	56.834 [a] 94.398 [b] 37.564 [c]
Vendor E				46.598 [a] 116.192 [b] 69.594 [c]

[a] Fill [b] Cut [c] Net

5.4.4 Surface Comparison Summary

A summary of the surface comparisons is shown in Table 5-18. The average of the differences in the surface elevations between the surveyed raster surface and the vendor raster surfaces is much higher than the average differences between comparing the vendors only in terms of net, fill, and cut volumes. Note that the cubic yard values are for the entire 2.9 mile section. The magnitude of the differences indicates that the vendor raster surfaces are much more accurate representing the actual surface than the surveyed surface. The inaccuracy of the surveyed surface 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, pavement seams, and alignment variations between cross sections. The accuracy that can be achieved using an MTLS raster surface to calculate materials volume will result in more accurate materials and cost estimates and a significant per lane-mile cost savings.

Table 5-18 Summary of Surface's Comparison

Average Difference in Surfaces		Inches	Cubic Yards	PSY
Between Vendors only	Fill	0.676	567.777	27.603
	Cut	0.656	864.841	42.046
	Net	0.193	432.648	21.034
Between Vendors and Surveyed	Fill	1.204	1056.196	51.349
	Cut	1.762	2312.678	112.436
	Net	0.574	1256.483	61.087

5.5 Horizontal and Vertical Alignment Comparison with Surveyed Data, Test Section 2

As previously described, Test Section 2 is located along a 2.9 mile length of East West Parkway in Anderson, SC, and can be categorized as having a rolling vertical profile, which includes a total of 14 vertical curves. Furthermore, this roadway Test Section can be characterized as extending along an aesthetically flowing curvilinear horizontal geometric alignment which includes a total of 7 horizontal curves. Collection of MTLS point cloud data along Test Section 2, allows determination of geometric variables to define both the vertical and horizontal alignments through post processing MTLS point clouds using differential control points and other known station locations. These results are compared and discussed for relative accuracy and evaluated against as-built geometric data obtained using conventional survey methods. The following report sections provide a series of analytical and visual comparisons of vendor collected geometric data to evaluate accuracy of MTLS point cloud data and potential for determining accurate estimates for roadway geometric variables.

5.5.1 Horizontal Alignment

All participating vendors provided roadway geometric alignment data. However, only three participating vendors provided roadway centerline, horizontal alignment data, in the requested format. Horizontal alignment comparisons were performed using curvature data obtained from the roadway centerline provided by each of the three compliant vendors. A visual comparison of horizontal centerlines extending along the 2.9 mile Test Section is provided in Figure 5-9. Please see Appendix E for additional centerline comparisons. Additional data deemed relevant, for comparison purposes, was extracted from the submitted LAS files for each of the roadway centerlines. A forth vendor provided some roadway centerline geometry data; however, their data did not comply with horizontal alignment submittal requirements and meaningful comparisons were not possible. Therefore, this data is not included.

Horizontal alignment elements compared include: radius (R), curve length (L), tangent length (T), horizontal point of curvature (PC), horizontal point of intersection (PI) and horizontal point of tangency (PT). The following discussion regarding elements compared offers some insight into measurement discrepancies observed.

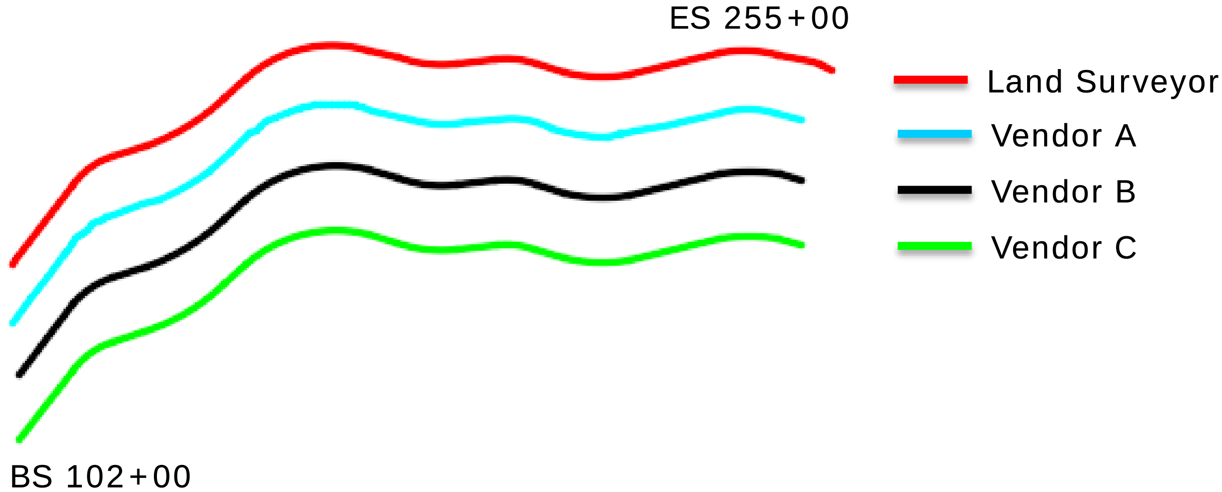

Figure 5-9 Roadway Centerline Geometry Comparisons

Radii (R) – The circular curve radii were relatively consistent throughout all horizontal curves for Vendors B and C. Vendor A appeared to have experienced some issues with respect to consistency and data quality, a plausible cause could have resulted from instrument calibration issues. Table 5-19 summarizes recorded radii measurements. Table 5-20 provides accuracy variations with respect to Survey/AS-BUILT horizontal alignment data.

Table 5-19 Radii Comparison

	Survey/AS-BUILT (Baseline)	Vendor A	Vendor B	Vendor C
Type	**Radius**	**Radius**	**Radius**	**Radius**
Curve 1	1432.41	1667.71	1443.13	1487.50
Curve 2	3819.72	3829.81	3828.80	3829.97
Curve 3	2291.83	2311.49	2291.89	2280.00
Curve 4	2864.79	2297.29	2863.23	2900.00
Curve 5	1909.86	3132.17	1908.05	1875.00
Curve 6	2291.83	2360.71	2291.41	2319.99
Curve 7	2291.83	2574.22	2278.25	2250.00

Table 5-20 Radii Measurement Accuracy Variations Using Mobile Lidar

	Vendor A	Vendor B	Vendor C
Type	**Radius 2**	**Radius 3**	**Radius 4**
Curve 1	235.3	10.7	55.1
Curve 2	10.1	9.1	10.3
Curve 3	19.7	0.1	-11.8
Curve 4	-567.5	-1.6	35.2
Curve 5	1222.3	-1.8	-34.9
Curve 6	68.9	-0.4	28.2
Curve 7	282.4	-13.6	-41.8

Curve Length (L) – Curve length values, shown in Table 5-21 and 5-22, were also consistent throughout the horizontal alignment for Vendors B and C with respect to Survey/AS-BUILT horizontal alignment data. However, Vendor A inconsistencies were apparent and accuracy problems were evident for all horizontal curvature elements, resulting in most curve lengths being off by as much as a few hundred feet.

Tangent (T) – Tangent lengths, shown in Table 5-21 and 5-22, from Survey/AS-BUILT and Vendors B and C were within a 36-feet error; whereas, data provided by Vendor A showed discrepancies greater than 150 feet on three occasions and nearly 80 feet on two occasions.

Table 5-21 Horizontal Curve 1 Data Caparison, Accuracy and Percent Difference

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Survey/AS-BUILT (Baseline)	1	Curve	857.35	1432.41	441.95	117+67.47	122+09.42	126+24.82
Vendor A	1	Curve	1000.29	1667.71	515.70	115+00.01	120+15.71	125+00.30
Vendor B	1	Curve	857.35	1443.13	441.75	117+72.07	122+13.82	126+29.42
Vendor C	1	Curve	889.56	1487.50	458.53	117+39.19	121+97.72	126+28.75

Table 5-22 Horizontal Curve Component Measurement Accuracy Using Mobile Lidar

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Vendor A	1	Curve	142.9	235.3	73.8	-267.5	-193.7	-124.5
Vendor B	1	Curve	0.0	10.7	-0.2	4.6	4.4	4.6
Vendor C	1	Curve	32.2	55.1	16.6	-28.3	-11.7	3.9

Table 5-23 Percent Change Difference between Measurements

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Vendor A	1	Curve	16.67%	16.43%	16.69%	2.27%	1.59%	0.99%
Vendor B	1	Curve	0.00%	0.75%	0.05%	0.04%	0.04%	0.04%
Vendor C	1	Curve	3.76%	3.85%	3.75%	0.24%	0.10%	0.03%

If the curve for the participant that varied the most, Vendor A, is removed from the comparative analysis, the resulting average absolute errors vary as follows: curve length varies from the baseline by 1.88%, radius of curvature varies by 2.3%, and tangent length varies by 1.9%. Stations of the PC, PI, and PT vary from the reference by average absolute errors of 0.14%, 0.07%, and 0.035%, respectively. Precisions ranged between 96% and 100%.

Table 5-24 Horizontal Curve 2 Data

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Survey/AS-BUILT (Baseline)	2	Curve	1630.10	3819.72	827.65	132+39.17	140+66.82	148+96.26
Vendor A	2	Curve	1000.15	3829.81	502.93	135+00.01	140+02.94	145+00.15
Vendor B	2	Curve	1629.55	3828.80	827.30	132+35.94	140+63.24	148+65.49
Vendor C	2	Curve	1614.92	3829.97	819.64	132+33.68	140+53.32	148+48.60

Table 5-25 Horizontal Curve Component Measurement Accuracy Using Mobile Lidar

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Vendor A	2	Curve	-629.9	10.1	-324.7	260.8	-63.9	-396.1
Vendor B	2	Curve	-0.5	9.1	-0.3	-3.2	-3.6	-30.8
Vendor C	2	Curve	-15.2	10.3	-8.0	-5.5	-13.5	-47.7

Table 5-26 Percent Change Difference between Measurements

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Vendor A	2	Curve	38.64%	0.26%	39.23%	1.97%	0.45%	2.66%
Vendor B	2	Curve	0.03%	0.24%	0.04%	0.02%	0.03%	0.21%
Vendor C	2	Curve	0.93%	0.27%	0.97%	0.04%	0.10%	0.32%

Similarly, in the comparison table for curve 2, if the curve for the participant that varied the most, Vendor A, is removed from the analysis, the resulting average absolute errors vary as follows:

Curve length varies from the reference by 0.48%, radius of curvature varies by 0.26%, and tangent length varies by 0.51%. Station of the point of curvature varies by 0.03%, point of intersection varies by 0.07%, and point of tangency varies by 0.27%. Hence, the research team found that precisions for curve 2 were greater than 99%.

Centerline Stationing – The research teams found that most inconsistencies discussed above may have been caused primarily due to minor stationing errors generated by the automated data collection equipment. All participants used equipment with different specifications, which explains some of the inconsistencies observed. Data provided by all vendors showed some stationing error. Curves 1 and 2, for instance, presented below, show how vendors A, B and C vary from the reference, Survey/AS-BUILT horizontal alignment data, as well as from one another.

Additional horizontal curve comparisons are included in Appendix G.

5.5.2 Vertical Alignment

Complete vertical alignment data, in the format that was requested, was only provided by one of the vendors participating in the rodeo. Nevertheless, since most vendors provided centerline geometric data, as discussed in the previous section, the research team was able to extract vertical profile and vertical curve parameters directly from these data source. Best-fit vertical alignments were created using the roadway centerline and a TIN surface based on surveyed coordinates at stations established along the roadway edge lines. A total of 14 vertical curves were observed, as shown below in Figure 5-10.

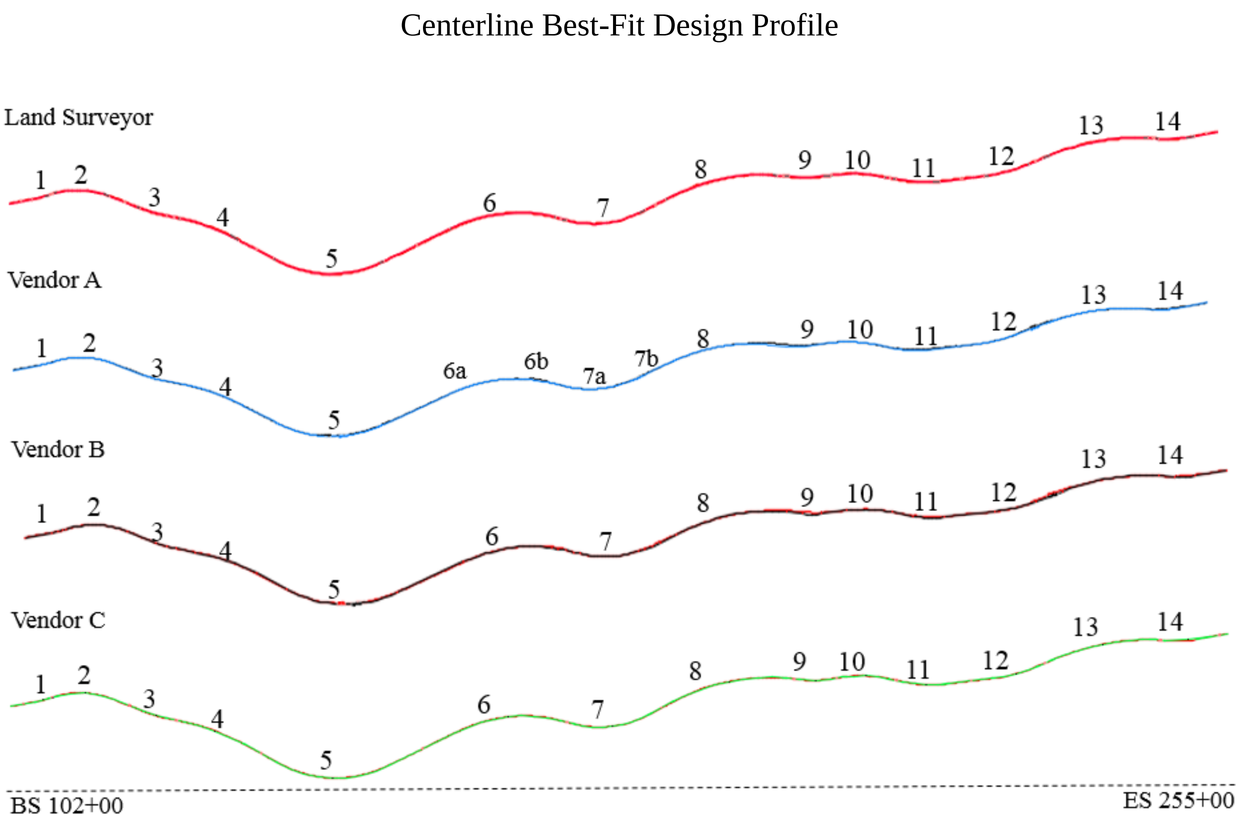

Figure 5-10 Centerline Best-Fit Design Profile View with Curve Numbers

Vertical curve variables for each vertical curve was extracted using existing tangent grades and resulting best-fit design grades. Observed lowest and highest elevations were 676.61 feet and 853.22 feet, respectively. Through evaluation of results, the research team found most of the profile data elements from all vendors contained only minor discrepancies, with average accuracy levels higher than those of the horizontal alignment data. In evaluating data for Vertical Curves 1 and 2, shown in Table 5-27 and 5-28, useful insight into measurement discrepancies can be readily observed, which is representative of all other portions of the alignment.

Table 5-27 Vertical Curve 1 Data

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Land Surveyor (Baseline)	1	Sag	152.69	105+76.90	780.00	106+53.24	781.32	107+29.59	783.36	1.73%	2.67%	0.95%
Vendor A	1	Sag	182.02	105+14.57	780.01	106+05.58	781.61	106+96.59	784.07	1.76%	2.70%	0.94%
Vendor B	1	Sag	150	105+42.73	780.48	106+17.73	781.79	106+92.73	783.98	1.74%	2.93%	1.18%
Vendor C	1	Sag	175.14	105+13.88	780.01	106+01.45	781.53	106+89.02	783.87	1.74%	2.67%	0.93%

Table 5-28 Vertical Curve Component Measurement Accuracy Using Mobile Lidar

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation
Vendor A	1	Sag	29.33	-62.33	0.01	-47.66	0.29	-33.00	0.71
Vendor B	1	Sag	-2.69	-34.17	0.48	-35.51	0.47	-36.86	0.62
Vendor C	1	Sag	22.45	-63.02	0.01	-51.79	0.21	-40.57	0.51

Table 5-29 Percent Change Difference between Measurements

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Vendor A	1	Sag	19.21%	0.59%	0.00%	0.45%	0.04%	0.31%	0.09%	1.73%	1.12%	1.05%
Vendor B	1	Sag	1.76%	0.32%	0.06%	0.33%	0.06%	0.34%	0.08%	0.80%	9.60%	24.49%
Vendor C	1	Sag	14.70%	0.60%	0.00%	0.49%	0.03%	0.38%	0.07%	0.58%	0.00%	2.11%

Results from all vendors were consistent for most components of the vertical alignment in all curves. In Vertical Curve 1, for instance, without excluding data from the components that varied the most, the resulting average absolute errors varied as follows: Profile curve length varied from the baseline by an average absolute error of 11.89%, PVC station varied by 0.50%, PVC elevation varied by 0.02%, PVI station varied by 0.42%, PVI elevation varied by 0.04%, PVT station varied by 0.34%, and PVT elevation varied by 0.08%. Grade in, grade out and grade change varied by 1.04%, 3.57%, and 9.22%, respectively. Except for the results for profile curve length, grade out and grade change, the research team found that the average precision for most components were within 98% and 99.9%. While this sounds high, this corresponds to a surveying precision of 1:50 to 1:1000 which is general order precision or less.

Table 5-30 Vertical Curve 2 Data

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Land Surveyor (Baseline)	2	Crest	755.80	107+91.76	785.02	111+69.67	795.12	115+47.57	782.16	2.67%	-3.43%	-6.10%
Vendor A	2	Crest	738.15	107+55.30	785.66	111+24.37	795.63	114+93.44	782.41	2.70%	-3.58%	-6.28%
Vendor B	2	Crest	775	107+26.48	784.97	111+13.98	796.31	115+01.48	782.10	2.93%	-3.67%	-6.59%
Vendor C	2	Crest	742.68	107+54.56	785.62	111+25.90	795.53	114+97.24	782.21	2.67%	-3.59%	-6.26%

Table 5-31 Vertical Curve Component Measurement Accuracy Using Mobile Lidar

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation
Vendor A	2	Crest	-17.65	-36.46	0.64	-45.30	0.51	-54.13	0.25
Vendor B	2	Crest	19.20	-65.28	-0.05	-55.69	1.19	-46.09	-0.06
Vendor C	2	Crest	-13.12	-37.20	0.60	-43.77	0.41	-50.33	0.05

Table 5-32 Percent Change Difference between Measurements

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Vendor A	2	Crest	2.34%	0.34%	0.08%	0.41%	0.06%	0.47%	0.03%	1.12%	4.37%	2.95%
Vendor B	2	Crest	2.54%	0.60%	0.01%	0.50%	0.15%	0.40%	0.01%	9.61%	6.90%	8.09%
Vendor C	2	Crest	1.74%	0.34%	0.08%	0.39%	0.05%	0.44%	0.01%	0.00%	4.66%	2.62%

Similarly, in Vertical Curve 2, without excluding from the analysis data from the components that varied the most, the resulting average absolute errors varied as follows: profile curve length varied from the baseline by an average absolute error of 2.21%, PVC station varied by 0.43%, PVC elevation varied by 0.06%, PVI station varied by 0.43%, PVI elevation varied by 0.09%, PVT station varied by 0.44%, and PVT elevation varied by 0.02%. Grade in, grade out and grade change varied by 3.58%, 5.31%, and 4.55%, respectively. Average precisions for most components were within 96% and 99.9%.

Additional vertical curve comparisons are included in Appendix G.

5.6 Mobile Lidar Costs

The vendors provided very limited cost data associated with mobile LiDAR collection. An estimate to collect data of $100 per mile is deemed reasonable based on the information provided however this cost would be much higher for short segments or if the request for additional attributes or processing is limited. Breakline extraction and manual drafting would add another $150 per lane mile but this can run higher depending on the physical features of the roadway (e.g., presence of curb and gutter, and sidewalk). Cross section sampling from breaklines is automated and would add little additional cost. Mobilization costs are not included in the estimate above. Typical MTLS studies require one pass for each direction. Depending on the application, additional passes may be needed—especially for roads with greater than two lanes per direction.

For design work to achieve improved absolute accuracy MTLS will require a ground control survey that can add significantly to the overall costs. However, for applications where absolute accuracy is not critical or if relative accuracy is of greatest importance a ground control survey may not be necessary.

For this research, an estimation of time requirements for collection, processing, and reporting for the three mile section of East West Parkway is provided in Table 5-33. The end product of these time estimates is the extraction of cross slope information. Extraction of other elements from the point cloud would add additional time. The estimate indicates that the time spent by the survey crew for locating the primary GCPs and establishing the secondary GCPs was greater than the time spent on collecting and processing the MTLS data. The surveying only estimate includes additional surveying along the pavement marking edge lines and the leveling work plus additional time in the office to create model and extract cross sections. The estimate indicates that there is a 40% time savings using MTLS to extract cross sections over conventional surveying alone. It is likely that even greater savings can be experienced for longer sections of roadway where the additional mileage does not require a proportional increase in time.

Table 5-33 Data Collection, Processing & Reporting Time Estimates for East West Pkwy

MTLS: The number of man-hours per work task for all activities for the MTLS process:		
	Planning	4 hours
	On-Site Planning	2 hours
	Scan Data Calibration and Acquisition	2 hours
	Scan Data Processing	2 hours
	LAS Data & Image Export	4 hours
	LAS Data Adjustment	4 hours
	CAD Work/Breakline/Extraction/DTM/GIS	14 hours
	Cross Section Sampling	2 hours
	Reporting	4 hours
	Ground Control Surveying (All Activities)	50 hours
	Total	88 hours
Surveying only:		
	All Surveying including office work	125 hours

For comparison purposes, the researchers identified a study conducted by Iowa DOT (IDOT) that looked at the point accuracy of MTLS compared to conventional surveying for use in highway improvement projects at IDOT (Miller at al. 2012). The comparison was done between 1823 points on the pavement that were surveyed by Iowa DOT staff using a total station and the same points generated through the MTLS process. The data acquired through the MTLS and data processing met the IDOT specifications for engineering survey. The project area selected for evaluation was the Interstate 35/Iowa State Route 92 interchange in Warren County, Iowa. This project covered approximately one mile of I-35, one mile of IA 92, 4 interchange ramps, and bridges within these limits. The time estimates for that study are shown in Table 5-34. It indicates that MTLS required greater time resources than conventional surveying.

Table 5-34 MTLS Time Estimates

MTLS: The number of hours per work task for all activities for the MTLS process:	
Planning	**22 hours**
Travel & Logistics	**34 hours**
On-Site Planning	**16 hours**
Scan Dta Acquisition	**16 hours**
On-Site Pre-Processing	**12 hours**
Trajectory Processing & Reporting	**8 hours**
Scan Data Processing, Adjustment & Reporting	**16 hours**
LAS Data& Image Export	**12 hours**
LAS Data Q/C & Refinement	**16 hours**
Data Extraction	**140 hours**
CAD Formatting	**16 hours**
DTM Development	**6 hours**
Final Reports	**24 hours**
Data Assembly & Delivery	**8 hours**
Total	**318 hours**
Total Station Survey: All field and office activities Total	**260 hours**

CHAPTER 6 : MOBILE LIDAR VALIDATION SITE TEST PROCEDURES

This chapter summarizes test procedures and specification criteria for the purpose of using East West Parkway (Study Section 2 of this research) in Anderson, SC as a Mobile LiDAR validation site for vendor pre-qualification. Mobile LiDAR data submittal and extraction procedures are described, along with details for Ground Control Points (GCP), pavement cross sections, horizontal alignment, vertical alignment, traverse profile data, and roadway attribute data. The procedures and specification criteria were developed based on lessons learned from the vendor rodeo. The intent of developing these procedures is to establish a reliable method which can be adopted by SCDOT to address the ongoing need of pre-qualifying prospective Mobile LiDAR vendors.

6.1 Site Description

The test site location is a 2.9-mile corridor along East West Parkway (EW Pkwy) in Anderson, SC shown in Figure 6-1. The study section originates at US-76 (Clemson Boulevard) and terminates at SC-81 (E Greenville St). EW Pkwy is a limited access 4-lane, 2-way, mostly divided highway. The suburban segment includes a variety of geometric design elements including: 15-vertical curves, 7-horizontal curves (all containing superelevation), one-bridge, two-intersections, traversable and non-traversable medians, two-lanes per direction, additional turn lanes at intersections, and sections with adjacent bike lanes and separate shared use path.

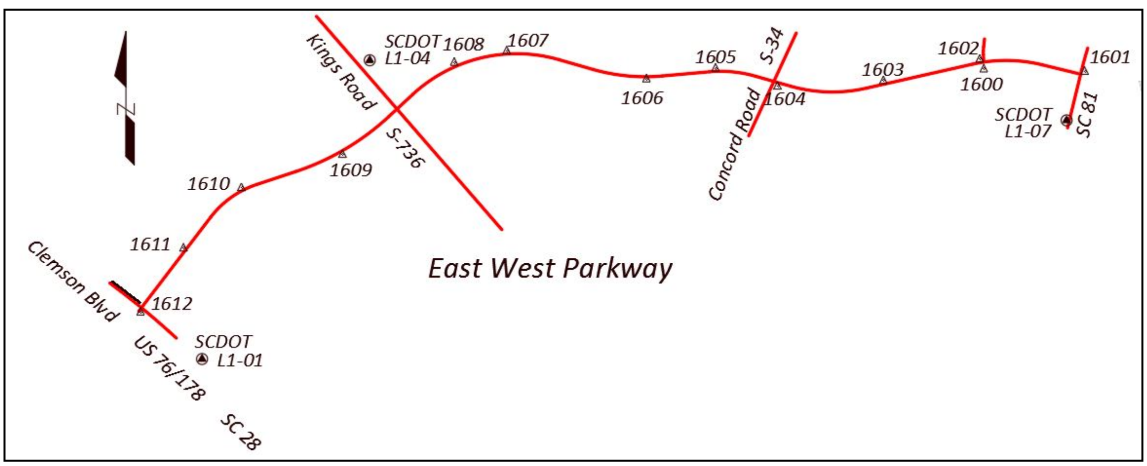

Figure 6-1 GCPs and check point along Clemson Boulevard and East West Parkway

6.2 Site Target Coordinates

Painted station centerline target coordinates near the beginning and end of the section are provided in Table 6-1 with accompanying station and mile point locations for use in identifying line and point attribute data along the test section in each direction. The painted targets are marked with PK nails and paint in the field (example shown in Figure 6-2).

Table 6-1 East West Parkway Painted Station Centerline Target Coordinates

N 992,432.67'	**N 995,853.50'**
E 1,495,960.48'	**E 1,509,784.45'**
Elev. = 774.50'	**Elev. = 857.14'**
(Station 102+00)	**(Station 255+00)**
(Assigned mile point 0.00)	**(Assigned mile point 2.90)**

Figure 6-2 Painted target with PK nail in center

6.3 Site Attribute List

In addition to cross slope data collection using MTLS, a variety of other attributes can be collected along this route as identified in Table 6-2. For asset management purposes, vendors should provide line attribute and point attribute data in terms of station locations and direction as shown in Table 6-2. Additional information about attribute data will be included in the SCDOT Asset Management research project final report.

Table 6-2 Line and Point Attribute Data Along the Test Section

<table>
<tr><td colspan="4">Line Attributes
1. Driveways
2. Barrier Systems (Types: Cable, W-beam, Tri-beam, concrete, crash cushion, or other)
3. Medians (types are Raised, TWLTL, Natural, Turn-lane, Barrier, Undivided, Painted)
4. Bridge Decks
5. Travel Lane Width and Shoulder Width
6. Intersections
7. Adjacent Sidewalk/Shared Path (Types: Sidewalk, Asphalt path, crosswalk, other)</td></tr>
<tr><td>ID No.</td><td>Start Station</td><td>End Station</td><td>Direction</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="4">Point Attributes
1. Ground Mounted Signs
2. Street Lighting Poles
3. Utility Poles
4. Manholes
5. Fire Hydrants
6. Individual Pavement Markings
7. Mailboxes
8. Spot Samples of Longitudinal Pavement Marking Retroreflectivity (including 30m Retroreflectivity Value, amplitude, or intensity)</td></tr>
<tr><td>ID No.</td><td>X Coordinate (Easting)</td><td>Y Coordinate (Northing)</td><td>Direction</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
</table>

6.4 Test Site Maintenance and Preparation

Prior to a vendor MTLS run, site preparation is necessary to ensure a fair evaluation. Primary and secondary GCPs (Figure 6-1) should be located, and missing or deteriorated survey stakes should be replaced. Reflective pavement marking tape and painted station labels should be inspected to ensure that they are readable and that the tape has not been displaced or damaged. Station locations are at 100 ft. intervals and are located along the white edge lines on both sides of the roadway. They are delineated with PK nails and reflective pavement marking tape as shown in Figure 6-3. New tape should be placed as appropriate in the shape and orientation as shown in the figure. Other preparation includes range pole setups at selected secondary control points (1600, 1603, 1608, and 1609), and placement of traffic cones at the transverse profile location (station 107+83).

Figure 6-3 Pavement Marking Tape Orientation and Station Label

6.5 Vendor Instructions and Coordination

Pre-data collection instructions and coordination should include a site review, locations of ground control points, data submittal requirements, procedures for mobile collection, and traffic control requirements to obtain comparable results. All MTLS vendors would need to obtain specific instructions and coordinate data collection with SCDOT beforehand. SCDOT needs to ensure reflective pavement tape is in place, traverse profile marked with cones, and range poles are in place before data collection begins. Vendors should be provided with primary GCP locations and corresponding coordinate data. Vendors should also be encouraged to use at least two base station GPS units for differential correction in the area or alternatively, a virtual Reference Station (VRS) could be used at the vendor's discretion. South Carolina operates a VRS real-time network, for more information refer to *http://rfa.sc.gov/geodetic/rtnstatus*. Vendors who desire to use SC VRS would need to make necessary arrangements for secure access.

Station location coordinates at 500 ft. station intervals are given in Table 6-3. These can be provided to the vendor for post process adjustment purposes or withheld for comparison purposes. Primary and secondary GCP point locations (except for the range pole locations) should be provided to the vendors for adjustment purposes.

Table 6-3 Station Coordinates for 500' Station locations

	LEFT			RIGHT		
Station	**North**	**East**	**Elevation**	**North**	**East**	**Elevation**
105+00	992,688.30	1,496,120.26	778.98	992,652.53	1,496,167.07	779.29
110+00	993,079.03	1,496,432.41	789.39	993,049.73	1,496,470.67	789.40
115+00	993,480.67	1,496,730.31	781.80	993,442.36	1,496,780.38	781.55
120+00	993,869.38	1,497,051.63	765.83	993,823.53	1,497,094.85	763.00
125+00	994,148.16	1,497,476.63	755.92	994,090.33	1,497,501.49	752.95
130+00	994,311.54	1,497,951.90	737.10	994,251.36	1,497,971.82	737.21
135+00	994,476.08	1,498,421.62	712.65	994,417.46	1,498,445.55	714.26
140+00	994,693.17	1,498,867.29	695.03	994,638.12	1,498,898.44	696.57
145+00	994,965.85	1,499,281.08	694.06	994,916.36	1,499,318.43	695.55
150+00	995,289.97	1,499,657.60	709.43	995,244.15	1,499,699.85	709.97
155+00	995,628.91	1,500,027.64	733.28	995,579.40	1,500,068.11	731.18
160+00	995,903.83	1,500,452.33	754.10	995,847.20	1,500,480.96	751.91
165+00	996,080.81	1,500,926.15	764.43	996,020.52	1,500,941.55	762.16
170+00	996,151.68	1,501,426.87	761.96	996,089.42	1,501,428.82	759.72
175+00	996,112.78	1,501,931.12	752.70	996,051.50	1,501,919.55	750.43
180+00	995,984.44	1,502,417.24	756.37	995,923.71	1,502,399.88	756.44
185+00	995,858.69	1,502,898.60	777.61	995,797.40	1,502,886.99	779.36
190+00	995,809.07	1,503,389.94	796.48	995,746.79	1,503,389.19	798.26
195+00	995,838.06	1,503,885.66	805.91	995,776.82	1,503,891.07	806.04
200+00	995,882.23	1,504,383.78	806.91	995,820.88	1,504,389.13	805.15
205+00	995,860.08	1,504,889.95	806.77	995,798.90	1,504,879.13	804.21
210+00	995,734.10	1,505,376.84	808.22	995,671.68	1,505,359.11	808.61
215+00	995,610.71	1,505,857.26	799.94	995,548.85	1,505,847.04	801.98
220+00	995,583.49	1,506,348.81	799.14	995,521.48	1,506,352.17	801.24
225+00	995,661.27	1,506,836.63	805.12	995,600.61	1,506,850.34	805.88
230+00	995,771.56	1,507,324.26	815.78	995,710.64	1,507,338.04	815.72
235+00	995,881.59	1,507,812.10	833.99	995.820.54	1,507,825.91	833.97
240+00	995,991.86	1,508,299.80	846,86	995,931.13	1,508,313.49	845.57
245+00	996,052.30	1,508,801.70	851.06	995,989.77	1,508,802.39	848.79
250+00	996,001.98	1,509,305.02	850.09	995,941.02	1,509,292.15	847.92
255+00	995,884.73	1,509,792.07	856.55	995,824.13	1,506,777.24	856.40

6.6 Evaluation Criteria

Evaluation criteria should be communicated to the MTLS vendors prior to data collection. The vendors will be required to evaluate the test site location based on a variety of criteria including:

- 3-D coordinate accuracy of selected reflective pavement tape locations at 100 ft. station intervals
- Selected secondary survey GCP locations delineated with range poles
- Comparison of mobile system cross sections with conventionally surveyed cross sections

Locations for desired cross sections are at Stations 110, 124, 128, 149, 203, 208, 227, and 232. An additional cross slope section located at station 107+83 requires Mobile LiDAR to provide comparison of data at 2 in. spacing intervals to allow creation of a more detailed transverse profile.

6.7 Mobile LiDAR Data Collection Procedures

MTLS vendors will need time to calibrate their systems on site prior to collection. Vendors will need to set up one or more GPS base stations prior to making their data collection runs. Base stations may be set up at available GCP point locations. Specific requirements are identified in Table 6-4. During data collection, they should make a single pass in each direction through the test site location. Vendors should be instructed to travel in the right most lane except when making a U-Turn at the end of the East West Parkway section. They should also be expected to travel at the posted speed limit. By following the same trajectory, fair comparisons can be made. Data collection runs can be repeated if vendors experience technical difficulty; however, only data from a single run should be accepted and used in evaluating results.

Table 6-4 Summary of Data Collection Procedures and Requirements

Easting, Northing, and Elevation at SCPs 1600, 1603, 1608, and 1609 **Vendor Mobile LiDAR data will be submitted for comparison with surveyed secondary control points labeled 1600, 1603, 1608, and 1609 on East West Parkway, see Figure 5-3. These locations will be identified using range poles when mobile LiDAR data was collected. Vendors should provide coordinates at the TOP of each range pole.**
Cross slope information at 8 station locations **Locations for desired roadway cross section data are as follows: Stations 110+00, 124+00, 128+00, 149+00, 203+00, 208+00, 227+00, and 232+00. Location are marked with yellow reflective tape. Format is flexible. Cross slopes should be provided in % grade for each lane, sidewalks and/or multiuse path. Grades can be calculated by the equation (change in elevation/lane width)*100. Vendors should also provide an AutoCAD or Microstation cross section drawing so the entire cross section including lanes, shoulders, foreslopes, backslopes, etc. can be evaluated.**
Complete transverse profile at station 107+83 **One specific roadway cross sections with surface irregularity was surveyed at 2” spacing to provide a more detailed transverse profile at station 107+83, marked with cones and transverse yellow pavement marking tape. Vendors should provide an AutoCAD or Microstation cross section drawing that includes all LAS formatted points along this cross section.**
Plan view of the roadway centerline **Vendors should provide a digital centerline file in AutoCAD or Microstation format that includes tangent lines and circular curves. Stationing is encouraged but not required.**
Profile view of the roadway centerline **Vendors should provide a centerline profile in AutoCAD or Microstation format as profile grades and parabolic vertical curves.**
3-D breaklines along longitudinal pavement markings **Vendors should provide breaklines that follow longitudinal pavement markings in an AutoCAD or Microstation format.**
Digital snapshot of sample photolog and corresponding laser data

6.8 MTLS Data Submittal Requirements

A description of required submittals by vendors is included in Appendix D (Quick Reference for Submitting Results). SCDOT should provide excel templates to vendors to use in submittal of required information and attribute data. MTLS Vendors should be required to provide equipment specifications and an adjusted point cloud with typical LiDAR attributes (e.g., elevation, amplitude/intensity) in ASPRS LAS format. Vendors should also provide the manufacturer and model for all equipment to be provided including specifications regarding GPS positioning, inertial measurement unit (IMU), LiDAR units, and digital cameras. In the event vendor vehicles include a pavement profiler, those specifications should also be included.

Vendors should also provide a rectified point cloud using GCPs. Whereas the test site location has numerous planimetric features, only a limited number of items identified in the quick reference should be requested. However, vendors should be asked to voluntarily provide additional attributes if they have an automated means to.

As currently envisioned, pavement condition data would not be required. Vendors should be notified that if they have the capability to collect pavement condition data this would be encouraged. Ideally pavement condition data should include IRI, rutting depth, fatigue cracking, longitudinal cracking, and transverse cracking. Raveling, patching percentage, and/or any other commonly collected asphalt distresses are additional attributes vendors could provide voluntarily. The data summary interval should be 0.1 miles. Any downward images (especially with distresses marked) would also be of interest, if available.

6.9 Mobile LiDAR Comparison and Standards

Mobile LiDAR evaluation criterion would include the ease that cross slope data can be extracted from the point cloud at the cross-section locations. Vendors should provide a workflow on how this is accomplished. The ability to accurately link photologged images with the LiDAR data must be evaluated. Adjacent lane/direction accuracy should also be evaluated, as well as the ability to collect shoulder, median, and clear-zone slopes. Finally, vendors should be asked to provide the level of data extraction automation. These levels include fully automated, semi-automated, or manual data extraction. Vendors should provide extractions and qualitatively discuss how this is done. In particular, vendors should demonstrate and/or describe their ability to extract roadway asset attributes from their MTLS data.

See Figure 6-4, for the process summarizing use of this test site to pre-qualify Mobile LiDAR Vendors.

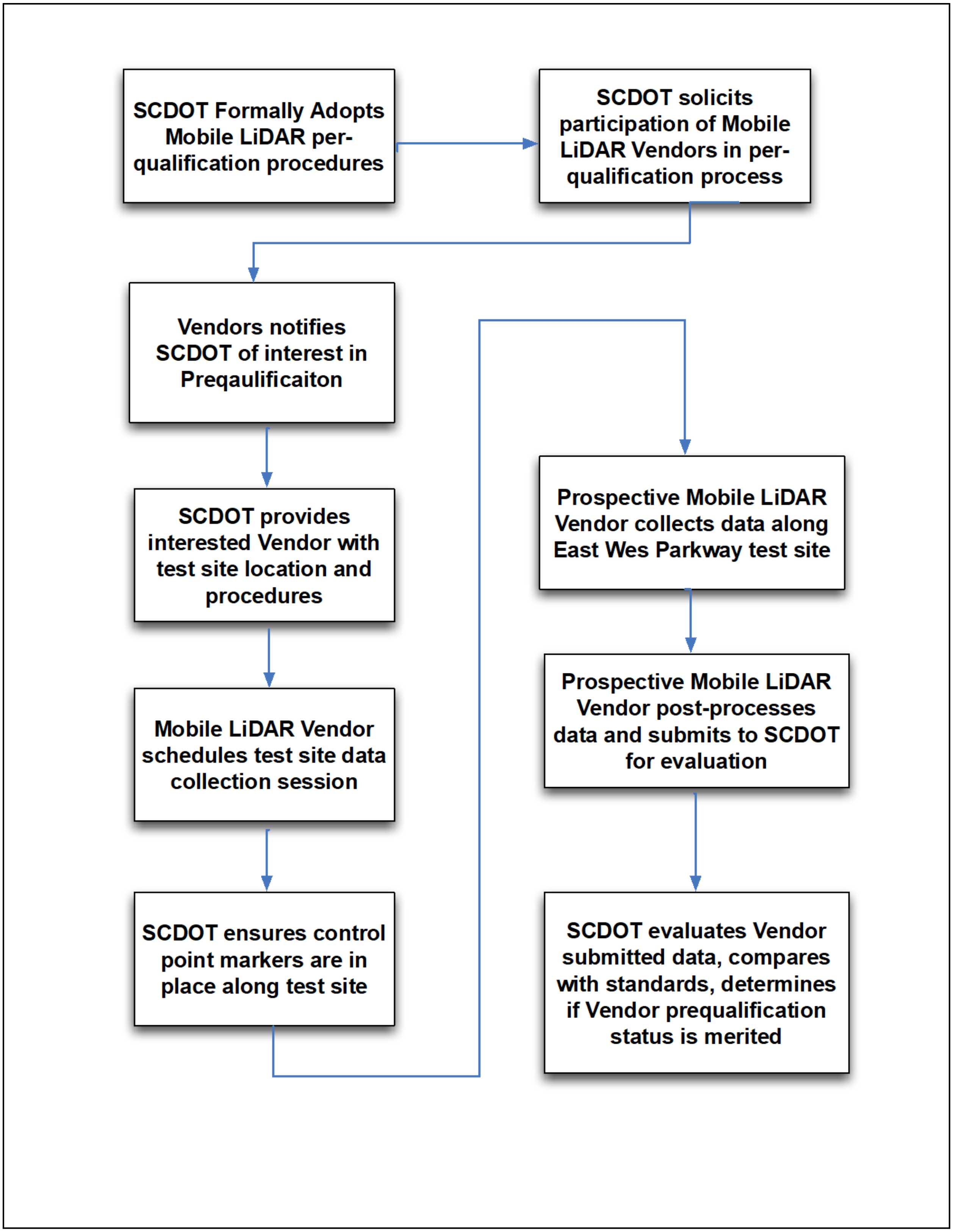

Figure 6-4 Mobile LiDAR Test Site Vendor Prequalification Process

CHAPTER 7 : CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

This research provides a technical evaluation of multiple MTLS systems with respect to accuracy and precision of collected cross slope data and procedures to calibrate, collect, and process data. The research approach covered various data elements and variables including detailed profile, alignment, and cross section comparisons, and ground proofing using conventional survey methods. The research was based on findings from the literature review and evaluation of data provided by vendors who participated in a MTLS rodeo at three Test Site locations in Anderson and Spartanburg, SC.

An important research disclaimer that should be clearly identified is that MTLS vendors were not compensated for their participation in the vendor rodeo. It is possible absence of compensation for work performed could have diminished vendor incentive to go through all of the necessary steps and extra effort required to ensure high quality standards of submitted data. In fact, all of the vendors had different levels of participation with regard to what specific data was submitted. It should be noted that none of the vendors submitted everything requested by the research team. Nevertheless, evidence for research results demonstrate that MTLS can be an effective method to collect accurate cross slope data, which was a primary objective of this research project.

In the next several sections, research findings are presented along with discussion on how research objectives for this project were achieved. Principal research findings and recommendations are also summarized.

Research Objectives

Project objectives were identified and outlined in the original SCDOT research problem statement and include:

7.2 MTLS Cross Slope Verification

The first objective of the research was *to perform technical and economic comparisons of the alternative mobile scanning technologies and conventional survey methods for cross slope verification*.

7.2.1 Cross Slope Verification from a Construction Specification Standpoint

SCDOT's typical design cross slope for normal crown on state routes is ¼" per foot (2.08%). Inherent variability in road construction and paving makes it difficult to adhere to a precise cross slope. SCDOT's construction specification allows ±0.174% (Level 1) and ±0.348% (Level 2) deviations from the design cross slope. Using the design cross slope of 2.08%, which results in a range of cross slopes of 1.732% to 2.428% that meet both Level 1 and Level 2 construction tolerances. SCDOT cross slope specifications suggest contractor penalties be assessed if certain levels of adherence are not achieved. The challenge for quality assurance is predicated upon how to fairly and accurately determine measures for adherence. Due to accuracy issues associated with mobile LiDAR, some leeway must be incorporated when using this technology to determine if construction specifications are met. Research results indicate MTLS can measure cross slope to within +/-0.14% grade for a single lane and to within +/-0.2% if 2 lanes are measured in one pass.

These values are based on post-process survey adjustments using ground control points. Analysis of data collected on US 123 indicated that MTLS can measure cross slope to within +/- 0.18 percent based on an unadjusted point cloud. All of these error thresholds are +/- errors. If measurement errors were averaged with regard to sign, the actual value is 0 in all cases indicating that errors are normally distributed about a mean error of 0.

Recommendation: If MTLS is used to determine construction adherence, the average slope should be measured from generated breaklines along longitudinal pavement markings at even 100 ft. stations in tangents, and even 50 ft. stations in curves. These average slopes should meet the Level 1 or Level 2 tolerances as indicated in the SCDOT cross slope specification. Road segments that do not meet the tolerances should be verified with a digital level at a minimum of two cross sections along the segment to ensure that there was not a systematic error in the MTLS data. SCDOT should consider having higher tolerances if averages slopes are greater than the design value. Slightly higher cross slopes will help facilitate drainage and minimize the chance of vehicles hydroplaning. Cross slopes should be less than 3% on tangent roadway sections so as to not diminish vehicle occupant comfort or cause vehicles to drift laterally.

7.2.2. Cross Slope Verification from a Safety Standpoint

From a safety standpoint, cross slopes should exceed 1.5% to minimize the potential for vehicles to experience hydroplaning. Statistically speaking, based on an average error of +/-0.14% (+/-0.21 RMSE), at a 95% level of confidence, MTLS measured mean cross slope for the section should be at least 1.84% for a single pass for each lane. Stated another way, if the cross slope mean is 1.84%, then 95% of the measured cross slopes will be 1.5% or higher. For a single pass for 2 lanes which assumes an average error of +/-0.2% (+/-0.30 RMSE), the MTLS measured mean cross slope for the section should be at least 1.99% for a 95% level of confidence.

Recommendation: To minimize the possibility for vehicle hydroplaning, mean MTLS Cross Slope measurements should be greater than 1.84% for a single pass for each lane and 1.99% for a single pass for two lanes.

7.2.3 Economic Evaluation

MTLS vendors provided very limited cost data associated with mobile LiDAR collection. An estimate to collect data of $100 per mile is deemed reasonable based on information provided, however, the resulting cost would be much higher for short roadway segments. Breakline extraction and manual drafting would add another $150 per lane mile. Cross section sampling from breaklines is automated and would add little additional cost. It should be noted that mobilization costs are not included in the estimated costs per mile. Typical MTLS studies require one pass for each direction. Depending upon use and application of MTLS results, additional data collection vehicle passes may be necessary, especially for roads with greater than two lanes per direction.

For design work to achieve improved absolute accuracy MTLS will require a ground control survey that can add considerably to the overall data collections costs. However, for applications of MTLS data end use where absolute accuracy is not critical, or if relative accuracy is of greatest importance, a ground control survey and establishment of strategically located corridor reference points may not be necessary.

For this research, an estimation of time requirements for collection, processing, and reporting for the 2.9- mile section of East West Parkway in Anderson, SC, an approximate 40% time savings would result by using MTLS to extract cross sections over conventional surveying methods alone. In the event that ground control is not needed as dictated by application of MTLS data end use, an almost 75% time savings could be achieved. Through extensive evaluation of data comparisons, research findings suggest that extensive ground control is not necessary to produce useful results for effective cross slope verification measurements.

Recommendation: The limited cost information and time savings indicates that MTLS can be a cost-effective method for measuring cross slope continuously along a roadway. Researchers recommend that MTLS be implemented as the preferred means of producing data for SCDOT's cross slope verification program. An even greater return on investment can be achieved by using the MTLS data for additional applications and asset management needs. It should be noted that additional extraction of data items can add to vendor costs unless these procedures are performed in-house, which would require added in-house resources.

7.3 MTLS Validation Site

The second and third objectives of the project are *establish a representative validation site that contains tangent and curve sections using traditional survey methods that may then be used to qualify mobile scanning vendors; and develop SCDOT guidelines for mobile scanning testing procedures and data delivery, ultimately applicable to statewide data collection, from results and feedback from the research team administered vendor rodeo.*

Chapter 6 summarized test procedures and specification criteria for the purpose of using EW Parkway (Test Section 2 of this research) in Anderson, SC as an MTLS validation site for vendor pre-qualification. The site was chosen because it has relatively new pavement, has representative geometric characteristics and roadway design elements. In-place survey ground control points will help facilitate evaluation of data collection capabilities and quality of any potential MTLS vendor. Successful use of this test site in conducting the vendor rodeo and evaluating data comparison support use of this roadway as a suitable location for similar MTLS vendor validation and prequalification in the future.

Recommendations: MTLS vendor prequalification is recommended due to potential for error and wide-ranging differencs in data collection equipment capabilities. Measurements and results can be highly variable and can include systematic errors due to insufficient Q Quality Assurance/Quality Control procedures. Reputable vendors with quality equipment and staff will be able to conduct careful calibration procedures to provide useful data at a high degree of accuracy free of systematic errors.

7.4 Potential Cost Savings and Benefits of MTLS

The forth objective is *to evaluate mobile scanning costs, potential benefits, application efficiencies, and comparison with conventional and existing SCDOT maintenance and construction practices.*

Evaluation of mobile scanning costs was limited because vendors provided minimal information on their data collection and processing costs. An economic discussion was provided in Section 7.2.3.

7.4.1 Summary of Benefits of MTLS

Benefits of MTLS data collection can be attributed to two primary category types: safety benefits and product benefits. Benefits resulting from use of MTLS data collection procedures, identified based on the literature review and research findings, are summarized as follows:

7.4.1.1 Safety Benefits:

Use of MTLS can result in improved safety in work zones by considerably reducing time surveyors and other personnel are exposed to risks associated with working in close proximity to the traveling public. While ground control surveys are still required for highest attainment of MTLS accuracy, the extent of exposure is far less than traditional surveying to acquire cross-sectional dimensions, pavement surface measurements, and horizontal and vertical alignment elements.

Improved safety for the traveling public can be experienced by minimizing the need for work zones associated with surveying operations. Work zones may include survey vehicles that can impair diver visibility for clear zones, shoulders, or even travel lanes. Work zone activities and personnel can also serve as distractions to motorists.

7.4.1.2 Product Benefits:

Field collection time is greatly reduced over conventional surveying. Data collection of 50 miles (or more) of highway per day is achievable, even with multiple passes in multiple directions.

Point density allows for a nearly continuous surface modeling in the direction of travel and significant point coverage transversely within the line of sight of the LiDAR scanning device(s). The density of the point cloud virtually eliminates the need to interpolate between points.

The data is multipurpose. This project focuses on roadway cross slope measurements and how the data can be used to ensure adequate cross slope as well as calculating material estimates for paving and reconstruction operations. There are numerous other applications within SCDOT that can benefit from MTLS data collection including clear zone and roadside safety audits, asset management, cross sectional measurements (e.g., lane and median width, foreslope, backslope, and ditch parameters), flood plain delineation, and numerous others.

Traverse profiling is possible. MTLS can also provide pavement profiling. While not at the resolution of specialized pavement profilers, this research indicated that wheel ruts and pavement surface abnormalities can be identified from MTLS data.

Mapping of all planimetric features within the field of view of the scanning devices. These features include traffic control devices, bridge structures, driveways, sidewalks, building locations, above ground utilities, and drainage inlets.

7.4.2 Sources of Error and Methods to Reduce Error

MTLS has different levels of positional accuracy due to error sources in the sensors including GPS, IMU, DMI, and the LiDAR scanning device(s). Accuracy can be improved with GPS post/real-time processing using base stations occupying project control throughout the project area. To minimize error, MTLS systems should be carefully calibrated prior to data collection. GPS mission planning should also be performed to ensure good satellite availability during data collection. Redundant data collection with overlapping data on each pass can also help reduce error. Note that point density is greatest in the MTLS travel lane and diminishes in adjacent travel lanes. Thus, making a pass in every travel lane can result in a denser point cloud collected at shorter distances which will enhance overall accuracy. During post-processing, least squares adjustment of the point cloud using available survey ground control points will improve accuracy. This adjustment is necessary to ensure absolute accuracy however our research indicated that relative accuracy is still very high without post-process adjustment and thus accurate cross slope data is possible even with unadjusted MTLS data. Note that unadjusted MTLS data used in this report refers to data that has been rectified using differential GPS, IMU, and DMI readings but has not undergone post-process adjustment using ground control survey point data.

7.4.3 Challenges and Drawbacks

The LiDAR scanning devices can only collect data within line of sight. This is why most vehicles used in an MTLS are trucks, vans, or SUVs that allow for higher LiDAR mounting heights. The higher vantage point allows for increased data collection beyond low lying objects such as guard rail, barriers, vegetation, or even the crown of a median.

The point density (and accuracy) diminishes as distance increases from the MTLS travel path in any direction. However, improved accuracy can be achieved by traveling in every lane.

Heavy vegetation adjacent to the travelway can make collection of shoulder, foreslope, ditch, and backslope section inaccurate. Mowing is advisable prior to MTLS to create a uniform surface, which will result in more accurate cross slope estimates.

Processing of the MTLS points clouds to create useful CAD drawings, TIN surfaces, and other useful products is time consuming unless some or most processes are automated. Some automated processes such as breakline creation using pavement marking intensity is common. There are commercial software products available that automate several processes related to extracting useful information from MTLS point clouds.

7.5 Applications

7.5.1 Adverse Crown

Cross slope accuracy levels achieved with MTLS indicate cross slope data extracted from an MTLS point cloud can be used to identify locations along the road with adverse crown. Automating this post-processing procedure can be a challenge. The work flow would require identifying curved sections and the direction the road deflects leading into the horizontal curve. Pavement areas with a cross slope in the opposite direction of the horizontal curve deflection would be identified to exhibit an adverse crown of the roadway cross slope.

7.5.2 Pavement Materials Estimation

As this research project progressed, it became evident that materials estimation for rehabilitation projects was of interest and a primary concern. This study provided a detailed technical evaluation of multiple MTLS systems with regard to the accuracy and precision of collected pavement surfaces. Comparisons were created between the pavement surface collected using traditional surveying methods and data collected by five MTLS. The average of differences in raster cell heights between MTLS surfaces and a conventional surveying surface were determined to be statistically significant, which can result in inaccurate pavement volume estimates. Results indicate LiDAR data has considerable potential for creating much more accurate pavement material volume estimates compared with traditional survey average end area volume estimates, which could potentially result in considerable savings per lane-mile.

7.5.3 Alignment Extraction

Horizontal and vertical alignments were extracted by three MTLS vendors for Test Section 2, East West Parkway in Anderson. Alignments were compared for relative accuracy and evaluated against as-built geometric data obtained using conventional survey methods. The following evaluations provide results of comparisons for horizontal and vertical alignment variables:

Horizontal Curve 1 - Using alignment data from Vendors B and C, resulting average absolute errors varied as follows: curve length varied from the baseline by 1.88%, radius of curvature varied by 2.3%, and tangent length varied by 1.9%. Stations for PC, PI and PT varied from the reference by average absolute errors of 0.14%, 0.07% and 0.035%, respectively. Precisions ranged between 96% and 100%.

Horizontal Curve 2 - Using alignment data for Vendors B and C, resulting average absolute errors vary as follows: curve length varied from the reference by 0.48%, radius of curvature varied by 0.26%, and tangent length varied by 0.51%. Station of the point of curvature varied by 0.03%, point of intersection varied by 0.07% and point of tangency varies by 0.27%. Precisions for curve 2 were greater than 99%.

Vertical Curve 1 - Using alignment data for Vendors A, B and C, curve length varied from the baseline by an average absolute error of 11.89%, PVC station varied by 0.50%, PVC elevation varied by 0.02%, PVI station varied by 0.42%, PVI elevation varied by 0.04%, PVT station varied by 0.34%, and PVT elevation varied by 0.08%. Grade in, grade out and grade change varied by 1.04%, 3.57%, and 9.22%, respectively. Except for curve length results, grade out and grade change, the research team found the average precision for most components were within 98% and 99.9%. This corresponds to a surveying precision of 1:50 to 1:1000.

Vertical Curve 2 - Using alignment data for Vendors A, B and C, curve length varied from the baseline by an average absolute error of 2.21%, PVC station varied by 0.43%, PVC elevation varied by 0.06%, PVI station varied by 0.43%, PVI elevation varied by 0.09%, PVT station varied by 0.44%, and PVT elevation varied by 0.02%. Grade in, grade out and grade change varied by

3.58%, 5.31%, and 4.55%, respectively. Average precisions for most components were within 96% and 99.9%.

7.6 Summary of Literature Review and Survey of States

The review of literature for this project covered a number of topics including:

- Definition of cross slope design, safety, and operational impacts
- Cross slope standards and specifications
- Cross slope data collection
- Evaluations of automated data collection systems and their benefits
- MTLS applications

Clearly from the early sections of the literature review, the proactive potential of MTLS data for safety improvement is significant. Cross slope can impact safety if it is either too flat or too steep, or when there are variations across the lane caused by deterioration and use. Typically, cross slope issues are identified when there is a problematic history of hydroplaning or run-off-road crashes. In recent years, AASHTO has published a provisional standard of practice for measuring the transverse profile of a pavement (AASHTO PP70-14). This standard outlines a method for collecting the transverse profile, which can then be used to determine the cross slope as well as certain pavement distresses (rutting, edge drop-off, water entrapment, and transverse deformation) as described in (AASHTO P 69-14). The data collection standard, however, does not specify particular equipment to be used to collect the profile data. According to the survey of states, those who are collecting data on cross slopes do favor the AASHTO standard of practice, however, a couple of states reported using their own state specifications. Ultimately, approximately a quarter of respondents indicated use of MTLS, but other states indicated plans to move in that direction in the future. Additional technologies currently in use include traditional surveying, laser profiling, and stationary LiDAR.

MTLS technology presents several benefits to transportation agencies, including safety, efficiency, accuracy, and cost. Compared to traditional survey techniques, MTLS has increased safety benefits because nearly all work is performed from within the vehicle. Further, the MTLS vehicle generally can move with the flow of traffic, eliminating the need to divert traffic or close roadways. Studies have also shown MTLS to be significantly more efficient than static TLS by orders of magnitude. One study reported data collection on an 80-mile test route collected using TLS took 120 working days, while the MTLS was able to capture all the data in three hours. The associated cost savings is also significant, and the MTLS data are far more comprehensive than a traditional survey. The SHRP2 project conducted the most comprehensive test of vendors at six unmarked test sites in Northern Virginia. Original test requirements sought a +/- 0.10% accuracy level; but after testing, a recommended accuracy of +/- 0.20% was deemed sufficient for most applications. Greater accuracy levels can be achieved using more sophisticated POS LV systems, but the cost to benefit ratio was not deemed necessary. Most states in the survey indicated accuracy levels of +/- 0.20%.

Finally, there are a number of potential uses of MTLS data beyond geometric feature extraction including: pavement monitoring and maintenance, surface analysis, cost estimating and volume extraction. Most of these applications indicate significant advancements over similar methods using traditional survey data and aerial LiDAR data. However, the survey of states indicates that many have yet to adopt these additional applications. For one state who has attempted to introduce other applications, there were issues with data storage and additional costs for processing software. Probably the most common use of MTLS is for compliance checks, where data collection is typically in response to high accident site investigations, drainage issues/hydroplaning, and pavement failures.

7.7 Chapter Summary

Results of this research project verify and support the feasibility of MTLS in comparison to human collection methods as the most effective means for collecting roadway cross slope data and estimating pavement material quantities. Conventional survey data collection methods are time consuming and require data collectors to be located within the roadway, which poses a considerable safety issue. The use of MTLS can increase data collection productivity, minimize road crew exposure to traffic concerns, and create robust data products and roadway asset information serving multiple uses and beneficial to virtually all SCDOT personnel who work with spatial data.

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<u>APPENDIX A</u>

THE COMPLETE SURVEY FORM

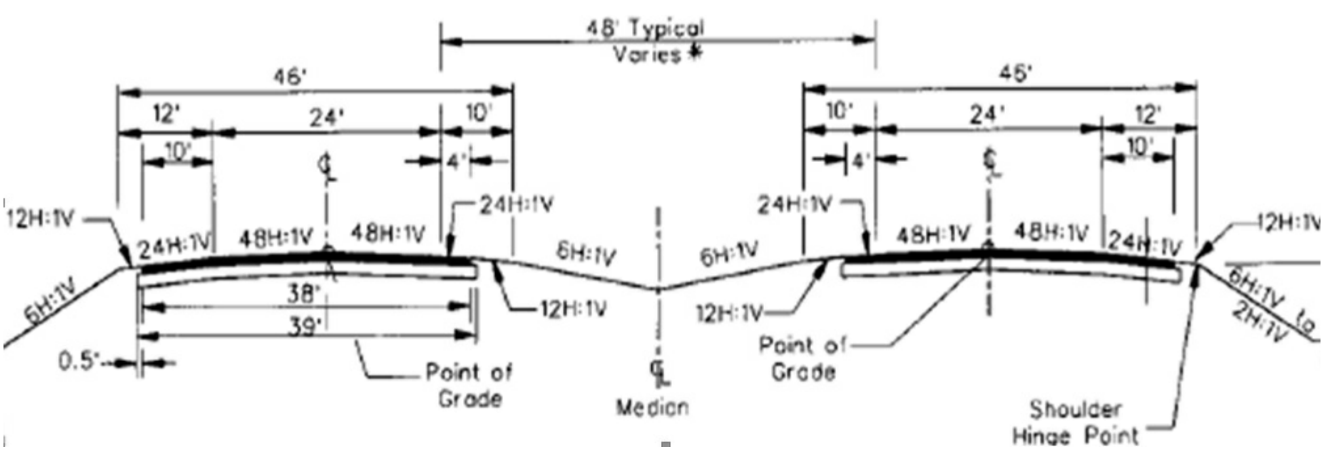
Cross-Slope Verification Survey

Cross Slope Verification Using Mobile Scanning Technologies

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

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

Thank you for taking your time to complete this survey! **Responses are requested on or before July 7.**



RESEARCH OBJECTIVE

To perform technical and economic comparisons of the alternative mobile scanning technologies and conventional survey methods for cross slope verification.

Cross-Slope Verification Survey

Contact Information

* 1. Contact Information

Name	
Agency (e.g. SCDOT)	
Department (e.g. Preconstruction)	
Title (e.g. Head surveyor)	
City/Town	
State/Province	
Email Address	
Phone Number	

Data Collection

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

- ◯ Yes
- ◯ No

If the answer is No, then why?

Data Collection

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

- ◯ Material quantity take off
- ◯ Compliance of cross-slope
- ◯ Asset collection
- ◯ Pavement distress
- ◯ Other (please specify)

Cross-Slope Verification Survey

Data Collection

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

- ◯ Yes
- ◯ No

If the answer is no, then why?

Cross-Slope Verification Survey

Data Collection

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

- ◯ Material quantity take off
- ◯ Compliance of cross slope
- ◯ Asset collection
- ◯ Pavement distress
- ◯ Other (please specify)

Data Collection

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

- [ ] Interstate highways
- [ ] US highways
- [ ] Other primary roads
- [ ] Secondary roads

Additional comments

Cross-Slope Data Collection Methods

* 7. How is cross slope-data collected?

- [ ] Surveying techniques
- [ ] Smart level / Slope meter
- [ ] Carpenter's level combined with tape measure / ruler
- [ ] Mobile method (e.g. LIDAR and/or Inertial device)
- [ ] Other (please specify)

Non-mobile Cross-slope Data Collection

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

- ☐ In-house Inspector
- ☐ In-house surveyor
- ☐ Contracted professional

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

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

- ☐ Inspection after new construction
- ☐ Inspection after maintenance / rehabilitation
- ☐ Prior to maintenance / rehabilitation
- ☐ Road Inventory / Attribute data collection
- ☐ Other (please specify)

Cross-slope Data Collection Intervals

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

Constant interval on tangents (e.g. 100 ft)

Constant interval on curves (e.g. 50 ft)

At critical stations (e.g.,PC, PT, end of TRO, beginning of full SE)

Other (please specify)

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

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

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

Construction Specification

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

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

High Speed Data Collection

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

- ◯ Yes
- ◯ No

Cross-Slope Verification Survey

High Speed Data Collection

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

- ◯ Cross-slope measurement
- ◯ Breakline extraction
- ◯ Roadway inventory/asset data collection
- ◯ Other (please specify / provide web link)

Cross-Slope Verification Survey

LIDAR

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

- [ ] Mobile LIDAR
- [ ] Aerial LIDAR
- [ ] Other (please specify)

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

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

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

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

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

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

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

20. What level of accuracy does your agency require for LIDAR data collection?

(If you have different levels of accuracy for different applications, please specify)

Cross-Slope Verification Survey

Laser Transverse Profiler

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

- ◯ Yes
- ◯ No

Laser Transverse Profiler

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

- [ ] Collect cross-slope data
- [ ] Pavement 3D Texture
- [ ] Crack detection
- [ ] Depth of roadway rutting
- [ ] Other (please specify)

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

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

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

Cross-Slope Verification Survey

Thank You

Thank you for completing this survey

APPENDIX B

SURVEY RESULTS WITH PERSONAL CONTACT INFO REDACTED

Q1 Contact Information

Answered: 20 Skipped: 0

Answer Choices	Responses	
Name	100.00%	20
Agency (e.g. SCDOT)	100.00%	20
Department (e.g. Preconstruction)	100.00%	20
Title (e.g. Head surveyor)	85.00%	17
City/Town	100.00%	20
State/Province	100.00%	20
ZIP/Postal Code	0.00%	0
Country	0.00%	0
Email Address	100.00%	20
Phone Number	90.00%	18

#	Name	Date
1		7/20/2017 1:10 PM
2		7/14/2017 11:49 AM
3		7/12/2017 2:38 PM
4		7/12/2017 9:36 AM
5		7/11/2017 6:02 PM
6		7/11/2017 12:03 PM
7		7/11/2017 8:30 AM
8		7/7/2017 10:45 AM
9		7/6/2017 5:01 PM
10		7/6/2017 4:14 PM
11		7/6/2017 3:48 PM
12		7/6/2017 2:04 PM
13		7/6/2017 2:03 PM
14		7/6/2017 12:52 PM
15		7/5/2017 4:54 PM
16		7/5/2017 6:32 AM
17		6/22/2017 3:31 PM
18		6/21/2017 9:22 AM
19		6/19/2017 4:08 PM
20		6/19/2017 2:52 PM
#	**Agency (e.g. SCDOT)**	**Date**
1	TxDOT	7/20/2017 1:10 PM
2	Caltrans	7/14/2017 11:49 AM
3	Oregon D.O.T.	7/12/2017 2:38 PM

4	GDOT	7/12/2017 9:36 AM
5	Transportation	7/11/2017 6:02 PM
6	IL Dept of Transportation	7/11/2017 12:03 PM
7	GADOT	7/11/2017 8:30 AM
8	Florida DOT	7/7/2017 10:45 AM
9	FDOT	7/6/2017 5:01 PM
10	NDOT	7/6/2017 4:14 PM
11	CDOT	7/6/2017 3:48 PM
12	FDOT	7/6/2017 2:04 PM
13	Florida DOT	7/6/2017 2:03 PM
14	Vermont AOT	7/6/2017 12:52 PM
15	Montana Department of Transportation	7/5/2017 4:54 PM
16	NCDOT	7/5/2017 6:32 AM
17	NJDOT	6/22/2017 3:31 PM
18	Indiana DOT	6/21/2017 9:22 AM
19	Kansas DOT	6/19/2017 4:08 PM
20	Alaska DOT	6/19/2017 2:52 PM

#	Department (e.g. Preconstruction)	Date
1	Design	7/20/2017 1:10 PM
2	Office of Land Surveys	7/14/2017 11:49 AM
3	Geometronics	7/12/2017 2:38 PM
4	Preconstruction Location Surveys	7/12/2017 9:36 AM
5	Researcg	7/11/2017 6:02 PM
6	Research	7/11/2017 12:03 PM
7	Engineering	7/11/2017 8:30 AM
8	Materials	7/7/2017 10:45 AM
9	State Materials Office	7/6/2017 5:01 PM
10	Location	7/6/2017 4:14 PM
11	Research	7/6/2017 3:48 PM
12	Pavement Systems	7/6/2017 2:04 PM
13	Pavement	7/6/2017 2:03 PM
14	Highway Division - AMP	7/6/2017 12:52 PM
15	Highway Bureau	7/5/2017 4:54 PM
16	Mobility and Safety Division - Traffic Safety Unit	7/5/2017 6:32 AM
17	Highway and Traffic Design	6/22/2017 3:31 PM
18	Research and Development	6/21/2017 9:22 AM
19	Construction and Materials	6/19/2017 4:08 PM
20	Asset Management Research	6/19/2017 2:52 PM

#	Title (e.g. Head surveyor)	Date
1		7/20/2017 1:10 PM
2		7/14/2017 11:49 AM

3		7/12/2017 2:38 PM
4		7/12/2017 9:36 AM
5		7/11/2017 12:03 PM
6		7/11/2017 8:30 AM
7		7/7/2017 10:45 AM
8		7/6/2017 5:01 PM
9		7/6/2017 4:14 PM
10		7/6/2017 2:04 PM
11		7/6/2017 2:03 PM
12		7/5/2017 4:54 PM
13		7/5/2017 6:32 AM
14		6/22/2017 3:31 PM
15		6/21/2017 9:22 AM
16		6/19/2017 4:08 PM
17		6/19/2017 2:52 PM

#	City/Town	Date
1	Austin	7/20/2017 1:10 PM
2	Sacramento	7/14/2017 11:49 AM
3	Salem	7/12/2017 2:38 PM
4	Atlanta	7/12/2017 9:36 AM
5	Sacramento	7/11/2017 6:02 PM
6	Springfield	7/11/2017 12:03 PM
7	Atlanta	7/11/2017 8:30 AM
8	Gainesville	7/7/2017 10:45 AM
9	Gainesville	7/6/2017 5:01 PM
10	Carson City	7/6/2017 4:14 PM
11	Denver	7/6/2017 3:48 PM
12	Gainesville	7/6/2017 2:04 PM
13	Gainesville	7/6/2017 2:03 PM
14	Montpelier	7/6/2017 12:52 PM
15	Helena	7/5/2017 4:54 PM
16	Garner	7/5/2017 6:32 AM
17	Trenton	6/22/2017 3:31 PM
18	West Lafayette	6/21/2017 9:22 AM
19	Topeka	6/19/2017 4:08 PM
20	Juneau	6/19/2017 2:52 PM

#	State/Province	Date
1	TX	7/20/2017 1:10 PM
2	CA	7/14/2017 11:49 AM
3	Oregon	7/12/2017 2:38 PM
4	Ga	7/12/2017 9:36 AM

5	95816	7/11/2017 6:02 PM
6	IL	7/11/2017 12:03 PM
7	GA	7/11/2017 8:30 AM
8	Florida	7/7/2017 10:45 AM
9	FL	7/6/2017 5:01 PM
10	NV	7/6/2017 4:14 PM
11	CO	7/6/2017 3:48 PM
12	Florida	7/6/2017 2:04 PM
13	Florida	7/6/2017 2:03 PM
14	VT	7/6/2017 12:52 PM
15	MT	7/5/2017 4:54 PM
16	NC	7/5/2017 6:32 AM
17	NJ	6/22/2017 3:31 PM
18	IN	6/21/2017 9:22 AM
19	KS	6/19/2017 4:08 PM
20	AK	6/19/2017 2:52 PM

#	ZIP/Postal Code	Date
	There are no responses.	

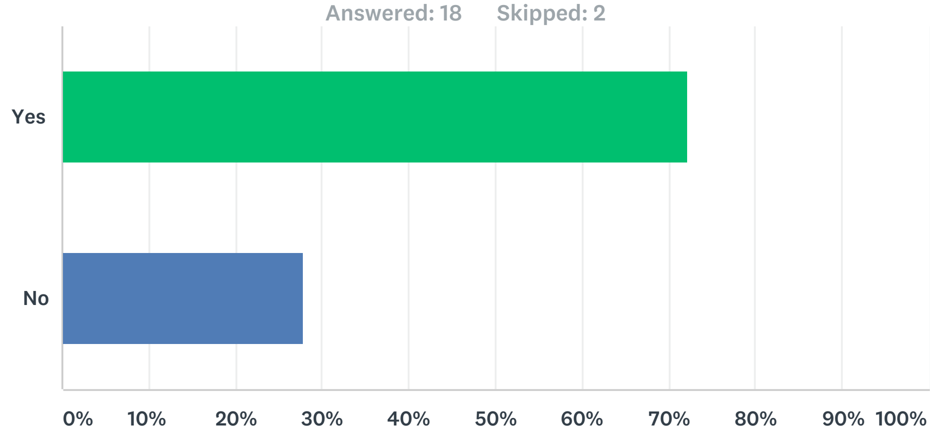
#	Country	Date
	There are no responses.	

#	Email Address	Date
1		7/20/2017 1:10 PM
2		7/14/2017 11:49 AM
3		7/12/2017 2:38 PM
4		7/12/2017 9:36 AM
5		7/11/2017 6:02 PM
6		7/11/2017 12:03 PM
7		7/11/2017 8:30 AM
8		7/7/2017 10:45 AM
9		7/6/2017 5:01 PM
10		7/6/2017 4:14 PM
11		7/6/2017 3:48 PM
12		7/6/2017 2:04 PM
13		7/6/2017 2:03 PM
14		7/6/2017 12:52 PM
15		7/5/2017 4:54 PM
16		7/5/2017 6:32 AM
17		6/22/2017 3:31 PM
18		6/21/2017 9:22 AM
19		6/19/2017 4:08 PM
20		6/19/2017 2:52 PM

#	Phone Number	Date
1		7/20/2017 1:10 PM
2		7/14/2017 11:49 AM
3		7/12/2017 2:38 PM
4		7/12/2017 9:36 AM
5		7/11/2017 12:03 PM
6		7/11/2017 8:30 AM
7		7/7/2017 10:45 AM
8		7/6/2017 5:01 PM
9		7/6/2017 4:14 PM
10		7/6/2017 3:48 PM
11		7/6/2017 2:04 PM
12		7/6/2017 2:03 PM
13		7/6/2017 12:52 PM
14		7/5/2017 4:54 PM
15		7/5/2017 6:32 AM
16		6/21/2017 9:22 AM
17		6/19/2017 4:08 PM
18		6/19/2017 2:52 PM

Q2 Does your agency currently collect cross-slope data for any purpose?

Answered: 18 Skipped: 2

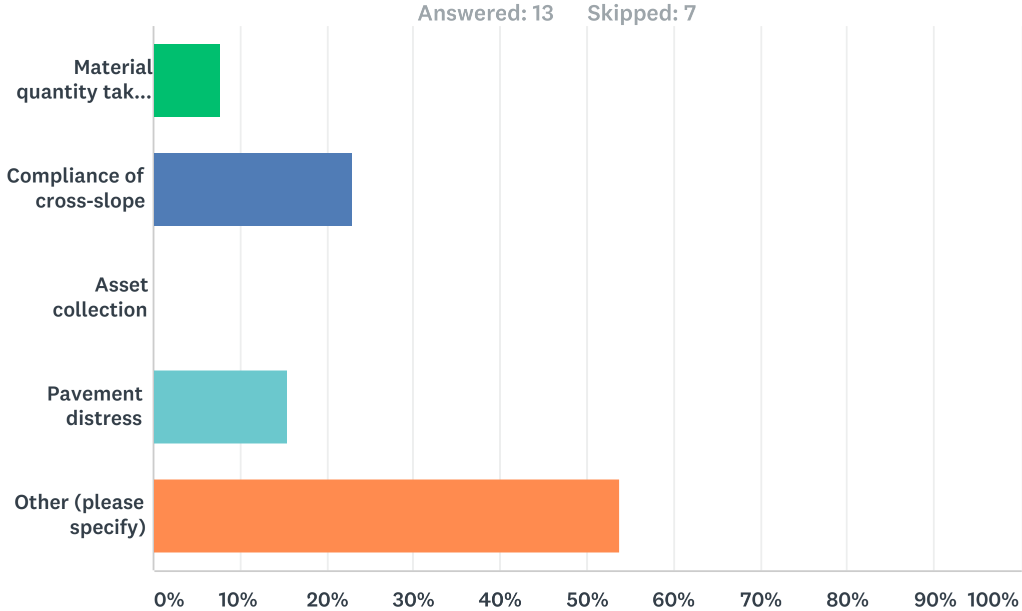


Answer Choices	Responses	
Yes	72.22%	13
No	27.78%	5
Total		18

#	If the answer is No, then why?	Date
1	We have not seen a need to this point	7/11/2017 8:30 AM
2	We do have the ability to collect cross-slope and have looked at it but not with much purpose.	6/19/2017 4:09 PM
3	Data storage and vendor issues. The vendor collects LiDAR but needs post processing program for use.	6/19/2017 2:53 PM

Q3 For what purpose/application do you collect cross-slope data?

Answered: 13 Skipped: 7

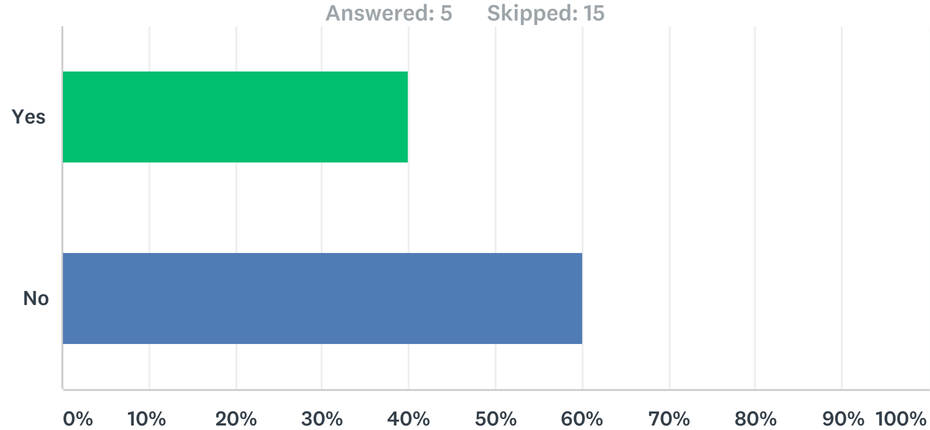


Answer Choices	Responses	
Material quantity take off	7.69%	1
Compliance of cross-slope	23.08%	3
Asset collection	0.00%	0
Pavement distress	15.38%	2
Other (please specify)	53.85%	7
Total		13

#	Other (please specify)	Date
1	accidents, hydroplaning, pavement failures	7/12/2017 9:37 AM
2	Cross-slope data is collected during the design phase so that cross-slope corrections can be made if needed and during safety investigations (roadway departures, etc.) to measure the hydroplaning potential.	7/7/2017 10:47 AM
3	Cross-slope data is collected during the overlay design process to know if corrections need to be made. It is also collected for safey investigations along with friction data.	7/6/2017 6:03 PM
4	pre-design and special evaluations	7/6/2017 2:05 PM
5	Drainage Path Analysis, Preconstruction	7/6/2017 2:04 PM
6	We collect this as an asset on all primary routes, but we will also be using this data for an upcoming project to determine MUTCD curve compliance. This data is being collected now for primary routes, and will be collected for all secondary routes in 2018. We also collect this data at very specific areas where we suspect there may be a drainage issue.	7/5/2017 6:35 AM
7	Investigation for high accidents	6/21/2017 9:22 AM

Q4 Does your agency have any plans to collect cross-slope data in the future?

Answered: 5 Skipped: 15

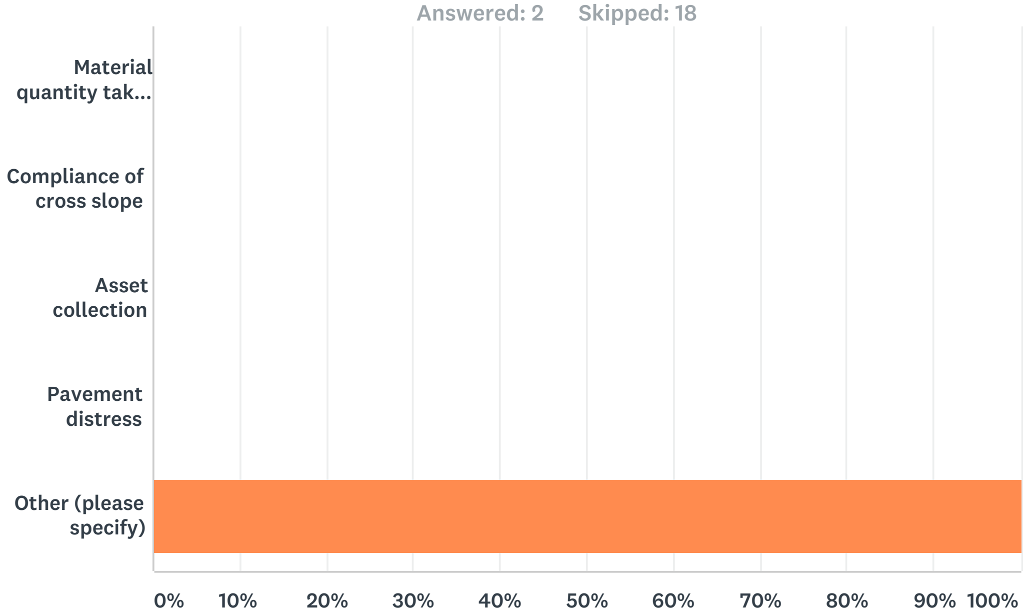


Answer Choices	Responses	
Yes	40.00%	2
No	60.00%	3
Total		5

#	If the answer is no, then why?	Date
1	Not that I am aware of due to other priorities	7/11/2017 8:30 AM

Q5 For what purpose/application do you wish to collect cross slope data?

Answered: 2 Skipped: 18

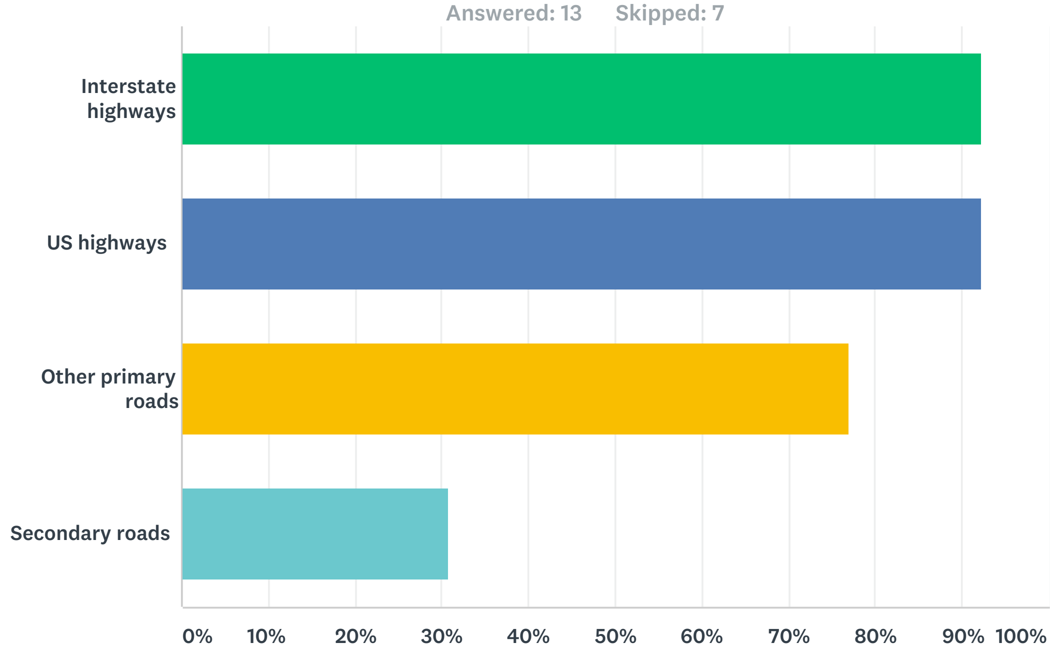


Answer Choices	Responses	
Material quantity take off	0.00%	0
Compliance of cross slope	0.00%	0
Asset collection	0.00%	0
Pavement distress	0.00%	0
Other (please specify)	100.00%	2
Total		2

#	Other (please specify)	Date
1	All of the above	6/19/2017 4:10 PM
2	Design aid	6/19/2017 2:54 PM

Q6 On what type of roads does your agency perform cross-slope data collection?

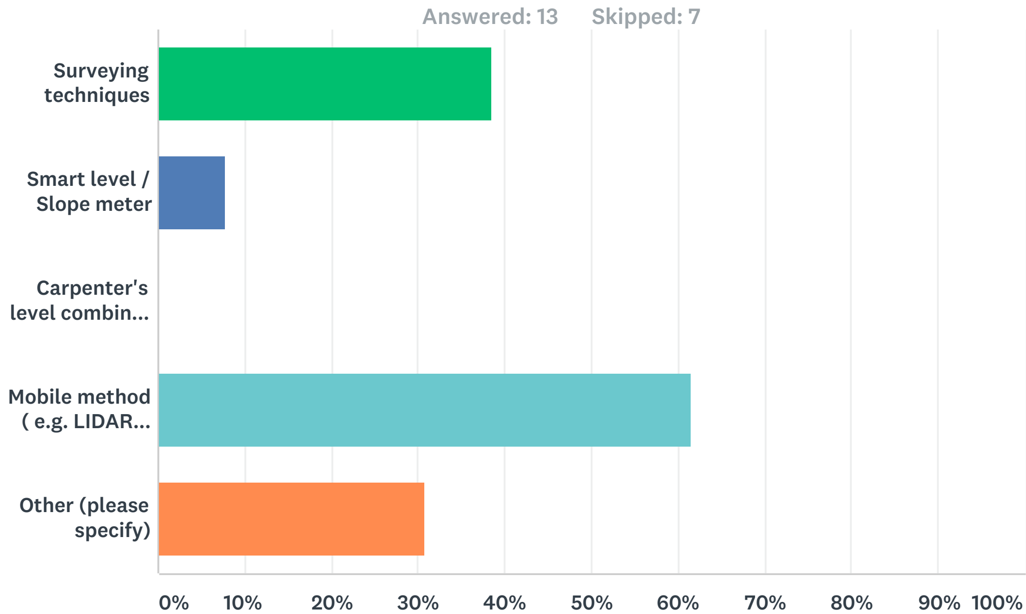
Answered: 13 Skipped: 7



Answer Choices	Responses	
Interstate highways	92.31%	12
US highways	92.31%	12
Other primary roads	76.92%	10
Secondary roads	30.77%	4
Total Respondents: 13		

#	Additional comments	Date
1	Cross-slope is collected during the design process for all asphalt overlay projects and on safety related projects.	7/7/2017 10:50 AM
2	Cross-slope is measured on all asphalt surfaced state maintained roadways that will be overlaid and for safety investigations which may include ramps, intersections, and mainline roadways.	7/6/2017 6:04 PM
3	We expect to collect this data on secondary routes in 2018.	7/5/2017 6:35 AM

Q7 How is cross slope-data collected?

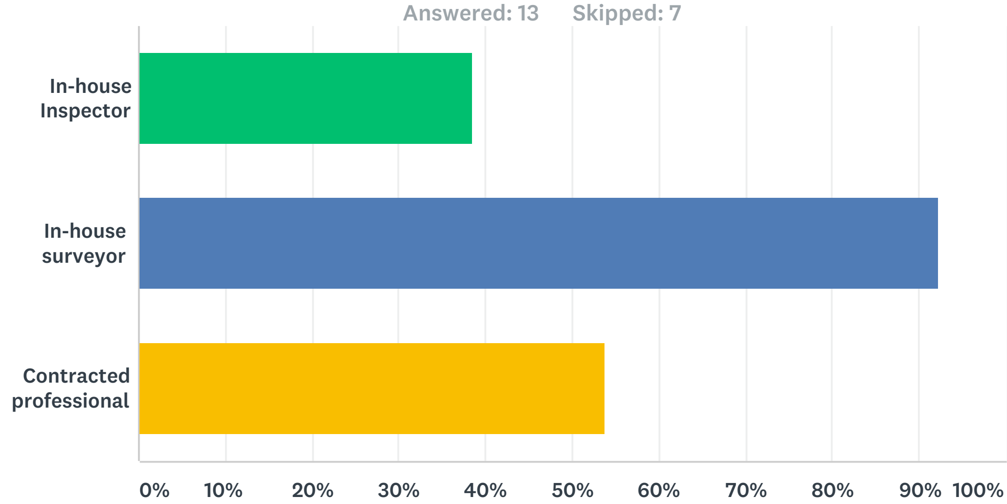


Answer Choices	Responses	
Surveying techniques	38.46%	5
Smart level / Slope meter	7.69%	1
Carpenter's level combined with tape measure / ruler	0.00%	0
Mobile method (e.g. LIDAR and/or Inertial device)	61.54%	8
Other (please specify)	30.77%	4
Total Respondents: 13		

#	Other (please specify)	Date
1	Pavement Maintenance - laser profiler, collected as part of survey for rutting & faulting. Design - Average slope based on ETW, lane lines, and breaklines.	7/14/2017 11:55 AM
2	either conventional surveying or terrestrial LIDAR	7/12/2017 9:38 AM
3	Various Field Methods	7/11/2017 12:04 PM
4	A multi-purpose survey vehicle (MPSV) equipped with a 5 laser profiler system, inertial measurement unit (IMU) and GPS. LIDAR data is also collected on some projects.	7/6/2017 6:04 PM

Q8 Who does non-mobile cross slope data collection?

Answered: 13 Skipped: 7

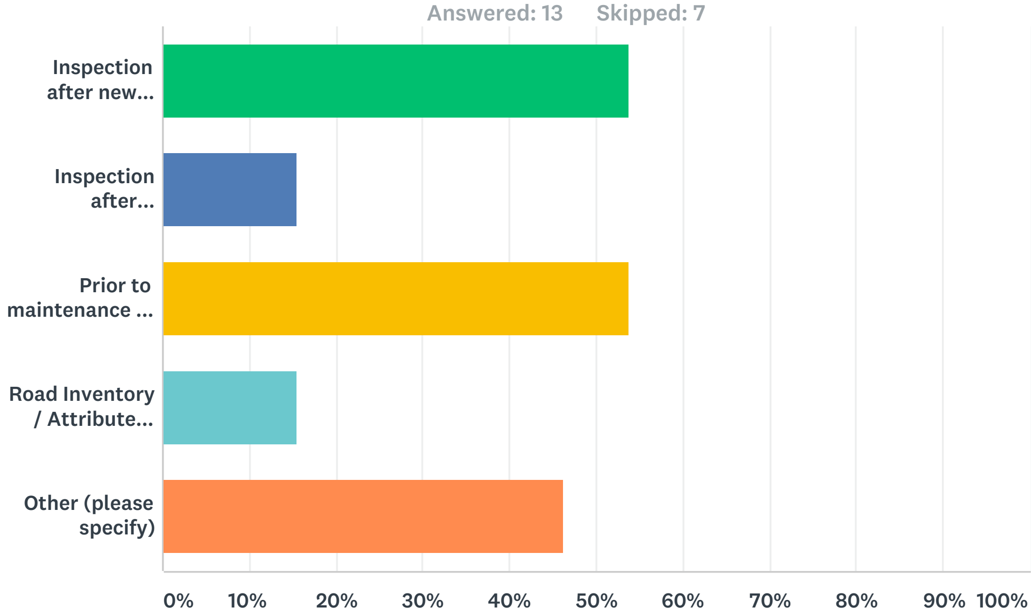


Answer Choices	Responses	
In-house Inspector	38.46%	5
In-house surveyor	92.31%	12
Contracted professional	53.85%	7
Total Respondents: 13		

#	Please provide contact information the most knowledgeable cross-slope surveyor (in-house or contractor)	Date
1	Districts preform Engineering (topo) Surveys.	7/14/2017 12:08 PM
2	Kevin LaVerdure - Oregon DOT (503) 986-3017	7/12/2017 2:37 PM
3	Benny Walden 404-805-7845	7/12/2017 9:39 AM
4	Cross-slope data is collected by State Materials Office staff.	7/6/2017 6:06 PM
5	We do not collect non-mobile cross-slope data for data inventory purposes. Non-mobile cross slope data is only surveyed as needed for a project. The data is retained with the project data, not for inventory purposes.	7/6/2017 9:20 AM
6	I'm not sure how often this is done. I would recommend contacting Mr. Joel Gulledge, PE, PLS at 919-707-6800 or rjgulledge@ncdot.gov for more information here.	7/5/2017 6:38 AM

Q9 When does your agency collect cross-slope data? (check all that apply)

Answered: 13 Skipped: 7



Answer Choices	Responses	
Inspection after new construction	53.85%	7
Inspection after maintenance / rehabilitation	15.38%	2
Prior to maintenance / rehabilitation	53.85%	7
Road Inventory / Attribute data collection	15.38%	2
Other (please specify)	46.15%	6
Total Respondents: 13		

#	Other (please specify)	Date
1	Engineering Surveys	7/14/2017 12:08 PM
2	on occasion after new construction if there is drainage problems, and accident sites	7/12/2017 9:39 AM
3	Cross-slope data is collected after new construction, but the data is used for information only.	7/6/2017 6:06 PM
4	Special evaluation requests	7/6/2017 2:07 PM
5	This data is collected as part of our annual pavement condition data collection.	7/5/2017 6:38 AM
6	Investigation, special cases	6/21/2017 9:23 AM

Q10 At what interval is cross-slope data collected? (non-mobile methods)

Answered: 13 Skipped: 7

Answer Choices	Responses	
At critical stations (e.g.,PC, PT, end of TRO, beginning of full SE)	46.15%	6
Constant interval on curves (e.g. 50 ft)	53.85%	7
Constant interval on tangents (e.g. 100 ft)	61.54%	8
Other (please specify)	61.54%	8

#	At critical stations (e.g.,PC, PT, end of TRO, beginning of full SE)	Date
1	also at critical alignment points	7/14/2017 12:09 PM
2	25'	7/12/2017 9:40 AM
3	pc,pt	7/6/2017 4:18 PM
4	20 Khz sampling rate at 50 mph vehicle speed	7/6/2017 2:14 PM
5	TS, SC, PC, PT, CS, ST	7/6/2017 9:33 AM
6	See note in "Other"	7/5/2017 6:57 AM
#	Constant interval on curves (e.g. 50 ft)	Date
1	50' sections along curves	7/14/2017 12:09 PM
2	25'	7/12/2017 9:40 AM
3	50 ft	7/6/2017 4:18 PM
4	20 Khz sampling rate at 50 mph vehicle speed	7/6/2017 2:14 PM
5	Collected at sub-inch intervals, 20 khz ouptut so its speed dependent	7/6/2017 2:07 PM
6	50	7/6/2017 9:33 AM
7	50 ft	7/5/2017 6:57 AM
#	Constant interval on tangents (e.g. 100 ft)	Date
1	Typical 100"sectioons	7/14/2017 12:09 PM
2	25'	7/12/2017 9:40 AM
3	100 ft	7/6/2017 4:18 PM
4	20 Khz sampling rate at 50 mph vehicle speed	7/6/2017 2:14 PM
5	Collected at sub-inch intervals, 20 khz ouptut so its speed dependent	7/6/2017 2:07 PM
6	50	7/6/2017 9:33 AM
7	50 ft	7/5/2017 6:57 AM
8	50' intervals, normally	6/22/2017 3:32 PM
#	Other (please specify)	Date
1	as needed dependent upon survey request	7/14/2017 12:09 PM
2	Random grade verification points are provided	7/12/2017 2:36 PM
3	25-50' if conventional/ 10' if LIDAR	7/12/2017 9:40 AM
4	Up to the Resident Engineer	7/11/2017 12:05 PM
5	na	7/7/2017 10:54 AM

6	Cross-sloope data is collected using high-speed mobile methods and can be processed at different intervals.	7/6/2017 6:07 PM
7	The data mentioned above is from our mobile primary system data collection vehicle. I'm not sure what is done for new projects.	7/5/2017 6:57 AM
8	Depends on the contract	6/21/2017 9:24 AM

Q11 What guideline does your agency follow to measure cross-slope?(Please describe and/or provide web link if available on-line)

Answered: 13 Skipped: 7

#	Responses	Date
1	http://www.dot.ca.gov/design/manuals/hdm/chp0300.pdf	7/14/2017 12:14 PM
2	yes	7/12/2017 2:36 PM
3	Control must be set conventional and elevated with digital levels. Pavement must be collected at 0.02' accuracy	7/12/2017 9:41 AM
4	Follows IDOT Construction Manual	7/11/2017 12:06 PM
5	FM5-611 Florida Method of Test for Automated Measurement of Pavement Cross Slope and Grade http://www.fdot.gov/materials/administration/resources/library/publications/fstm/methods/fm5-611.pdf	7/7/2017 10:55 AM
6	Cross-slope data collection specification http://www.fdot.gov/materials/administration/resources/library/publications/fstm/methods/fm5-611.pdf	7/6/2017 6:03 PM
7	Our in house manual	7/6/2017 4:19 PM
8	FDOT Plans Preparation Manual, Section 25.4.6 Roadway Cross-Slope. http://www.fdot.gov/roadway/ppmmanual/2013PPM.shtm	7/6/2017 2:19 PM
9	http://www.fdot.gov/materials/administration/resources/library/publications/fstm/methods/fm5-611.pdf	7/6/2017 2:08 PM
10	http://www.mdt.mt.gov/other/webdata/external/photosurvey/survey/manual_guides_forms/survey_manual/sm_entire_manual.pdf The MDT survey manual provides procedure for survey.	7/6/2017 9:34 AM
11	Measured as part of automated data collection done for pavement condition survey.	7/5/2017 7:03 AM
12	Not sure of the ask here. We follow normal survey procedures. Spot elevations are taken at each edge of pavement, lane line and the shoulder stripe. When doing pavement analysis, the smart level is used to provide spot checks.	6/22/2017 3:34 PM
13	Since we are using the mobile data collection for investigation, it is only to screen the suspect of non compliance of cross slope. Actual surveying will follow.	6/21/2017 9:25 AM

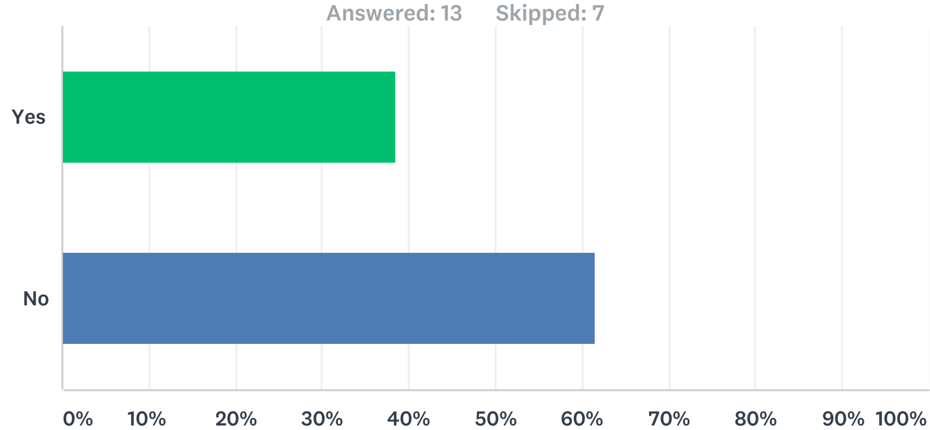
Q12 What level of tolerance is accepted for construction specification? (e.g 0.2% of design plan) (Please describe and/or provide web link if available on-line)

Answered: 11 Skipped: 9

#	Responses	Date
1	http://www.dot.ca.gov/hq/row/landsurveys/SurveysManual/Manual_TOC.html	7/14/2017 12:17 PM
2	1	7/12/2017 2:35 PM
3	2% cross slope is standard	7/12/2017 9:46 AM
4	Varies	7/11/2017 12:06 PM
5	0.2%	7/7/2017 10:55 AM
6	Standard : 0.2% Allowable Range: 0.015-0.030 (two-lane roads) 0.015-0.040 (multiple lane roads)	7/6/2017 2:24 PM
7	.2%	7/6/2017 2:08 PM
8	http://www.mdt.mt.gov/other/webdata/external/const/specifications/2014/division_100.pdf section 105.08.6 C at the link above.	7/6/2017 9:34 AM
9	There are several ways / reasons this is measured. One would be for the verification of that the roadway is constructed to plan specifications. I am not as knowledgeable about this area, but provided a contact name earlier. The other would be system-wide mobile data collection. We have not conducted much validation of this method, but will be working on this aspect later this year.	7/5/2017 7:05 AM
10	N/A	6/22/2017 3:34 PM
11	N/A	6/21/2017 9:25 AM

Q13 Does your agency use mobile LIDAR data collection?

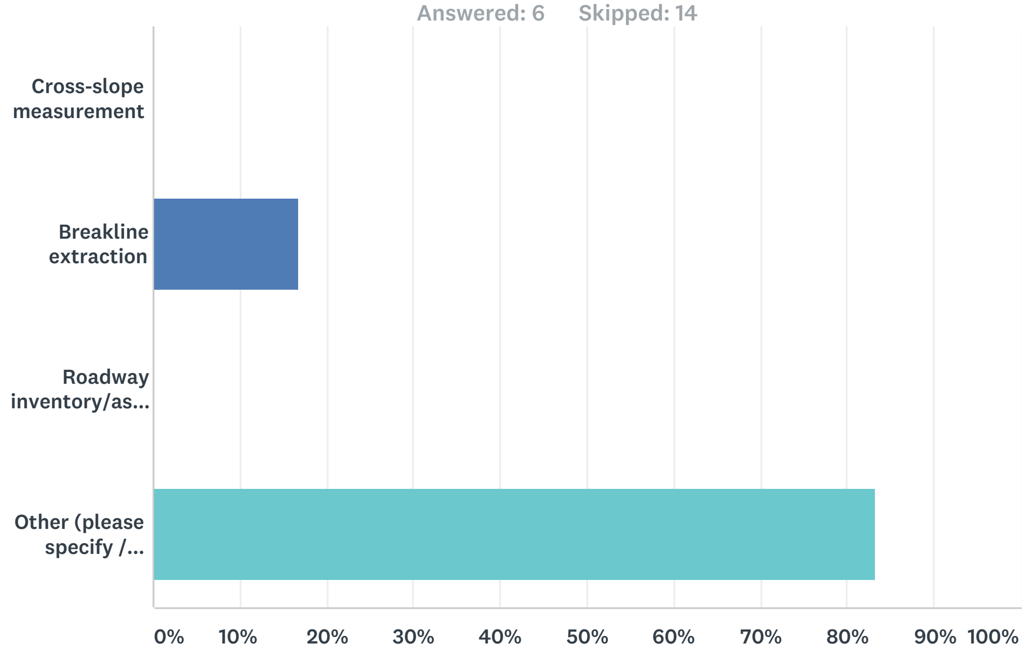
Answered: 13 Skipped: 7



Answer Choices	Responses	
Yes	38.46%	5
No	61.54%	8
Total		13

Q14 What applications are LIDAR data used for? (Check all that apply)

Answered: 6 Skipped: 14

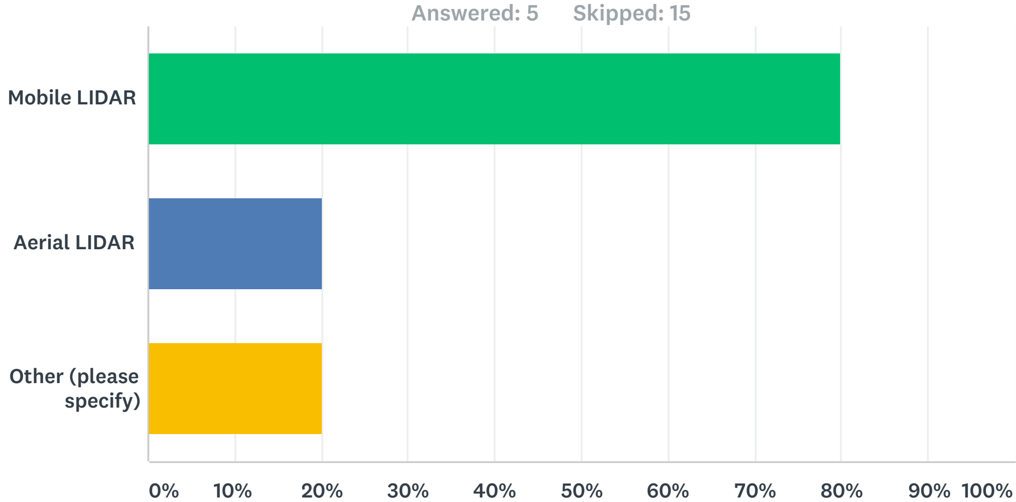


Answer Choices	Responses	
Cross-slope measurement	0.00%	0
Breakline extraction	16.67%	1
Roadway inventory/asset data collection	0.00%	0
Other (please specify / provide web link)	83.33%	5
Total		6

#	Other (please specify / provide web link)	Date
1	Tried to check all but they wouldn't stick,,,,all the above	7/14/2017 12:18 PM
2	We map our entire state highway system with survey-grade LiDAR	7/12/2017 2:35 PM
3	consultants supply us data for road design using Moblile, Aerial Lidar. the deliverable is still a linework .dgn file. we use lidar to enhance obscure mapping, pavement, other topo items and high traffic areas.	7/12/2017 9:47 AM
4	We will sometimes use this for very specific areas where we suspect there may be a problem with water draining across the roadway. We do not utilize LIDAR system-wide.	7/5/2017 7:06 AM
5	Trying to use for asset collection need to develop asset data base	6/19/2017 2:55 PM

Q15 Which LIDAR data collection methods does your agency currently use? (Check all that apply)

Answered: 5 Skipped: 15

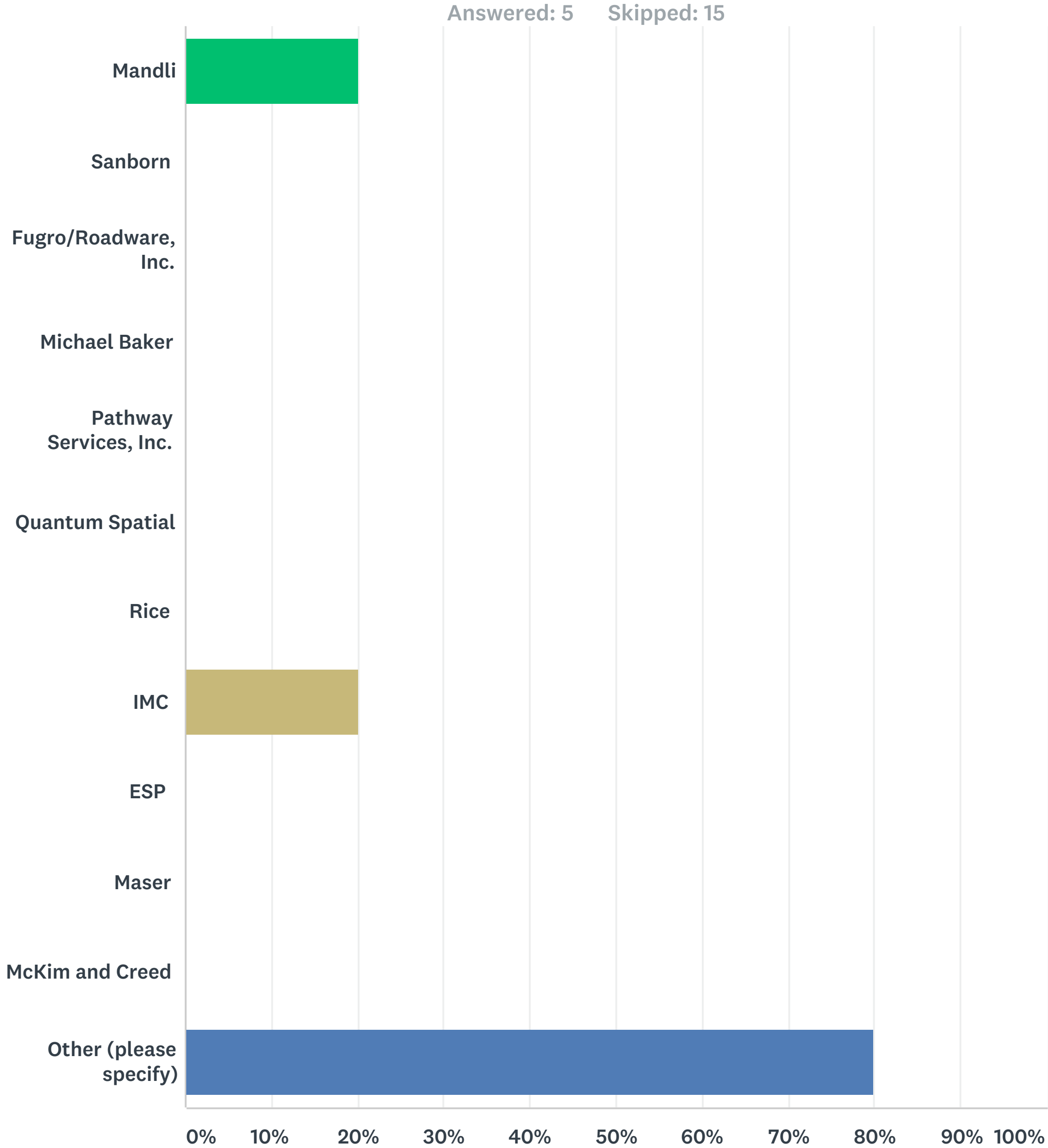


Answer Choices	Responses	
Mobile LIDAR	80.00%	4
Aerial LIDAR	20.00%	1
Other (please specify)	20.00%	1
Total Respondents: 5		

#	Other (please specify)	Date
1	GDOT ownes terrestrial LIDAR, we use consultants that supply us with Aerial and Mobile.	7/12/2017 10:04 AM

Q16 What LIDAR vendors has your agency use? (Check all that apply)

Answered: 5 Skipped: 15



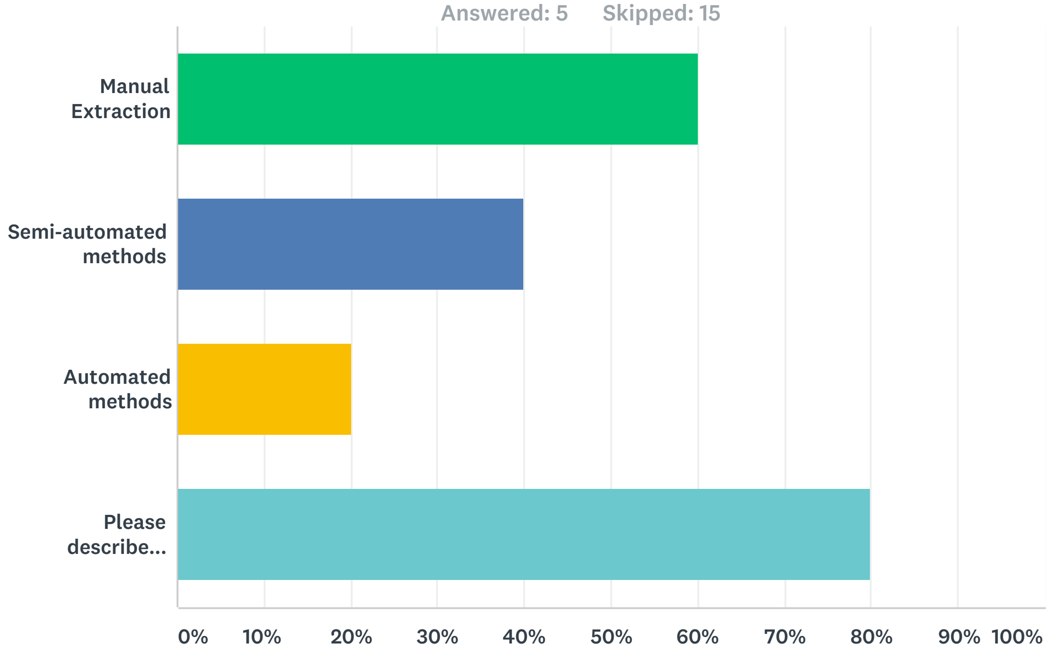
Answer Choices	Responses	
Mandli	20.00%	1
Sanborn	0.00%	0
Fugro/Roadware, Inc.	0.00%	0
Michael Baker	0.00%	0
Pathway Services, Inc.	0.00%	0
Quantum Spatial	0.00%	0
Rice	0.00%	0
IMC	20.00%	1

ESP	0.00%	0
Maser	0.00%	0
McKim and Creed	0.00%	0
Other (please specify)	80.00%	4
Total Respondents: 5		

#	Other (please specify)	Date
1	Various private vendors through A&E contracts	7/14/2017 12:20 PM
2	None, we own a Leica: Pegasus 2 mobile mapper	7/12/2017 2:34 PM
3	IMC just signed new contract for aerial lidar. no work done yet. Arcadis and Settimio has supplied us with aerial lidar. Wolverton did a test run of mobile for us that worked out great .	7/12/2017 10:04 AM
4	Not sure	7/5/2017 7:07 AM

Q17 How does your agency extract attribute data from the LIDAR raw data? (Check all that apply)

Answered: 5 Skipped: 15

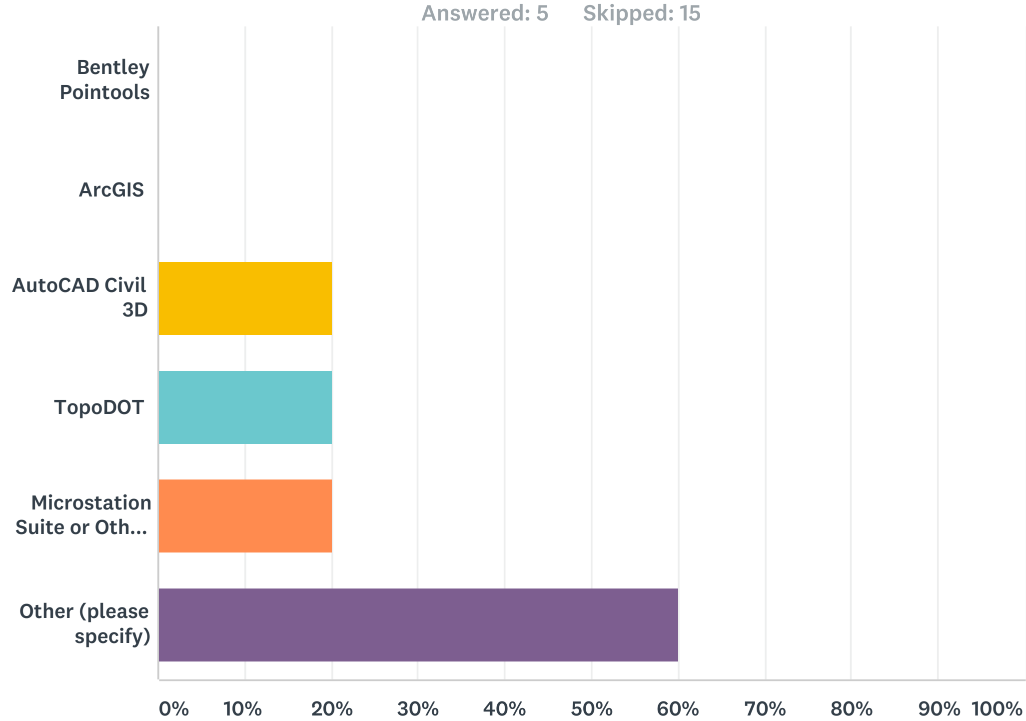


Answer Choices	Responses	
Manual Extraction	60.00%	3
Semi-automated methods	40.00%	2
Automated methods	20.00%	1
Please describe semi-automates and automated methods	80.00%	4
Total Respondents: 5		

#	Please describe semi-automates and automated methods	Date
1	Use TopoDOT tools for semi -automated extraction	7/14/2017 12:20 PM
2	Leica TOPO II has automated features to collect grid points and ground points. Leica Cyclone will auto select curb/gutter and easily remove traffic and trashy data. We use virtual surveyor to manually extract points needed with our codes and features	7/12/2017 10:04 AM
3	Not sure	7/5/2017 7:07 AM
4	Post processing program provided by Mandli consultant	6/19/2017 3:01 PM

Q18 What software tools does your agency use to process LIDAR data?

Answered: 5 Skipped: 15



Answer Choices	Responses	
Bentley Pointools	0.00%	0
ArcGIS	0.00%	0
AutoCAD Civil 3D	20.00%	1
TopoDOT	20.00%	1
Microstation Suite or Other Bentley Tools (including GeoPak, InRoads, or Descartes)	20.00%	1
Other (please specify)	60.00%	3
Total Respondents: 5		

#	Other (please specify)	Date
1	Cyclone & RealWorks	7/14/2017 12:20 PM
2	currently we use Leica Cyclone inhouse. the data is already processed coming from our consultants	7/12/2017 10:04 AM
3	Not sure	7/5/2017 7:07 AM

Q19 What is the typical resolution of LIDAR scanning? (e.g. 1 point every 0.04")

Answered: 5 Skipped: 15

#	Responses	Date
1	Chapter 15 http://www.dot.ca.gov/hq/row/landsurveys/SurveysManual/Manual_TOC.html	7/14/2017 12:20 PM
2	1	7/12/2017 2:34 PM
3	0.10' relative point cloud	7/12/2017 10:04 AM
4	Not sure	7/5/2017 7:07 AM
5	Specified by contractor	6/19/2017 3:01 PM

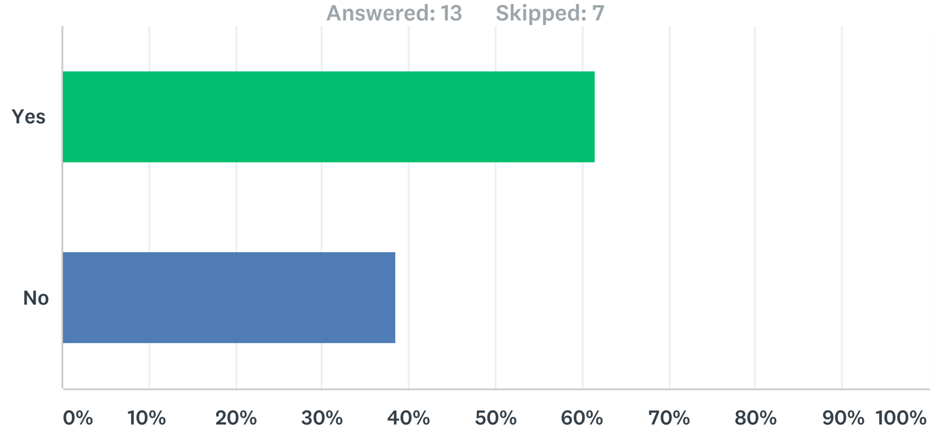
Q20 What level of accuracy does your agency require for LIDAR data collection?(If you have different levels of accuracy for different applications, please specify)

Answered: 4 Skipped: 16

#	Responses	Date
1	http://www.dot.ca.gov/hq/row/landsurveys/SurveysManual/Manual_TOC.html	7/14/2017 12:20 PM
2	0.10' on pavement/ 0.50' on ground/ 0.02' on bridges . 0.02' on accident sites.	7/12/2017 10:04 AM
3	Not sure. I can get more information on this if needed.	7/5/2017 7:07 AM
4	We didn't specify technology in contract.	6/19/2017 3:01 PM

Q21 Does your agency use a laser transverse profiler?

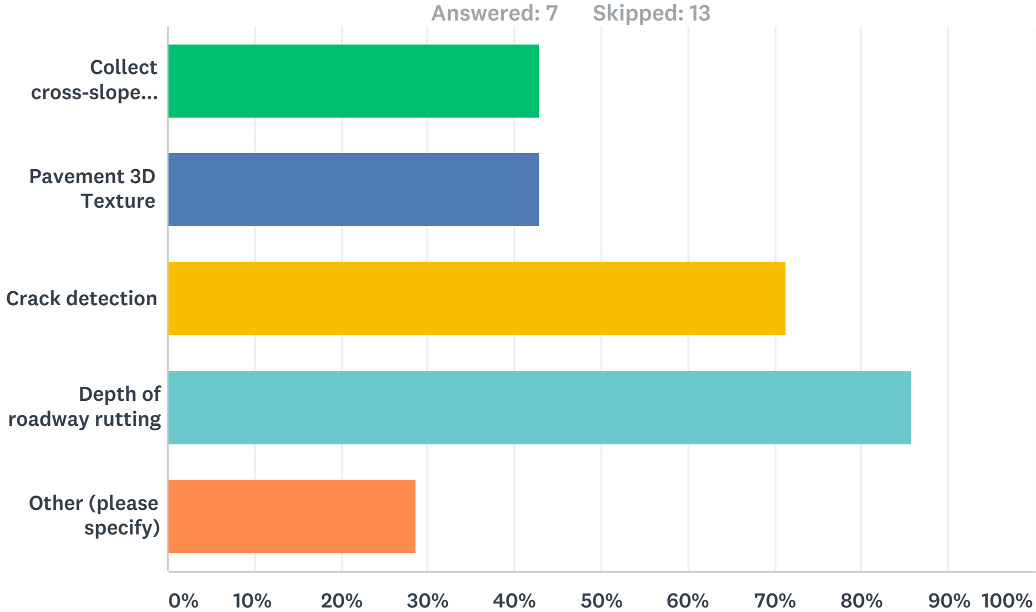
Answered: 13 Skipped: 7



Answer Choices	Responses	
Yes	61.54%	8
No	38.46%	5
Total		13

Q22 What is the purpose of using a laser transverse profiler? (Check all that apply)

Answered: 7 Skipped: 13



Answer Choices	Responses	
Collect cross-slope data	42.86%	3
Pavement 3D Texture	42.86%	3
Crack detection	71.43%	5
Depth of roadway rutting	85.71%	6
Other (please specify)	28.57%	2
Total Respondents: 7		

#	Other (please specify)	Date
1	also use for smoothness or rode assessment	7/7/2017 10:58 AM
2	Not sure	7/5/2017 7:08 AM

Q23 What laser transverse profiler does your agency use?

Answered: 7 Skipped: 13

#	Responses	Date
1	Pathway	7/14/2017 12:21 PM
2	Front-bumper mounted three laser profiler system for pavement management and fiver laser profiler system for cross-slope and grade.	7/7/2017 10:58 AM
3	Pathrunner	7/6/2017 9:34 AM
4	Not sure	7/5/2017 7:08 AM
5	Waylink System, high intensity green laser	6/21/2017 9:26 AM
6	Pavemetrics	6/19/2017 4:10 PM
7	Data Collection vendor supplied. It changes with contract.	6/19/2017 3:02 PM

Q24 Which guideline does your agency follow for transverse profiling? (e.g. AASHTO pp 69-10)

Answered: 7 Skipped: 13

#	Responses	Date
1	Caltrans automated pavement condition survey manual. Contact Dulce Feldman 916-595-4586	7/14/2017 12:26 PM
2	in-house methods. FM5-611 Florida Method of Test for Automated Measurement of Pavement Cross Slope and Grade http://www.fdot.gov/materials/administration/resources/library/publications/fstm/methods/fm5-611.pdf FM5-549 Florida Method of Test for Measuring Pavement Longitudinal Profiles using a High Speed Inertial Profiler http://www.fdot.gov/materials/administration/resources/library/publications/fstm/methods/fm5-549.pdf	7/7/2017 10:59 AM
3	AASHTO PP69-14	7/6/2017 9:34 AM
4	Not sure	7/5/2017 7:08 AM
5	N/A, depends on the system. Because we are using it for screening on compliance of cross slope only.	6/21/2017 9:27 AM
6	AASHTO PP 69-14	6/19/2017 4:13 PM
7	Federal regulations now	6/19/2017 3:03 PM

APPENDIX C

VENDOR RODEO DATA COLLECTION PLAN

Plan and Test Procedure (Revised as of 9/5/2016)
Clemson Mobile LIDAR Vendor Rodeo
Contact: Wayne Sarasua, Ph.D., P.E.
Glenn Department of Civil Engineering
Clemson University
864-650-4983
sarasua@clemson.edu

INTRODUCTION

Clemson University, in cooperation with the Citadel, is conducting a Mobile Lidar vendor rodeo that initially took place June 30, 2016 however participation can occur throughout the summer. The rodeo is a component of two research projects that are sponsored by SCDOT and FHWA. One of these projects focuses on cross-slope measurements and the other on asset management. The rodeo will take place in the upstate of South Carolina. The results of the rodeo will be published in two separate FHWA reports.

This document serves as a data collection plan and test procedure for the rodeo. Questions should be sent by email to Dr. Sarasua.

TIME AND PLACE

The next rodeos are scheduled for August 23, August 30, and September 8, 2016 however vendors may elect to do the test sections on a different day if there is a scheduling conflict. SCDOT and/or local agencies will assist with traffic control and safety aspects of conducting the rodeo. Three test sections will be included in the rodeo. The locations are shown in Figure 1. The first section is a 2000 foot 4-lane urban arterial section on US 76 (Clemson Blvd) in Anderson, South Carolina. The section begins at Forest Hill Drive and ends at the intersection of Clemson Blvd. with East West Parkway (Figure 2). The second section is 2.9 miles of East West Parkway that starts at the end of the urban section (Figure 3). The third section is a 3.5 mile length of freeway known as Business 85 in Spartanburg (Figure 4). The section of interest is between Interstate 585 and Interstate 85.

Vendors who will participate on June 30 are asked to meet at the staging area for Section 1 located in the Logan's Restaurant Parking lot (3402 Clemson Blvd., Anderson SC, 29621) at the intersection of US 76 and Forest Hill Drive at 9:30 AM. We will begin by discussing the test procedure and any last minute instructions. Data collection will take place directly following the initial meeting. Vendor vehicles will leave in a platoon and are asked to follow the Clemson research van. Vehicles will continue collecting data on Section 2 immediately following Section 1. After completion of the data collection for Sections 1 and 2, vendors may break for lunch and travel to Section 3. The staging area for Section 3 is at the Bi-Lo grocery store parking lot at 100 N Town Dr, Spartanburg, SC 29303. Vendors are asked to meet at the staging area for Section 3 at 2:00 PM. Section 3 is roughly a 50 minute drive from the end of Section 2 via SR 81 and Interstate 85. Please note that there will be no traffic control on Section 3.

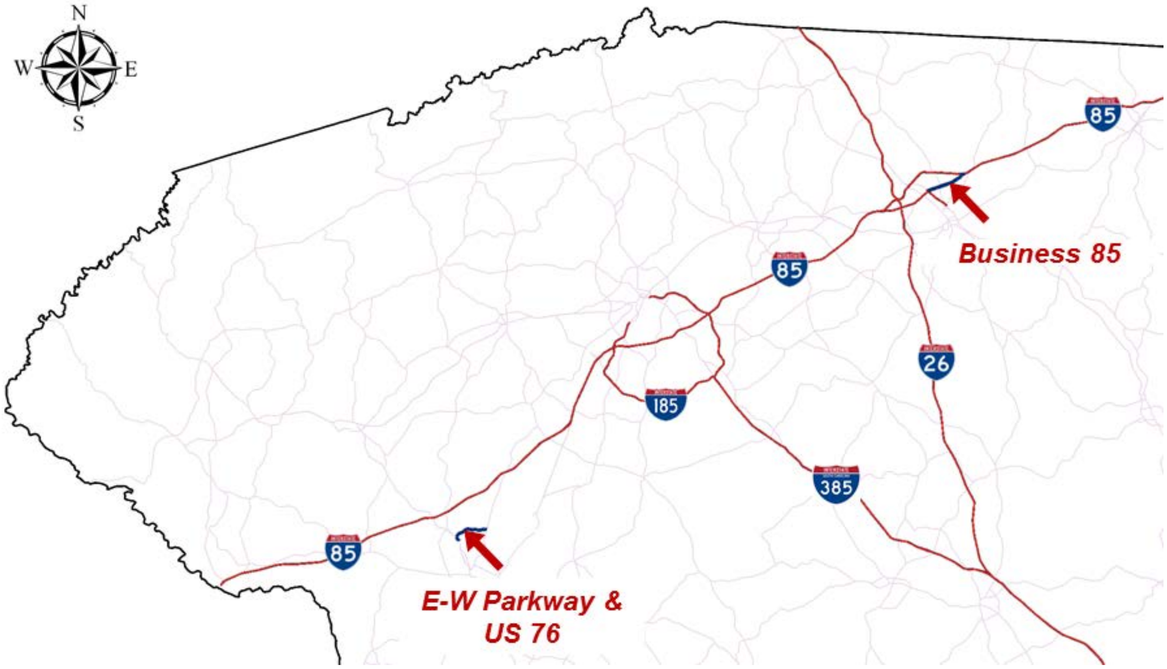


Figure 1: Overview Map of Rodeo Sections

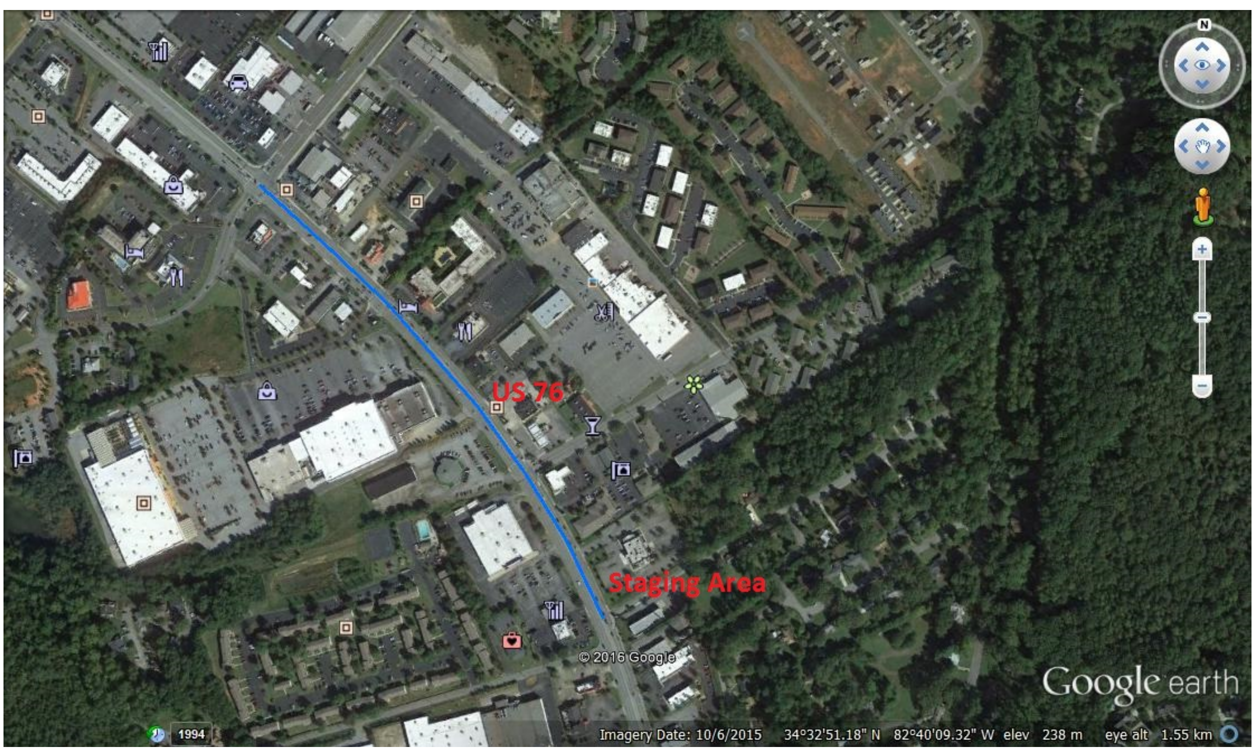


Figure 2: Section 1 - US 76 in Anderson, SC

Figure 3: Section 2 - East West Parkway in Anderson, SC

Figure 4: Section 3 - Business 85 in Spartanburg, SC

TEST PROCEDURE

Each vendor will have the opportunity to calibrate their systems and make a single pass in each direction through the test sections. Everyone will follow the same trajectory and are expected to travel at the posted speed limit. Vendor vehicles should always be in the right most 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. The researchers understand that accuracy may be a function of distance and incidence angle relative to the vehicle. Since everyone is following the same trajectory, fair comparisons can be made. The runs may be repeated if a vendor experiences technical difficulty but only data from one run may be used when submitting results.

Vendors may elect to set up a GPS base station prior to making their runs. Base stations may be set up at available control point locations. Alternatively, a VRS may be used at the Vendor's discretion. South Carolina does have a VRS real-time network. Please see *rfa.sc.gov/geodetic* for more information. Vendors who desire to use the SC VRS should contact Dr. Sarasua in advance so necessary arrangements can be made for secure access.

Primary and secondary survey control locations and selected panel locations for Sections 1 and 2 are provided in separate PDF files. Hard copies will be available at the rodeo. Coordinates for these locations are provided in Table 1 for control points and in Table 2 for panel locations at even 500' stations for station 2. . Figure 5 provides a map of the primary and secondary (panel points) survey control locations for Section 3. Coordinates for the primary control point locations for Section 3 are provided in Table 3 and coordinates for Section 3 panel points are shown in Table 4. Primary and Secondary control point accuracy meets SCDOT standards for pre-construction. These standards can be found in the SCDOT Survey manual posted on the their website at: (http://www.scdot.org/doing/technicalpdfs/publicationsmanuals/survey_manual.pdf)

Painted Station Centerline target coordinates near the beginning and end of Sections 1 and 2 are given below. The station targets have PK Nails identifying the precise locations of the coordinates.

Clemson Blvd (US 76):

N 991,090.49'
E 1,497,072.82'
Elev = 770.99'
(Assigned Station 0+00 Near Logan's Steakhouse)
(Assigned mile point 0.00)

N 992,252.71'
E 1,495,965.30'
Elev = 773.06'
(Assigned Station 16+05.415 Station Near Grady's Outfitters)
(Assigned mile point 0.304)

East West Parkway:

N 992,432.67'
E 1,495,960.48'
Elev = 774.50'
(Station 102+00)
(Assigned mile point 0.00)

N 995,853.50'
E 1,509,784.45'
Elev = 857.14'
(Station 255+00)
(Assigned mile point 2.90)

Table 1: Primary and Secondary Survey Control Coordinates for Sections 1 and 2

Mon.	North Coord	East Coord	Elev	
L1-01	991,551.32	1,496,784.55	777.83	
L1-04	996,019.10	1,499,301.22	718.12	
L1-06	992,188.42	1,503,672.15	788.7*	(GPS derived elevation)
L1-07	995,120.48	1,509,736.71	847.97	
1600	Range Pole Location			
1601	995,850.92	1,510,006.75	860.88	
1602	996,033.49	1,508,435.07	848.58	
1603	Range Pole Location			
1604	995,632.27	1,505,410.54	807.34	
1605	995,897.74	1,504,481.75	805.84	
1606	995,737.19	1,503,449.34	799.47	
1607	996,156.02	1,501,354.22	762.81	
1608	Range Pole Location			
1609	Range Pole Location			
1610	994,110.57	1,497,380.39	758.04	
1611	993,205.82	1,496,515.47	789.73	
1612	992,245.82	1,495,872.81	773.65	

Table 2: Panel Point Coordinates for 500' Station locations for Section 2

		LEFT			RIGHT	
Station	**North**	**East**	**Elevation**	**North**	**East**	**Elevation**
105+00	992,688.30	1,496,120.26	778.98	992,652.53	1,496,167.07	779.29
110+00	993,079.03	1,496,432.41	789.39	993,049.73	1,496,470.67	789.40
115+00	993,480.67	1,496,730.31	781.80	993,442.36	1,496,780.38	781.55
120+00	993,869.38	1,497,051.63	765.83	993,823.53	1,497,094.85	763.00
125+00	994,148.16	1,497,476.63	755.92	994,090.33	1,497,501.49	752.95
130+00	994,311.54	1,497,951.90	737.10	994,251.36	1,497,971.82	737.21
135+00	994,476.08	1,498,421.62	712.65	994,417.46	1,498,445.55	714.26
140+00	994,693.17	1,498,867.29	695.03	994,638.12	1,498,898.44	696.57
145+00	994,965.85	1,499,281.08	694.06	994,916.36	1,499,318.43	695.55
150+00	995,289.97	1,499,657.60	709.43	995,244.15	1,499,699.85	709.97
155+00	995,628.91	1,500,027.64	733.28	995,579.40	1,500,068.11	731.18
160+00	995,903.83	1,500,452.33	754.10	995,847.20	1,500,480.96	751.91
165+00	996,080.81	1,500,926.15	764.43	996,020.52	1,500,941.55	762.16
170+00	996,151.68	1,501,426.87	761.96	996,089.42	1,501,428.82	759.72
175+00	996,112.78	1,501,931.12	752.70	996,051.50	1,501,919.55	750.43
180+00	995,984.44	1,502,417.24	756.37	995,923.71	1,502,399.88	756.44
185+00	995,858.69	1,502,898.60	777.61	995,797.40	1,502,886.99	779.36
190+00	995,809.07	1,503,389.94	796.48	995,746.79	1,503,389.19	798.26
195+00	995,838.06	1,503,885.66	805.91	995,776.82	1,503,891.07	806.04
200+00	995,882.23	1,504,383.78	806.91	995,820.88	1,504,389.13	805.15
205+00	995,860.08	1,504,889.95	806.77	995,798.90	1,504,879.13	804.21
210+00	995,734.10	1,505,376.84	808.22	995,671.68	1,505,359.11	808.61
215+00	995,610.71	1,505,857.26	799.94	995,548.85	1,505,847.04	801.98
220+00	995,583.49	1,506,348.81	799.14	995,521.48	1,506,352.17	801.24
225+00	995,661.27	1,506,836.63	805.12	995,600.61	1,506,850.34	805.88
230+00	995,771.56	1,507,324.26	815.78	995,710.64	1,507,338.04	815.72
235+00	995,881.59	1,507,812.10	833.99	995.820.54	1,507,825.91	833.97
240+00	995,991.86	1,508,299.80	846,86	995,931.13	1,508,313.49	845.57
245+00	996,052.30	1,508,801.70	851.06	995,989.77	1,508,802.39	848.79
250+00	996,001.98	1,509,305.02	850.09	995,941.02	1,509,292.15	847.92
255+00	995,884.73	1,509,792.07	856.55	995,824.13	1,506,777.24	856.40

Note 1: Coordinate values in red are corrected from the June plan but were included in the July 6 plan.

Note 2: Identifying the precise locations of the station panel points may be tricky because the PK nails are located in the middle of the white edge line. It may be difficult to distinguish the white edge line from the reflective tape. In hindsight, placing station locations on the white edge lines was not a good idea. It was assumed that the intensity attributes would allow differentiation between the pavement markings and the pavement tape used. In many locations, the pavement tape is placed over painted stationing labels. The painted stationing labels do not have retroreflective beads in them so they should have very little intensity. With filtering, the hope is the pavement tape will be much clearer allowing easy identification of the PK nail location. Also, the taper of the reflective tape should begin on the pavement section so that the point can be distinguishable by projecting the taper through the edge line. Figure 6 illustrates this.

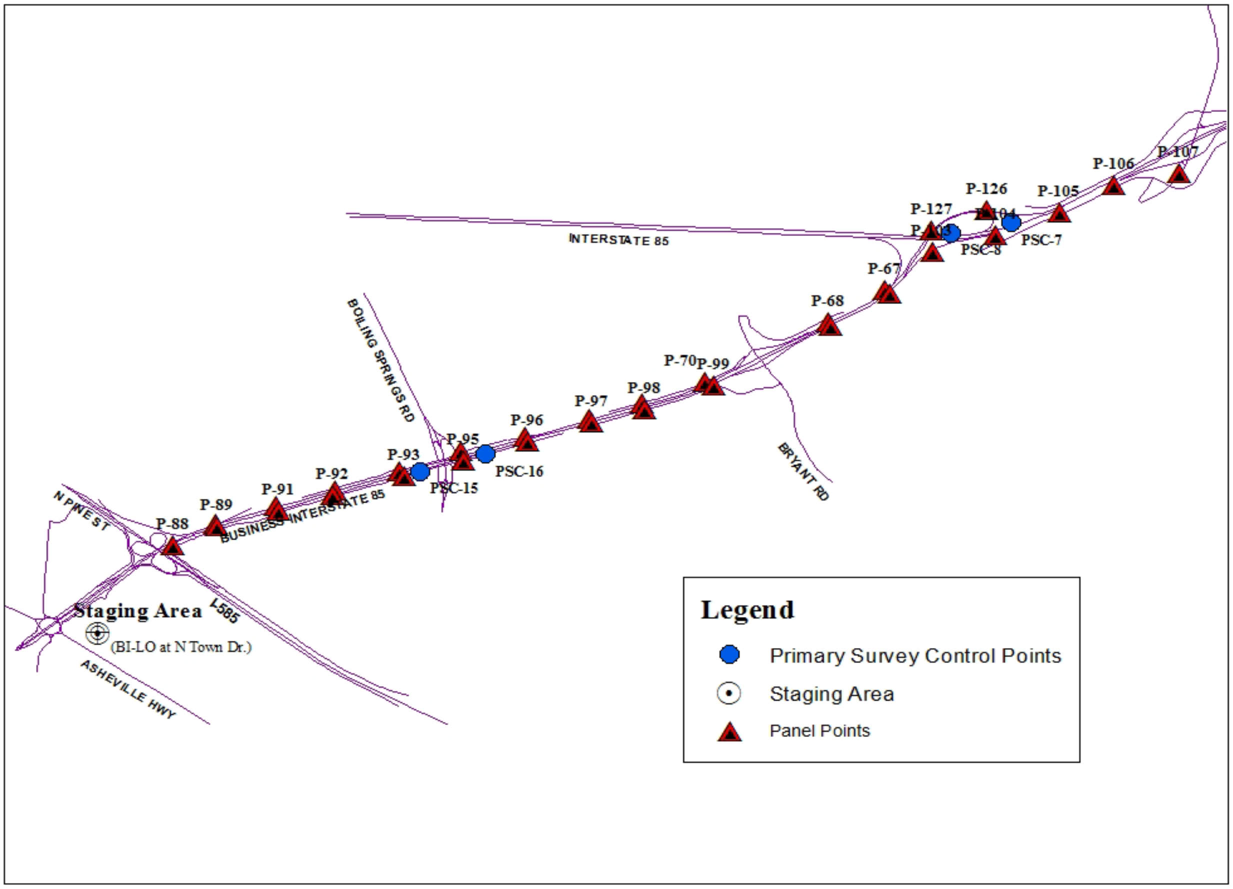


Figure 5: Survey Control Point Locations for Section 3 (Business 85)

Table 3: Primary Survey Control Coordinates for Section 3, Business 85
Horizontal Datum/Coordinate System: NAD 83 (2011) SC State Plane, Vertical Datum: NAVD 88

PSC	Grid Easting (iFT)	Grid Northing (iFT)	Project Elevation
7	1727798.57	1157849.73	860.39
8	1726604.13	1157597.35	831.73
15	1716026.30	1151632.87	790.26
16	1717325.42	1152057.34	774.90

On Business 85, Primary Control Points, are located with rebar and aluminum caps with nearby wooden stakes. They can be easily found from painted labels marked on the nearby pavement. PCPs can be used by vendors for base station setups if desired. Note that the pavement label "GPS 16" corresponds to PSC 16. Panel points are marked with a painted white chevrons and yellow retroreflective tape. A PK nail is located at the tip of the tape.

.

Table 4: Panel Point Coordinates for Section 3, Business 85

Horizontal Datum/Coordinate System: NAD 83 (2011) SC State Plane, Vertical Datum: NAVD 88			
Panel #	**Northing**	**Easting**	**Elevation**
P-67	1156154.97	1725284.53	817.45
P-68	1155360.07	1724159.26	785.34
P-70	1153873.91	1721684.58	809.34
P-71	1153351.68	1720426.34	782.86
P-72	1152934.04	1719384.92	750.34
P-73	1152519.96	1718094.40	759.54
P-74	1152151.58	1716838.20	779.31
P-76	1151685.58	1715608.31	791.55
P-77	1151177.98	1714322.75	806.90
P-78	1150770.49	1713138.00	842.44
P-80	1150363.22	1711950.34	870.36
P-88	1149796.33	1711067.04	873.36
P-89	1150300.96	1711972.84	870.42
P-91	1150698.83	1713210.51	841.43
P-92	1151058.97	1714250.96	809.36
P-93	1151553.89	1715696.60	793.07
P-95	1151910.98	1716875.37	779.52
P-96	1152406.78	1718153.33	758.52
P-97	1152853.41	1719435.12	750.56
P-98	1153214.95	1720491.13	776.44
P-99	1153797.42	1721854.75	808.43
P-101	1155261.19	1724174.81	786.30
P-102	1156086.11	1725363.61	822.32
P-103	1157176.27	1726199.15	840.56
P-104	1157564.40	1727483.97	858.98
P-105	1158114.16	1728737.27	867.22
P-106	1158810.70	1729837.43	842.05
P-107	1159094.14	1731157.27	826.09
P-126	1158179.23	1727320.71	852.24
P-127	1157665.32	1726217.91	856.31

Note that panel points highlighted in yellow have been added to the table. Most of these points are on a nearby frontage road and may be visable by LiDAR. Values in red are corrections from the previous plan.

Submitting Results

As a minimum, vendors will be asked to provide equipment specifications and a raw point cloud with attributes (e.g. elevation, amplitude/intensity, etc.) in ASPRS LAS format. Vendors may also choose to provide a rectified point cloud using primary control coordinate information provided in this document.

Equipment specifications should include information about GPS positioning, the inertial measurement unit, the LIDAR units, and cameras. If your vehicle includes a pavement profiler, those specifications should also be provided. Manufacturers and models for all equipment should be specified.

The researchers totally understand that extraction of attributes can be a time consuming process. While the test sections may have a significant number of planimetric features, only a limited number of items identified in this plan will be requested. Additionally, the vendors may voluntarily provide additional attributes. Requested information varies by segment.

While pavement condition data is not required, it would be beneficial if vendors have the capability to collect pavement condition data. The researchers are aware that equipment specifications may vary significantly for vehicles capable of collecting this data. Ideally pavement condition data should include IRI, rutting depth, fatigue cracking, longitudinal cracking, and transverse cracking. Raveling, patching percentage, and/or any other commonly collected asphalt distresses are additional attributes vendors may provide voluntarily. The data summary interval should be 0.1 miles. Any downward images (especially with distresses marked) are also of great interest if available.

<u>Section 1 (Urban Section, Clemson Blvd in Anderson)</u>

The urban segment includes sidewalks, driveways, lighting, and a variety of traffic control devices. Cross Slope information is required at a single location delineated by cones on either side of the road. The location is also marked with traverse yellow pavement marking tape. The ability to accurately link photologged images with the laser data will be evaluated. Vendors will be asked to voluntarily provide multiple levels of data extraction vs. raw data. While vendors will be encouraged to do this extraction, they may elect to qualitatively discuss how this can be done using their data collected and also provide associated costs for each level of additional data. These levels may include fully automated, semi-automated, or manual data extraction. In particular, the researchers are interested in the ability of vendors to be able to extract attributes from the raw LIDAR/photologged data. Attachment 1 identifies desirable asset attributes for Section 1 and the submittal format and requests details on how attributes are extracted. If a vendor prefers not to provide a particular attribute please answer the questions associated with “attribute not collected”.

<u>Section 2 (East West Parkway in Anderson)</u>

Vendor systems will be evaluated at this site based on several criteria including 3D coordinate accuracy of selected reflective pavement tape locations at 100’ station intervals (Figure 6) and selected secondary survey control locations that will be delineated with range poles (Figure 7) as well as a comparison of mobile system cross sections with the surveyed cross sections. Cross slope deviations from surveyed data will be given for each lane of each cross section collected. One of the goals of this research is to find out reasonable allowable measurement deviations for SCDOT construction and rehabilitation projects. The locations for desired cross sections are at whole stations 110, 124, 128, 149, 203, 208, 227, and 232. One of the cross slope sections was surveyed at 2” spacing to give a more detailed transverse profile. It is located at station 107+83 and is marked with cones and transverse yellow pavement marking tape. The section was chosen due to its surface irregularity. Vendor systems will be evaluated on how well their system can replicate the surveyed 2” spacing transverse profile.

Figure 6: Sample Station Location

Figure 7: Range Pole Location

Another evaluation criterion will be the ease at which cross slope data can be extracted from the point cloud at the cross section locations. The ability to accurately link photologged images with the laser data will be evaluated. The adjacent lane/direction accuracy will also be evaluated as well as the ability to collect shoulder, median, and clear-zone slopes. Finally, vendors will be asked to voluntarily provide multiple levels of data extraction vs. raw data. While vendors will be encouraged to do this extraction, they may elect to qualitatively discuss how this can be done using their data collected and also provide associated costs for each level of additional data. These levels may include fully automated, semi-automated, or manual data extraction. In particular, the researchers are interested in the ability of vendors to be able to extract attributes from the raw LIDAR/photologged data. Attachment 2 identifies desirable asset attributes for section 2 and the submittal format and requests details on how attributes are extracted. If a vendor prefers not to provide a particular attribute please answer the questions associated with "attribute not collected".

<u>Section 3 (Interstate Freeway Section)</u>

The vendors will be asked to map a selected section of interstate freeway. The 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. See Figure 8 for an example. Detailed surveying of horizontal/vertical elements will not be done for the freeway however primary and secondary geodetic control has been established along the shoulder.

Vendor mobile mapping data will be evaluated through comparisons with RTK GPS surveyed data labeled CU 1, CU 2, CU 3, and CU 4. The approximate map locations of these points are:

CU 1 - Between P92 and P93
CU 2 - Between P97 and P98
CU 3 - Between P73 and P74
CU 4 - Between P77 and P78

Figure 8: Section 3 Panel Point

Additionally, the vendor data will also be compared to SCDOT as-built plans as well as aerial LIDAR data that have already been collected. SCDOT is interested in the comparative accuracy of mobile and aerial LIDAR. Comparisons of the vendor collected mobile LIDAR data will be made with the surveyed data/as-built plans/aerial LIDAR data at selected stationing and control point locations; and selected edge line elevations/cross sections in tangents and on curves, and at the beginning of tangent runout (remove crown), at the beginning and end of superelevation runoff, at PC's and PT's, and at the begin and end of bridges. Results will be tabulated and will include deviations and accuracy levels (between mobile measured and survey measured cross slopes). Tolerance levels will also be noted in relation to South Carolina current cross-slope specifications. The vendors will be asked to voluntarily provide multiple levels of data extraction vs. raw data. While vendors will be encouraged to do this extraction, they may elect to qualitatively discuss how this can be done using their data collected and also provide associated costs for each level of additional data. These levels may include fully automated, semi-automated, or manual data extraction. In particular, the researchers are interested in the ability of vendors to be able to extract attributes from the raw LIDAR/photologged data. Extraction of breaklines is also of interest. Attachment 3 identifies desirable asset attributes for section 3 and the submittal format and requests details on how attributes are extracted. If a vendor prefers not to provide a particular attribute please answer the questions associated with "attribute not collected".

Final Report

There will be 2 research final reports associated with the rodeo that will be published by SCDOT and FHWA. One report focuses on cross slopes and the other report focuses on assets and LIDAR's use in asset management.

The cross slope research report will thoroughly discuss the results of the rodeo and include a revised testing procedure that details how mobile pavement cross slope data should be collected and data formats to be delivered as well as a cross-slope verification specification for SCDOT. Mobile scanning systems that meet the test standards will be deemed qualified to collect cross slope data for SCDOT.

The asset management research report will thoroughly discuss the results of the rodeo from an asset management standpoint and discuss challenges in extracting different types of assets from raw LIDAR data combined with the photologged data.

Vendors will receive their own results which can be used as the vendor pleases (marketing, publishing, etc.). The format for the final report has not yet been determined. One possibility is that the results for each vendor including the vendor's name be published. Another possibility is that a list of participating vendors be provided however results will refer to vendors anonymously. Regardless, vendors may choose to have their name removed from the report prior to being published.

Attachment 1
Section 1 - Urban Section, Clemson Blvd in Anderson Desired Asset Attributes

<u>**Note**</u>s:
Please provide equipment specifications and discuss software used in data collection, processing, and attribute extraction.
Files to submit:
Required: raw and adjusted LAS file
Encouraged: Digital snapshot of sample photolog and corresponding laser data
Required: Asset/attribute spreadsheet
Encouraged: Cross section at cones—format is flexible. E.g. digital snapshot with labeled lane by lane cross-slopes. Cross slope should be given in %. It can be calculated by the equation (change in elevation/lane width)*100. Alternatively, an AutoCAD or Microstation drawing of the cross section may be provided.

A final set of desired attributes will be made available at the rodeo. A digital Excel template file will be sent to each vendor that participates in the rodeo. The format will be similar to the printed format below. Example data is provided.

Coordinate data (if requested) should be in NAD 83 (2011) South Carolina State Plane International Feet.
Elevation data (if requested) should be NAVD 88
Examples of methods used are:
Fully Automated- automated software was primarily used to automatically extract asset data. *Semi-Automated*- automated software supplemented manual extraction of asset data.
Manual- coordinate information was retrieved in some manual fashion from the lidar data. Photo logged data was manually used to verify/extract attributes.
Linear reference data should be in station format however mile marker is also acceptable. Precise coordinate data for starting and end stations of the entire segment will be provided.

Linear Event Data Collection:

<u>Driveway</u>s (access to landuse): Includes a fictitious example

Start Station	End Station	Direction
2+00	2+24	Northbound

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting driveway attributes ($/driveway, $/mile/direction, etc.)

If the attribute **was not** collected answer the following questions:

Do you have the capability to extract the attributes? Yes No

If yes, how would you extract the attribute? (Circle one):

Fully Automated Semi-Automated Manual

What data would you use? (Circle all that applies)

Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting driveway attributes ($/driveway, $/mile/direction, etc.)

Point Event Data Collection:

Note on signs-in this template, coordinates are only associated with sign posts—not signs. Sign data can be linked to sign posts using the Sign Post ID field.

Sign Posts: Includes a fictitious example

ID	X Coordinate (Easting)	Y Coordinates (Northing)	Direction
1	1692626.03	1142911.46	Northbound

If the attribute **was** collected answer the following questions:

How was the attribute extracted? (Circle one):

Fully Automated Semi-Automated Manual

What data was used? (Circle all that applies)

Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting sign post attributes ($/sign post, $/mile/direction, etc.)

If the attribute **was not** collected answer the following questions:

Do you have the capability to extract the attributes? Yes No

If yes, how would you extract the attribute? (Circle one):

Fully Automated Semi-Automated Manual

What data would you use? (Circle all that applies)

Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting sign post attributes ($/sign post, $/mile/direction, etc.)

Signs:

Sign Post ID	MUTCD Code	Legend/Description
1	R1-1	Stop
1	R1-4	All way

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting sign attributes ($/sign, $/mile/direction, etc.)
If the attribute **was not** collected answer the following questions:
Do you have the capability to extract the attributes? Yes No
If yes, how would you extract the attribute? (Circle one):
Fully Automated Semi-Automated Manual
What data would you use? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting sign attributes ($/sign, $/mile/direction, etc.)

Street Lights, Utility Poles, Manholes, Fire hydrants (format same for each)

X Coordinate (Easting)	Y Coordinate (Northing)	Direction	Description
1692626.03	1142911.46	Northbound	Light Pole

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting attributes ($/unit, $/mile/direction, etc.)
If the attribute **was not** collected answer the following questions:

Do you have the capability to extract the attributes? Yes No
If yes, how would you extract the attribute? (Circle one):
Fully Automated Semi-Automated Manual
What data would you use? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting attributes ($/unit, $/mile/direction, etc.)

Pavement Markings (any markings on the road other than lines):

X Coordinate (Easting)	Y Coordinate (Northing)	Direction	Description
1692626.03	1142911.46	Northbound	Left arrow

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting pavement marking attributes ($/marking, $/mile/direction, etc.)
If the attribute **was not** collected answer the following questions:
Do you have the capability to extract the attributes? Yes No
If yes, how would you extract the attribute? (Circle one):
Fully Automated Semi-Automated Manual
What data would you use? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting pavement marking attributes ($/marking, $/mile/direction, etc.)

Pavement Condition Data (if provided)

Voluntary pavement condition data should be provided using milepoint rather than stationing. Beginning and end milepoints for the section 1 is provided on page 4. Pavement condition data should include IRI, rutting depth, fatigue cracking, longitudinal cracking, and transverse cracking. Raveling, patching percentage, and/or any other commonly collected asphalt distresses are additional attributes vendors may provide voluntarily. The format for this data is flexible however an Excel spreadsheet is preferred. The data summary interval should be 0.1 miles. Any downward images (especially with distresses marked) are also of great interest if available. If pavement condition information is provided by the vendor, the vendor should include specifics about the data collection methodology (e.g., type of technology, sampling/measurement frequency/spacing (longitudinal and transverse), dimensions of evaluation frame, sensor height above pavement, etc.), analysis methodology, and verification procedures.

Attachment 2

Section 2 – Parkway Section, East West Parkway in Anderson Desired Asset Attributes

Notes:

Please provide equipment specifications and discuss software used in data collection, processing, and attribute extraction.

Files to submit:

Required: raw and adjusted LAS file

Encouraged: 3D breaklines along the linear pavement markings in a cad format (AutoCAD or Microstation)

Encouraged: Digital snapshot of sample photolog and corresponding laser data

Required: Asset/attribute spreadsheet

Encouraged: Transverse profiles (cross sections) at preselected locations that includes slope parameters of the median, travel lanes, shoulders, foreslope, backslope, multiuse path. Slopes for lanes and shoulders should be given in %. It can be calculated by the equation (change in elevation/lane width)*100. Ditches can be given in % or as a ratio (e.g. 4h:1v) An AutoCAD or Microstation drawing of the cross sections is preferred. The locations for desired cross sections are at whole stations 110, 124, 128, 149, 203, 208, 227, and 232. One of the cross slope sections was surveyed at 2" spacing to give a more detailed transverse profile. It is located at station 107+83 and is marked with cones and transverse yellow pavement marking tape. The section was chosen due to its surface irregularity. Vendor systems will be evaluated on how well their system can replicate the surveyed 2" spacing transverse profile.

Encouraged: A plan view of the roadway centerline in an AutoCAD or Microstation format. Only tangent lines and circular curves should be used. Stationing is encouraged but not required. Note that the centerline station coordinates will be provided for two stations near the beginning and end of section 2. Painted survey targets with PK nails delineate these locations.

Encouraged: A profile view of the roadway centerline in an AutoCAD or Microstation format. Points are acceptable however profile grades and parabolic vertical curves are encouraged.

Vendor mobile mapping data will be evaluated through comparisons with RTK GPS surveyed secondary control points labeled 1600, 1603, 1608, and 1609 on East West Parkway Sheet 1. These locations are identified with range poles when the liDAR data was collected. Please provide the coordinate at the TOP of each range pole.

A final set of desired attributes will be made available at the rodeo. A digital Excel template file will be sent to each vendor that participates in the rodeo. The format will be similar to the printed format below. Example data is provided.

Coordinate data (if requested) should be in NAD 83 South Carolina State Plane International Feet.

Longitude, Latitude is acceptable however the datum should be specified (e.g. WGS 84)

Elevation data (if requested) should be NAVD 88

Examples of methods used are:

Fully Automated- automated software was primarily used to automatically extract asset data. *Semi-Automated*- automated software supplemented manual extraction of asset data.

Manual- coordinate information was retrieved in some manual fashion from the lidar data. Photo logged data was manually used to verify/extract attributes.

Linear reference data should be in station format however mile marker is also acceptable. Precise coordinate data for starting and end stations of the entire segment will be provided.

Linear Event Data Collection:

Driveways or Intersections:

Start Station	End Station	Direction
2+00	2+24	Eastbound

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting driveway attributes ($/driveway, $/mile/direction, etc.)
If the attribute **was not** collected answer the following questions:
Do you have the capability to extract the attributes? Yes No
If yes, how would you extract the attribute? (Circle one):
Fully Automated Semi-Automated Manual
What data would you use? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting driveway attributes ($/driveway, $/mile/direction, etc.)

Barrier Systems: Possible types are Cable, W-beam, Tri-beam, concrete, crash cushion, other. Possible direction can be Eastbound, Westbound, or Median.

Type	Start Station	End Station	Direction
	2+00	2+24	Eastbound

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting barrier system attributes ($/barrier system, $/mile/direction, etc.)
If the attribute **was not** collected answer the following questions:
Do you have the capability to extract the attributes? Yes No
If yes, how would you extract the attribute? (Circle one):
Fully Automated Semi-Automated Manual
What data would you use? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting bridge attributes ($/barrier system, $/mile/direction, etc.)

Medians: Possible types are Raised, TWLTL, Natural, Turn-lane, Barrier, Undivided, Painted Asphalt.

Type	Start Station	End Station	Width
Undivided	2+00	2+24	0

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting median attributes ($/mile, etc.)
If the attribute **was not** collected answer the following questions:
Do you have the capability to extract the attributes? Yes No
If yes, how would you extract the attribute? (Circle one):
Fully Automated Semi-Automated Manual
What data would you use? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting median attributes ($/mile, etc.)

Bridges: Note that there is only one bridge in Section 2

Start Station	End Station
2+00	2+24

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting bridge attributes ($/bridge, $/mile/direction, etc.)
If the attribute **was not** collected answer the following questions:
Do you have the capability to extract the attributes? Yes No
If yes, how would you extract the attribute? (Circle one):
Fully Automated Semi-Automated Manual
What data would you use? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting bridge attributes ($/bridge, $/mile/direction, etc.)

Travel lane width: Additional records should only be included if there is a change in lane width by more than .5'. Widths should be to the nearest .5'/

Start Station	End Station	WB Outside	WB Inside	EB Inside	EB Outside	Turn Lane
2+00	22+24	12.5	12	12	12.5	

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting lane width attributes ($/lane mile/direction, etc.)
If the attribute **was not** collected answer the following questions:
Do you have the capability to extract the attributes? Yes No

If yes, how would you extract the attribute? (Circle one):
Fully Automated   Semi-Automated   Manual
What data would you use? (Circle all that applies)
    Lidar   Photolog   Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting lane width attributes ($/lane mile/direction, etc.)

Point Event Data Collection:

Note on signs-in this template, coordinates are only associated with sign posts—not signs. Sign data can be linked to sign posts using the Sign Post ID field.

Sign Posts:

ID	X Coordinate (Easting)	Y Coordinates (Northing)	Direction
1	1692626.03	1142911.46	Northbound

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated   Semi-Automated   Manual
What data was used? (Circle all that applies)
    Lidar   Photolog   Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting sign post attributes ($/sign post, $/mile/direction, etc.)
If the attribute **was not** collected answer the following questions:
Do you have the capability to extract the attributes?   Yes   No
If yes, how would you extract the attribute? (Circle one):
Fully Automated   Semi-Automated   Manual
What data would you use? (Circle all that applies)
    Lidar   Photolog   Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting sign post attributes ($/sign post, $/mile/direction, etc.)

Signs:

Sign Post ID	MUTCD Code	Legend/Description
1	R1-1	Stop
1	R1-4	All way

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting sign attributes ($/sign, $/mile/direction, etc.)
If the attribute **was not** collected answer the following questions:
Do you have the capability to extract the attributes? Yes No
If yes, how would you extract the attribute? (Circle one):
Fully Automated Semi-Automated Manual
What data would you use? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting sign attributes ($/sign, $/mile/direction, etc.)

<u>Street Lights, Utility Poles, Manholes, Fire hydrants</u> (format same for each)

X Coordinate (Easting)	Y Coordinate (Northing)	Direction
1692626.03	1142911.46	Northbound

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting attributes ($/unit, $/mile/direction, etc.)
If the attribute **was not** collected answer the following questions:
Do you have the capability to extract the attributes? Yes No
If yes, how would you extract the attribute? (Circle one):
Fully Automated Semi-Automated Manual
What data would you use? (Circle all that applies)

Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting attributes ($/unit, $/mile/direction, etc.)

Longitudinal Pavement markings

The only pavement marking attribute requested is 30 meter geometry retroreflectivity at one specified location: Station 176+25. The location is shown below. The researchers are interested in the retroreflectivity of the reflective tape markings AND the paint parallel to the reflective tape markings. It is not expected that any vendor will provide this attribute. The researchers will look at how intensity/amplitude attributes of the laser data correlate with retroreflectivity.


Pavement Markings (any markings on the road other than lines):

X Coordinate (Easting)	Y Coordinate (Northing)	Direction	Description
1692626.03	1142911.46	Northbound	Left arrow

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting pavement marking attributes ($/marking, $/mile/direction, etc.)
If the attribute **was not** collected answer the following questions:
Do you have the capability to extract the attributes? Yes No
If yes, how would you extract the attribute? (Circle one):
Fully Automated Semi-Automated Manual
What data would you use? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting pavement marking attributes ($/marking, $/mile/direction, etc.)

Pavement Condition Data (if provided)

Voluntary pavement condition data should be provided using milepoint rather than stationing. Beginning and end milepoints for the sections will be provided prior to the rodeo. Pavement condition data should include IRI, rutting depth, fatigue cracking, longitudinal cracking, and transverse cracking. Raveling, patching percentage, and/or any other commonly collected asphalt distresses are additional attributes vendors may provide voluntarily. The format for this data is flexible however an Excel spreadsheet is preferred. The data summary interval should be 0.1 miles. Any downward images (especially with distresses marked) are also of great interest if available. If pavement condition information is provided by the vendor, the vendor should include specifics about the data collection methodology (e.g., type of technology, sampling/measurement frequency/spacing (longitudinal and transverse), dimensions of evaluation frame, sensor height above pavement, etc.), analysis methodology, and verification procedures.

Attachment 3
Section 3 – Business 85 in Spartanburg Desired Asset Attributes

Notes:
Please provide equipment specifications and discuss software used in data collection, processing, and attribute extraction.
Files to submit:
Required: raw and adjusted LAS file
Encouraged: 3D breaklines along the linear pavement markings in a cad format (AutoCAD or Microstation)
Encouraged: Digital snapshot of sample photolog and corresponding laser data
Required: Asset/attribute spreadsheet
Encouraged: Cross sections at pre-selected locations that includes slope parameters of the median, travel lanes, shoulders, foreslope, backslope. Slopes for lanes and shoulders should be given in %. It can be calculated by the equation (change in elevation/lane width)*100. Ditches can be given in % or as a ratio (e.g. 4h:1v) An AutoCAD or Microstation drawing of the cross sections is preferred. The pre-selected 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.

Encouraged: Panel Coordinates and elevations at locations indicated by a PK nail and chrevrons.

Vendor mobile mapping data will be evaluated through comparisons with RTK GPS surveyed data labeled CU 1, CU 2, CU 3, and CU 4. The approximate map locations of these points are:

- CU 1 - Between P92 and P93
- CU 2 - Between P97 and P98
- CU 3 - Between P73 and P74
- CU 4 - Between P77 and P78

A final set of desired attributes will be made available at the rodeo. A digital Excel template file will be sent to each vendor that participates in the rodeo. The format will be similar to the printed format below. Example data is provided.

Coordinate data (if requested) should be in NAD 83 South Carolina State Plane International Feet.
Longitude, Latitude is acceptable however the datum should be specified (e.g. WGS 84)
Elevation data (if requested) should be NAVD 88
Examples of methods used are:
Fully Automated- automated software was primarily used to automatically extract asset data. *Semi-Automated*- automated software supplemented manual extraction of asset data.
Manual- coordinate information was retrieved in some manual fashion from the lidar data. Photo logged data was manually used to verify/extract attributes.
Linear reference data should be in station format however mile marker is also acceptable. Precise coordinate data for starting and end stations of the entire segment will be provided.

Linear Event Data Collection:

<u>Barrier Systems</u>: Possible types are Cable, W-beam, Tri-beam, concrete, crash cushion, other. Possible direction can be Northbound, Southbound, or Median.

Type	Start Station	End Station	Direction
W-beam	2+00	2+24	Northtbound

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting barrier system attributes ($/barrier system, $/mile/direction, etc.)
If the attribute **was not** collected answer the following questions:
Do you have the capability to extract the attributes? Yes No
If yes, how would you extract the attribute? (Circle one):
Fully Automated Semi-Automated Manual
What data would you use? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting bridge attributes ($/barrier system, $/mile/direction, etc.)

<u>Medians</u>: Possible types are Natural, Barrier.

Type	Start Station	End Station	Width
Natural	2+00	2+24	24

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting median attributes ($/mile, etc.)
If the attribute **was not** collected answer the following questions:

Do you have the capability to extract the attributes? Yes No
If yes, how would you extract the attribute? (Circle one):
Fully Automated Semi-Automated Manual
What data would you use? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting median attributes ($/mile, etc.)

<u>Bridges</u>: Types: Overpass, underpass

Crossing Road Type	Start Station	End Station
Overpass	2+00	2+24

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting bridge attributes ($/bridge, $/mile/direction, etc.)
If the attribute **was not** collected answer the following questions:
Do you have the capability to extract the attributes? Yes No
If yes, how would you extract the attribute? (Circle one):
Fully Automated Semi-Automated Manual
What data would you use? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting bridge attributes ($/bridge, $/mile/direction, etc.)

<u>Travel lane width:</u> Additional records should only be included if there is a change in lane width by more than .5’. Widths should be to the nearest .5’/

Start Station	End Station	WB Outside	WB Inside	EB Inside	EB Outside
2+00	22+24	12.5	12	12	12.5

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting lane width attributes ($/lane mile/direction, etc.)
If the attribute **was not** collected answer the following questions:
Do you have the capability to extract the attributes? Yes No
If yes, how would you extract the attribute? (Circle one):
Fully Automated Semi-Automated Manual
What data would you use? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting lane width attributes ($/lane mile/direction, etc.)

Longitudinal Pavement markings

The only pavement marking attribute requested is 30 meter geometry retroreflectivity near panel point P93. The location is shown below. The reesearchers are interested in the retroreflectivity of the reflective tape markings AND the paint parallel to the reflective tape markings. See figure. It is not expected that any vendor will provide this attribute. The researchers will look at how intensity/amplitude attributes of the laser data correlate with retroreflectivity.

Pavement Markings (any markings on the road other than lines):

X Coordinate (Easting)	Y Coordinate (Northing)	Direction	Description
1692626.03	1142911.46	Northbound	Left arrow

If the attribute **was** collected answer the following questions:
How was the attribute extracted? (Circle one):
Fully Automated Semi-Automated Manual
What data was used? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting pavement marking attributes ($/marking, $/mile/direction, etc.)
If the attribute **was not** collected answer the following questions:
Do you have the capability to extract the attributes? Yes No
If yes, how would you extract the attribute? (Circle one):
Fully Automated Semi-Automated Manual
What data would you use? (Circle all that applies)
Lidar Photolog Other

Briefly describe the process for attribute extraction?

Please estimate a cost and associated units for extracting pavement marking attributes ($/marking, $/mile/direction, etc.)

Pavement Condition Data (if provided)

Voluntary pavement condition data should be provided using milepoint rather than stationing. Beginning and end milepoints for the sections will be provided prior to the rodeo. Pavement condition data should include IRI, rutting depth, fatigue cracking, longitudinal cracking, and transverse cracking. Raveling, patching percentage, and/or any other commonly collected asphalt distresses are additional attributes vendors may provide voluntarily. The format for this data is flexible however an Excel spreadsheet is preferred. The data summary interval should be 0.1 miles. Any downward images (especially with distresses marked) are also of great interest if available. If pavement condition information is provided by the vendor, the vendor should include specifics about the data collection methodology (e.g., type of technology, sampling/measurement frequency/spacing (longitudinal and transverse), dimensions of evaluation frame, sensor height above pavement, etc.), analysis methodology, and verification procedures.

APPENDIX D

QUICK REFERENCE FOR SUBMITTING RESULTS

QUICK REFERENCE FOR SUBMITTING RESULTS IN ADDITION TO EXCEL TEMPLATES
(Note that horizontal coordinate data is NAD 83, 2011, elevation data is NAVD 88)

<u>Section 1 (Urban Section, Clemson Blvd in Anderson)</u>

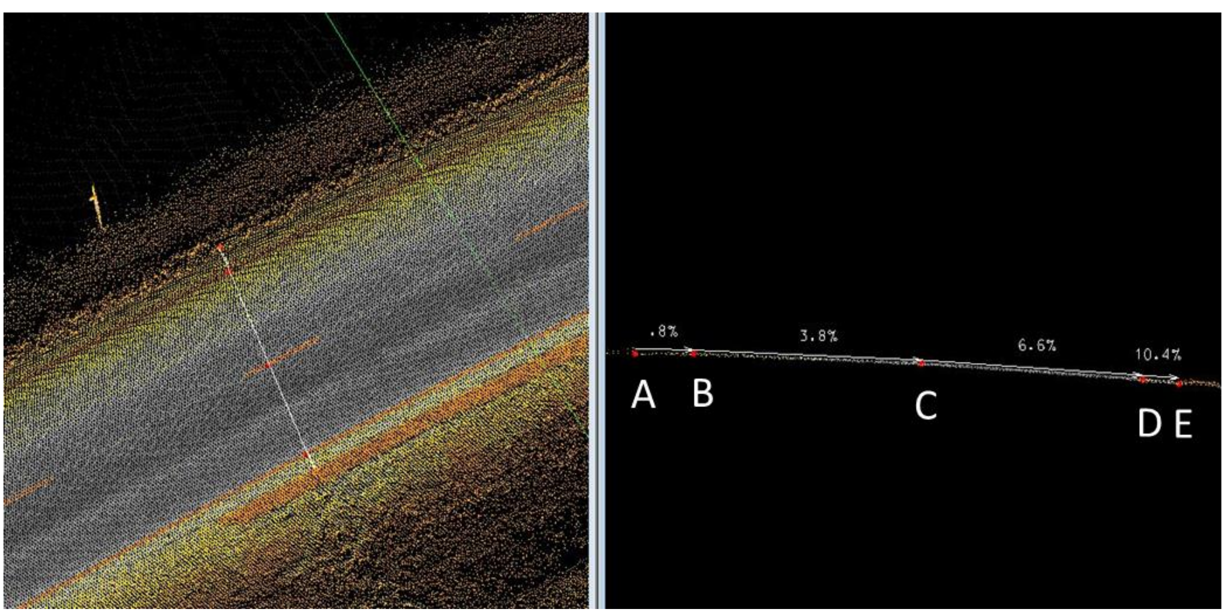
Painted Station Centerline target coordinates near the beginning and end of Sections 1 are given below. Note the assigned station and mile point locations to use for providing attributes in the Excel spreadsheets.

N 991,090.49'
E 1,497,072.82'
Elev = 770.99'
(Assigned Station 0+00 Near Logan's Steakhouse)
(Assigned mile point 0.00)

N 992,252.71'
E 1,495,965.30'
Elev = 773.06'
(Assigned Station (16+05.415 Station Near Grady's Outfitters)
(Assigned mile point 0.304)

<u>Cross slope information at a single location</u>

Cross Slope information is required at a single location delineated by cones on either side of the road. The location is also marked with yellow reflective tape. Format is flexible. Cross slope should be given in % for each lane and for the sidewalks. It can be calculated by the equation (change in elevation/lane width)*100. For the rural 2-lane highway below, line AB represents the inside shoulder, BC is the inside lane, CD is the outside lane, and DE is the outside shoulder. Only the elevations at A, B, C, D, and E are used to calculate the cross slopes for the shoulders and the travel lanes. In lieu of calculations, an AutoCAD or Microstation drawing of the cross section may be provided and the researchers will calculate the cross slopes.



Section 2 (East West Parkway in Anderson)

Painted Station Centerline target coordinates near the beginning and end of Sections 2 are given below. Note the assigned station and mile point locations to use for providing attributes in the Excel spreadsheets.

N 992,432.67’
E 1,495,960.48’
Elev = 774.50’
(Station 102+00)
(Assigned mile point 0.00)

N 995,853.50’
E 1,509,784.45’
Elev = 857.14’
(Station 255+00)
(Assigned mile point 2.90)

Easting, Northing, and Elevation at SCPS 1600, 1603, 1608, and 1609

Vendor mobile mapping data will be evaluated through comparisons with RTK GPS surveyed secondary control points labeled 1600, 1603, 1608, and 1609 on East West Parkway Sheet 1. These locations are identified with range poles when the liDAR data was collected. Please provide the coordinate at the TOP of each range pole.

Cross slope information at 8 stations:locations:110, 124, 128, 149, 203, 208, 227, and 232

The locations for desired cross sections are at whole stations 110+00, 124+00, 128+00, 149+00, 203+00, 208+00, 227+00, and 232+00. The calculation and the format for delivery is similar to that of section one. While cross slope grades can be just listed for the lanes and the multi-use path, vendors should also provide an AutoCAD or Microstation cross section drawing so that the entire cross section including lanes, shoulders, foreslopes, backslopes, etc. can be evaluated.

Complete transverse profile at station 107+83.

One of the cross slope sections was surveyed at 2” spacing to give a more detailed transverse profile. It is located at station 107+83 and is marked with cones and transverse yellow pavement marking tape. The section was chosen due to its surface irregularity. Please provide an AutoCAD or Microstation cross section drawing that includes all LAS points along this cross section.

Plan view of the roadway centerline in an AutoCAD or Microstation format

Only tangent lines and circular curves should be used. Stationing is encouraged but not required.

A profile view of the roadway centerline in an AutoCAD or Microstation format

Points are acceptable however profile grades and parabolic vertical curves are encouraged.

3D breaklines along the linear pavement markings in a cad format (AutoCAD or Microstation)

Digital snapshot of sample photolog and corresponding laser data

Section 3 (Interstate Freeway Section)

Cross slope information at 6 panel point locations: P78, P91, P98, P103, P126 and P127

The locations for desired cross sections are at 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. The calculation and the format for delivery is similar to that of section one. Cross slope grades can be just listed for the lanes and the shoulders. Vendors may choose to provide AutoCAD or Microstation cross section drawings.

Easting, Northing, and Elevation at CU 1, CU 2, CU 3, and CU 4

Vendor mobile mapping data will be evaluated through comparisons with RTK GPS surveyed data labeled CU 1, CU 2, CU 3, and CU 4. The approximate map locations of these points are:

- CU 1 - Between P92 and P93
- CU 2 - Between P97 and P98
- CU 3 - Between P73 and P74
- CU 4 - Between P77 and P78

The points are marked with a painted chevron, yellow reflective pavement marking tape, and a PK nail.

3D breaklines along the linear pavement markings in a cad format (AutoCAD or Microstation)

Digital snapshot of sample photolog and corresponding laser data

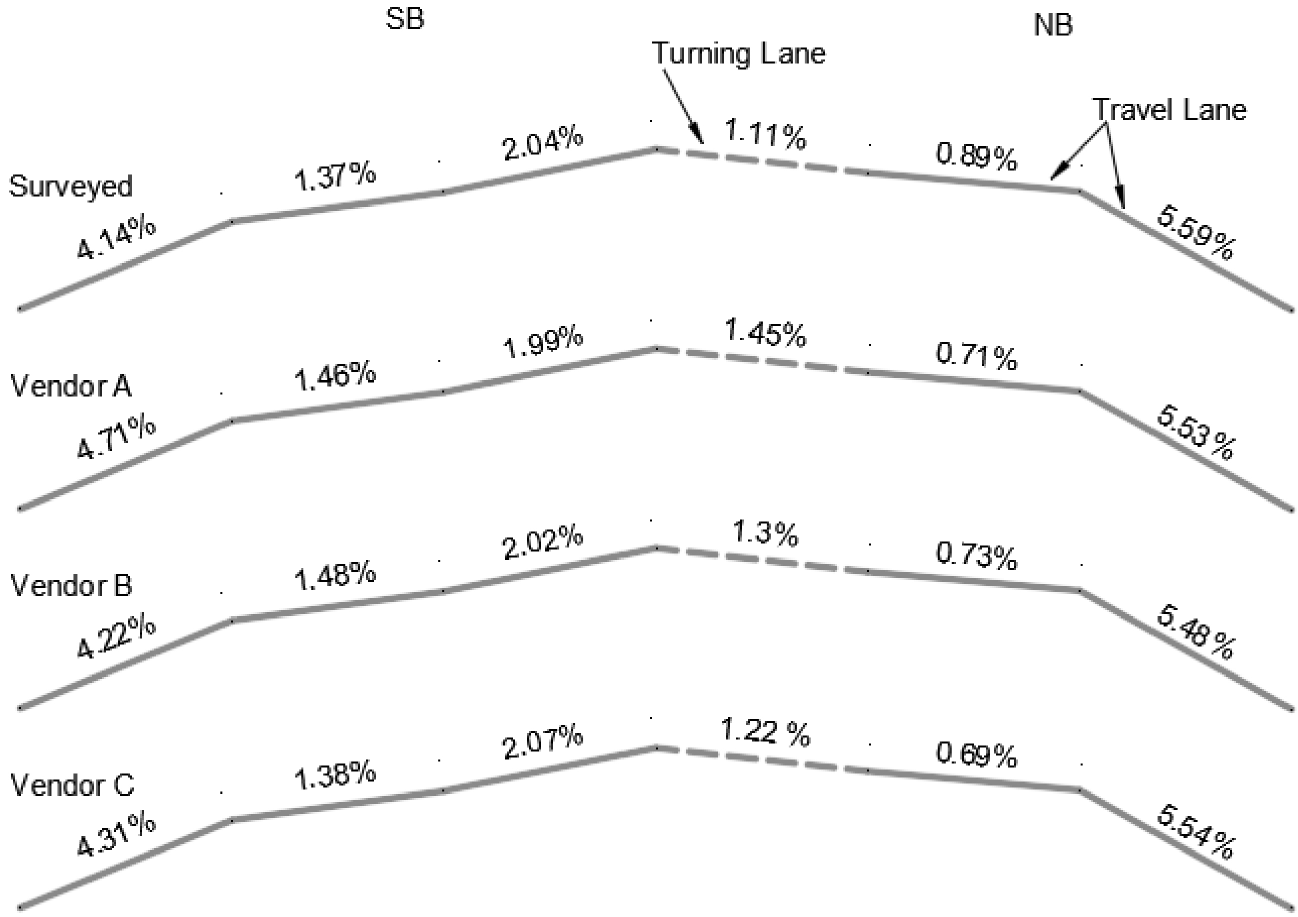
Pavement Condition Data (if provided)

Voluntary pavement condition data should be provided using milepoint rather than stationing. Beginning and end milepoints for the sections will be provided prior to the rodeo. Pavement condition data should include IRI, rutting depth, fatigue cracking, longitudinal cracking, and transverse cracking. Raveling, patching percentage, and/or any other commonly collected asphalt distresses are additional attributes vendors may provide voluntarily. The format for this data is flexible however an Excel spreadsheet is preferred. The data summary interval should be 0.1 miles. Any downward images (especially with distresses marked) are also of great interest if available. If pavement condition information is provided by the vendor, the vendor should include specifics about the data collection methodology (e.g., type of technology, sampling/measurement frequency/spacing (longitudinal and transverse), dimensions of evaluation frame, sensor height above pavement, etc.), analysis methodology, and verification procedures.

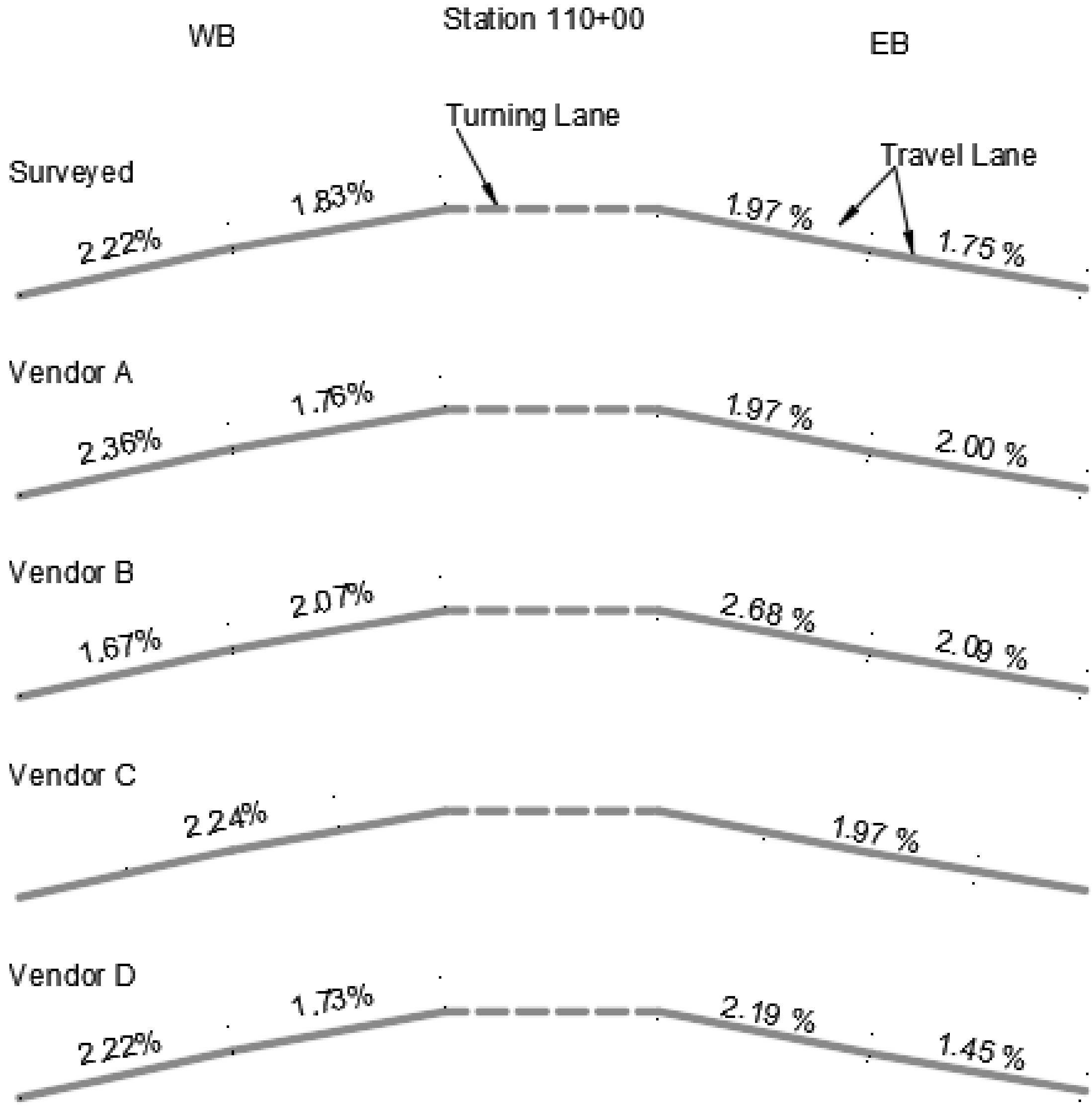
<u>APPENDIX E</u>

CROSS SECTION COMPARISONS FOR ALL SECTIONS

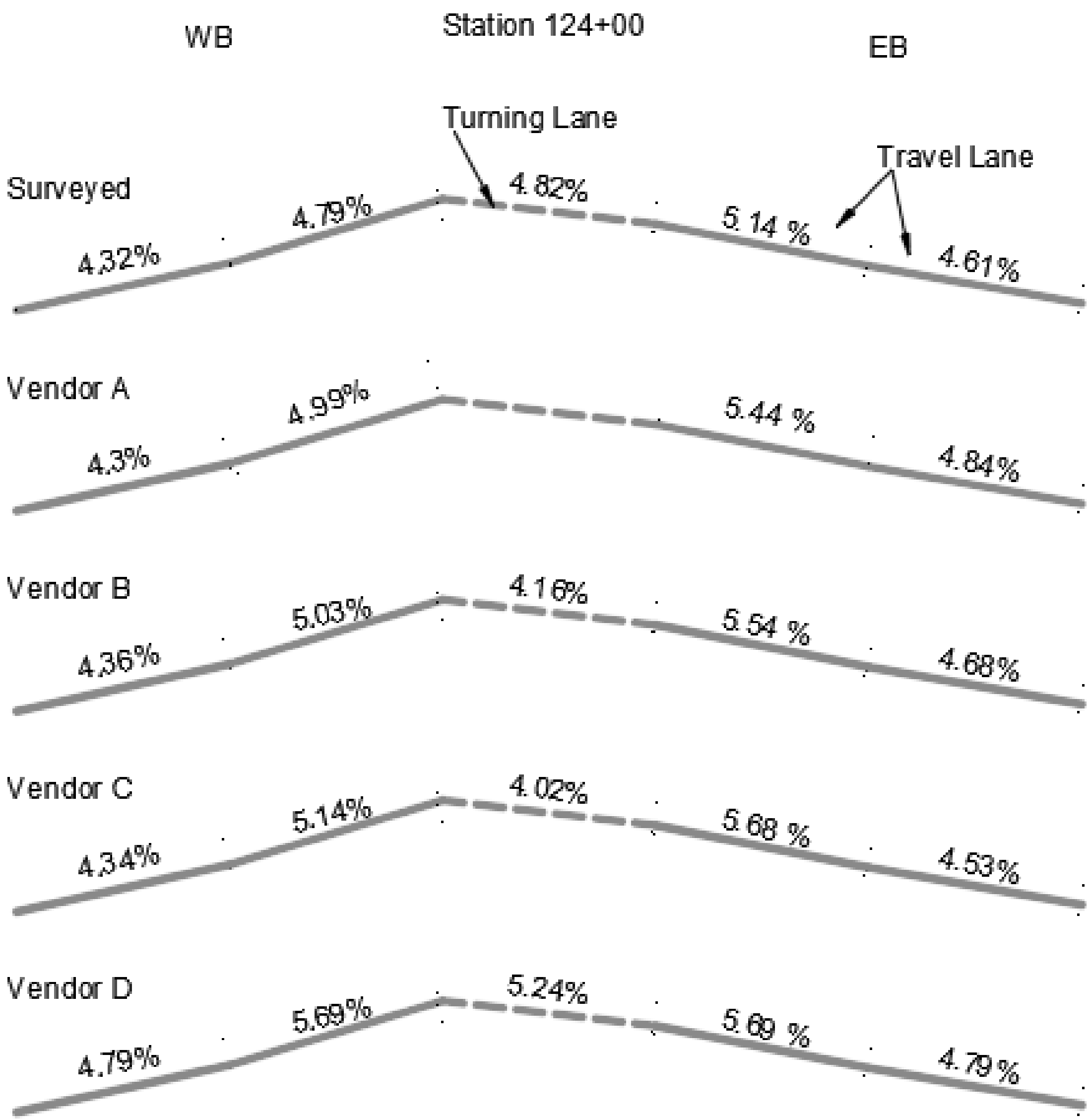
Section 1 – US 76, Anderson, SC



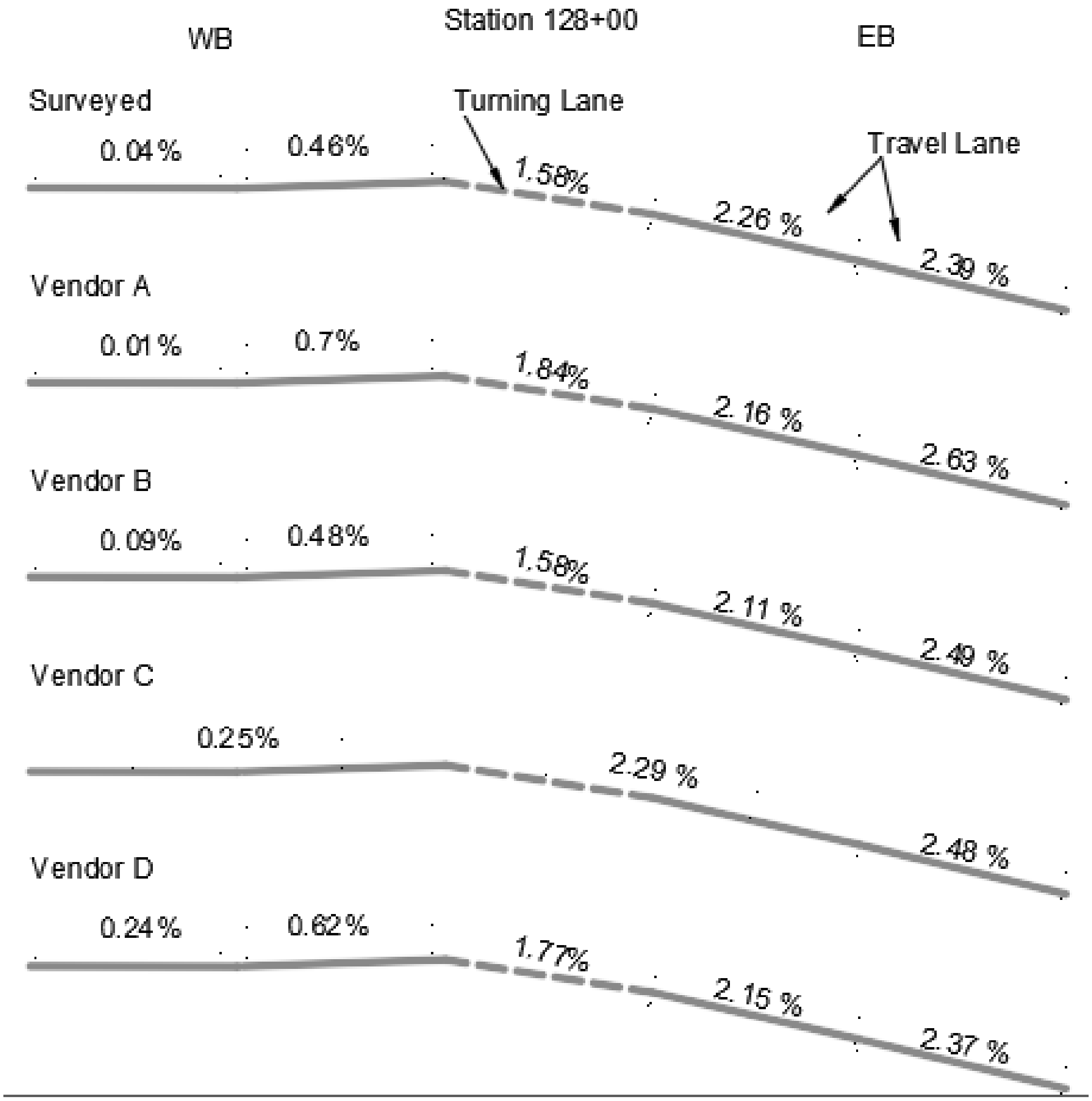
Section 2 – East West Parkway, Anderson, SC



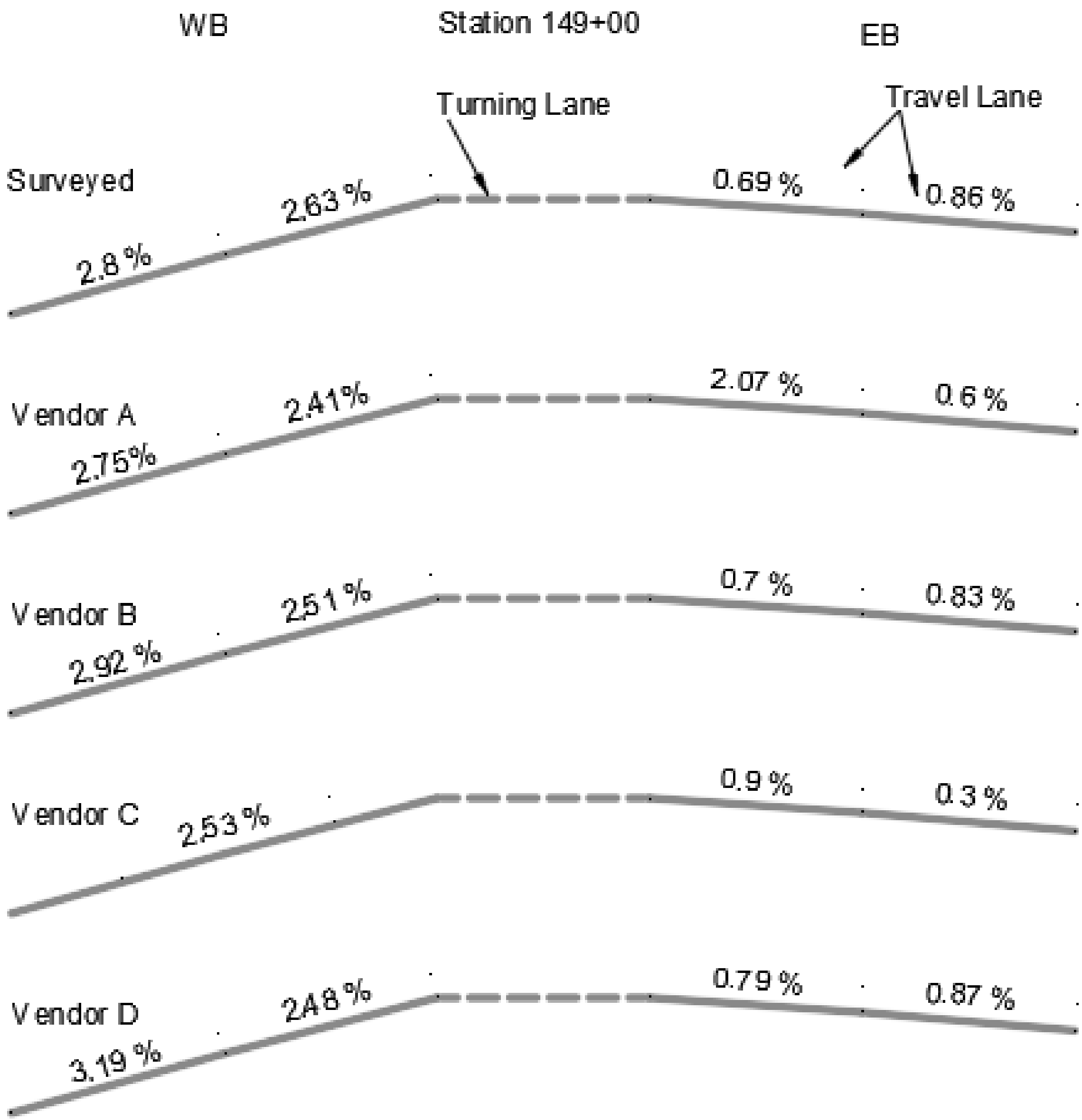
Section 2 – East West Parkway, Anderson, SC



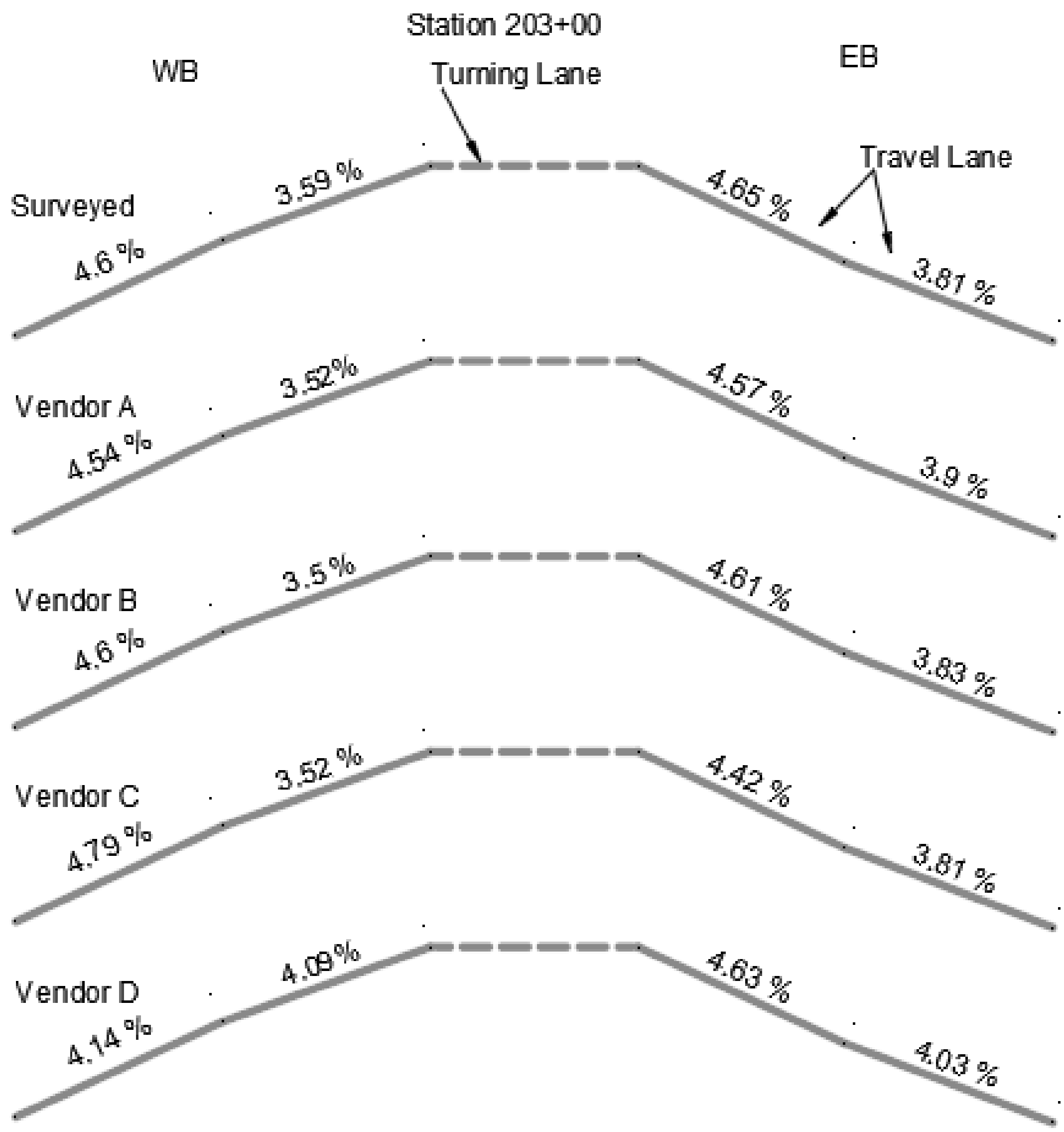
Section 2 – East West Parkway, Anderson, SC



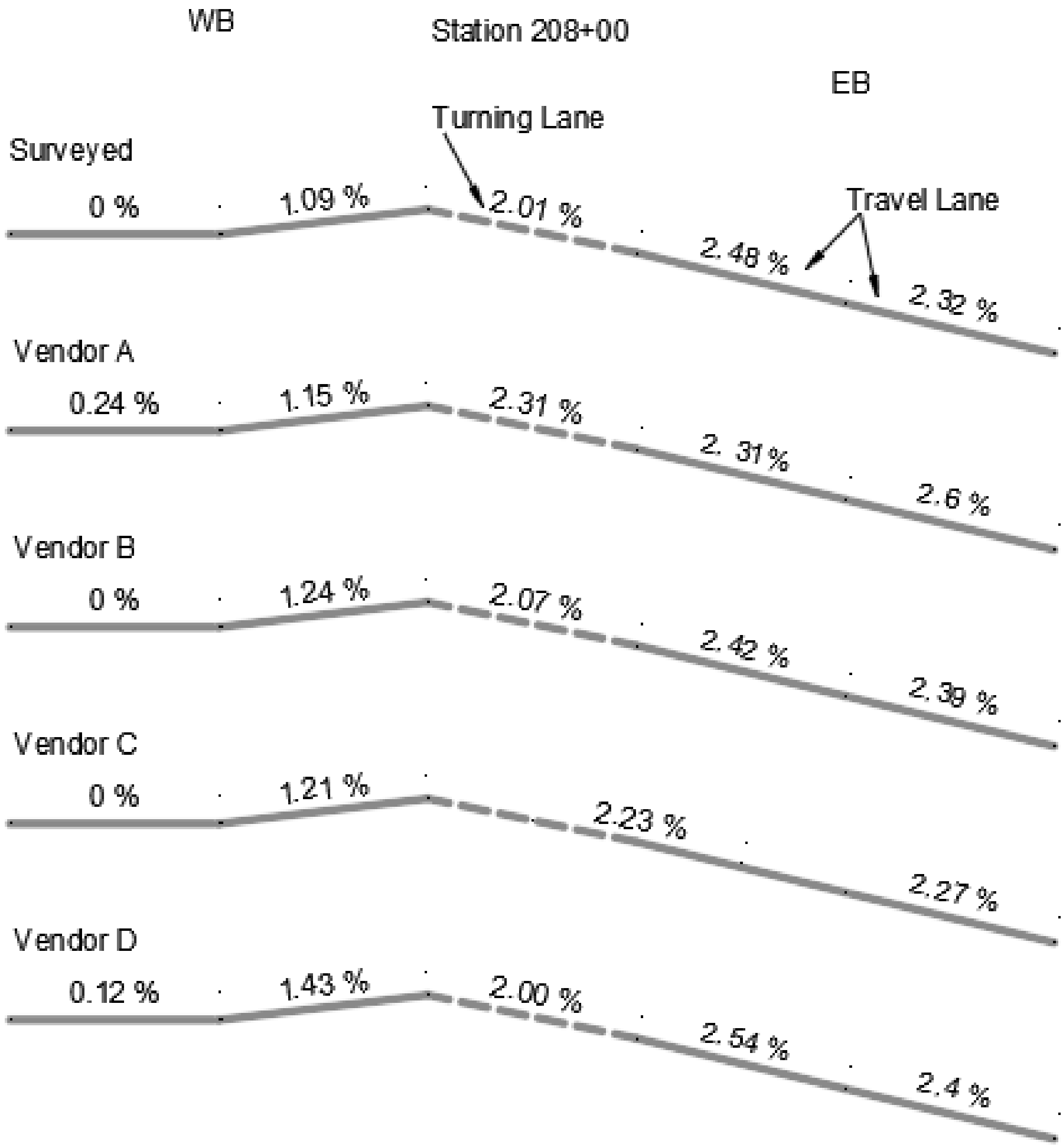
Section 2 – East West Parkway, Anderson, SC



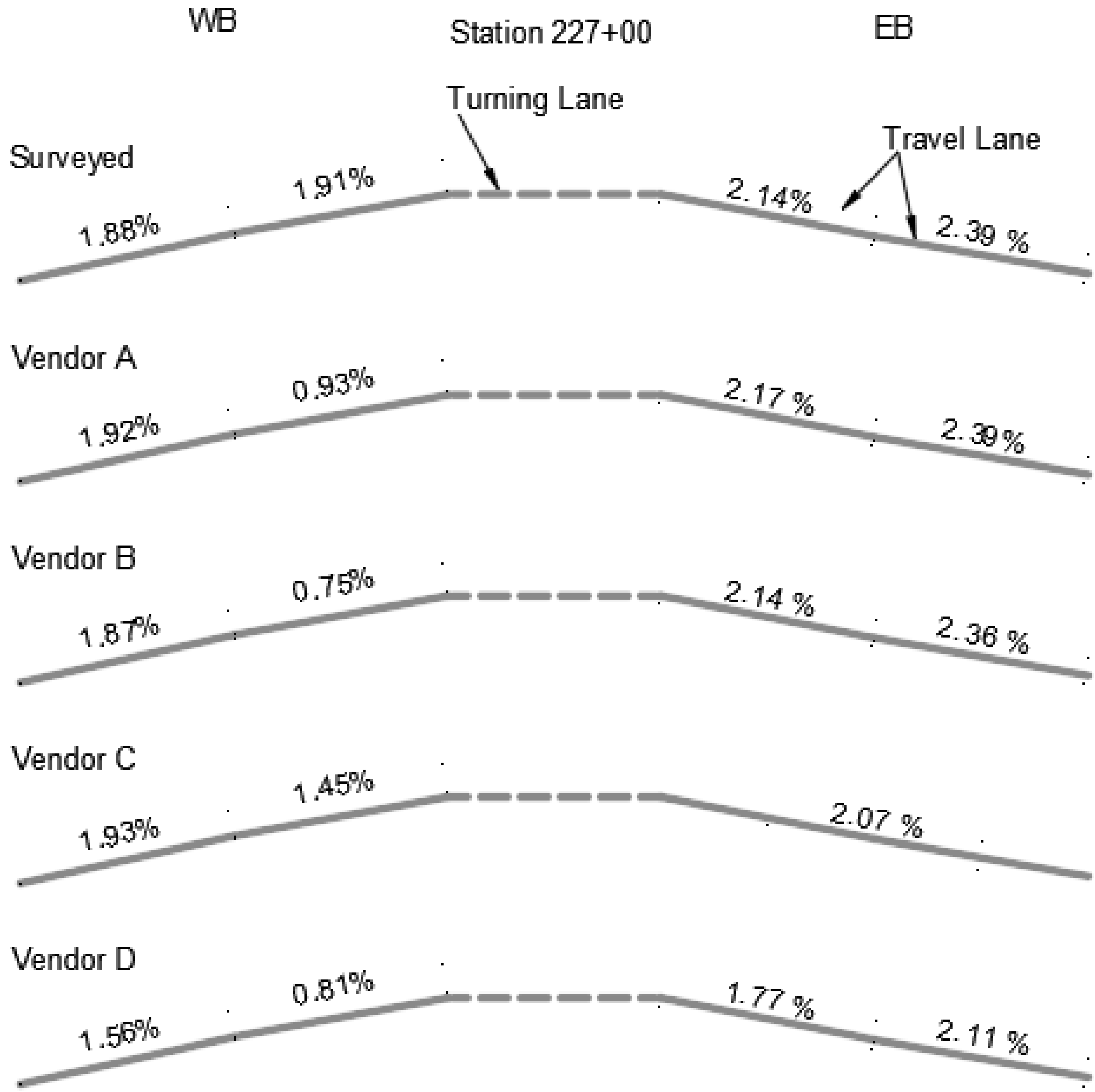
Section 2 – East West Parkway, Anderson, SC



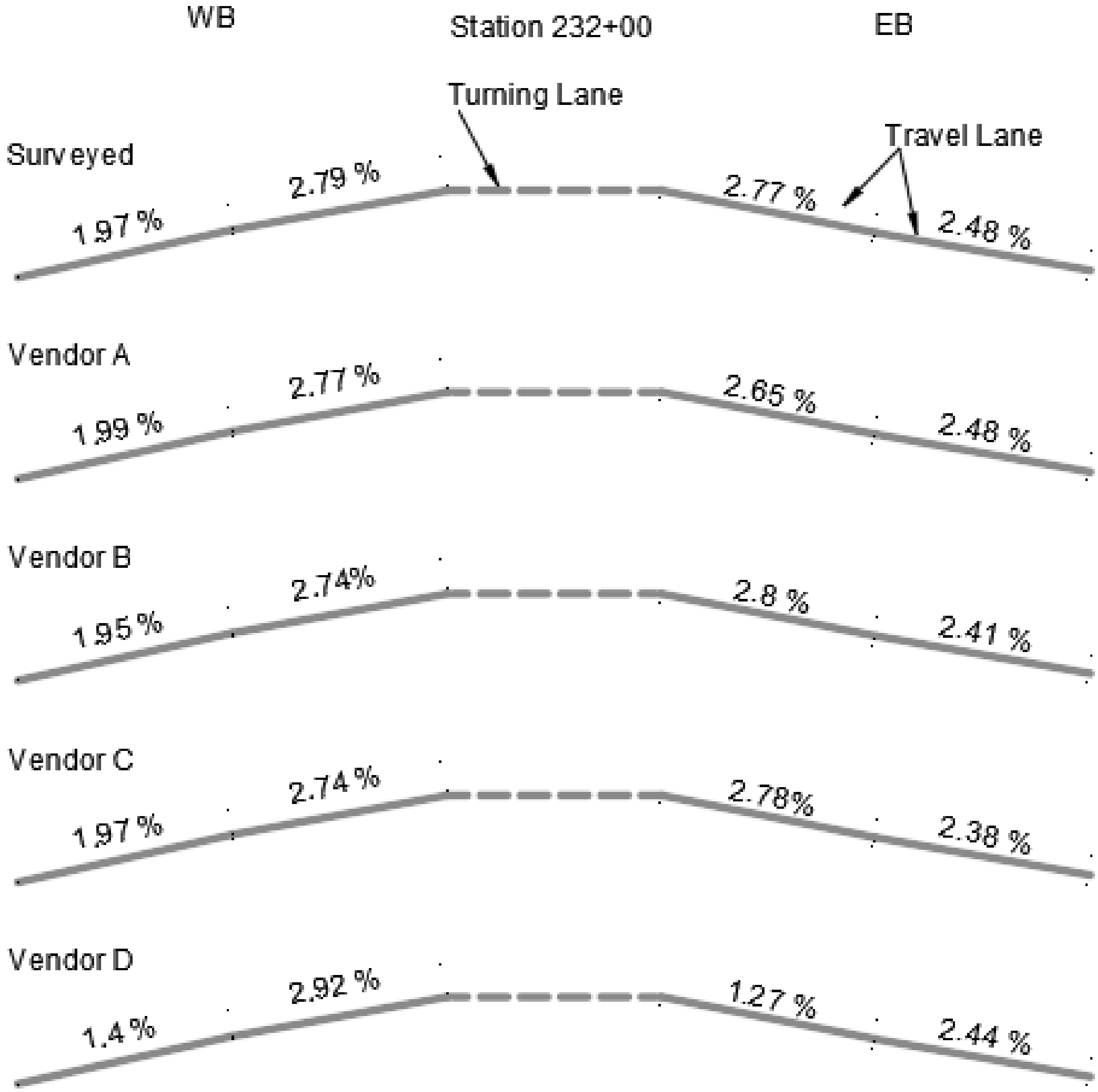
Section 2 – East West Parkway, Anderson, SC



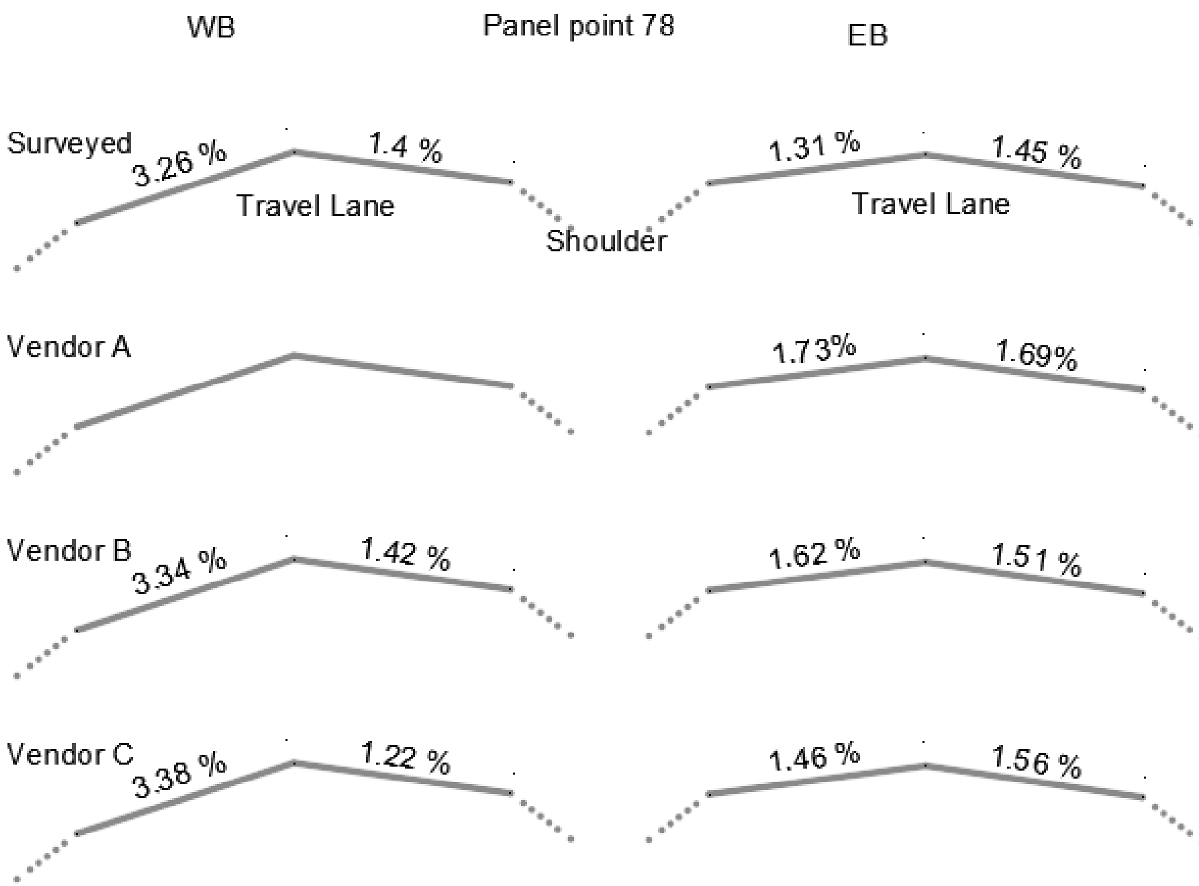
Section 2 – East West Parkway, Anderson, SC



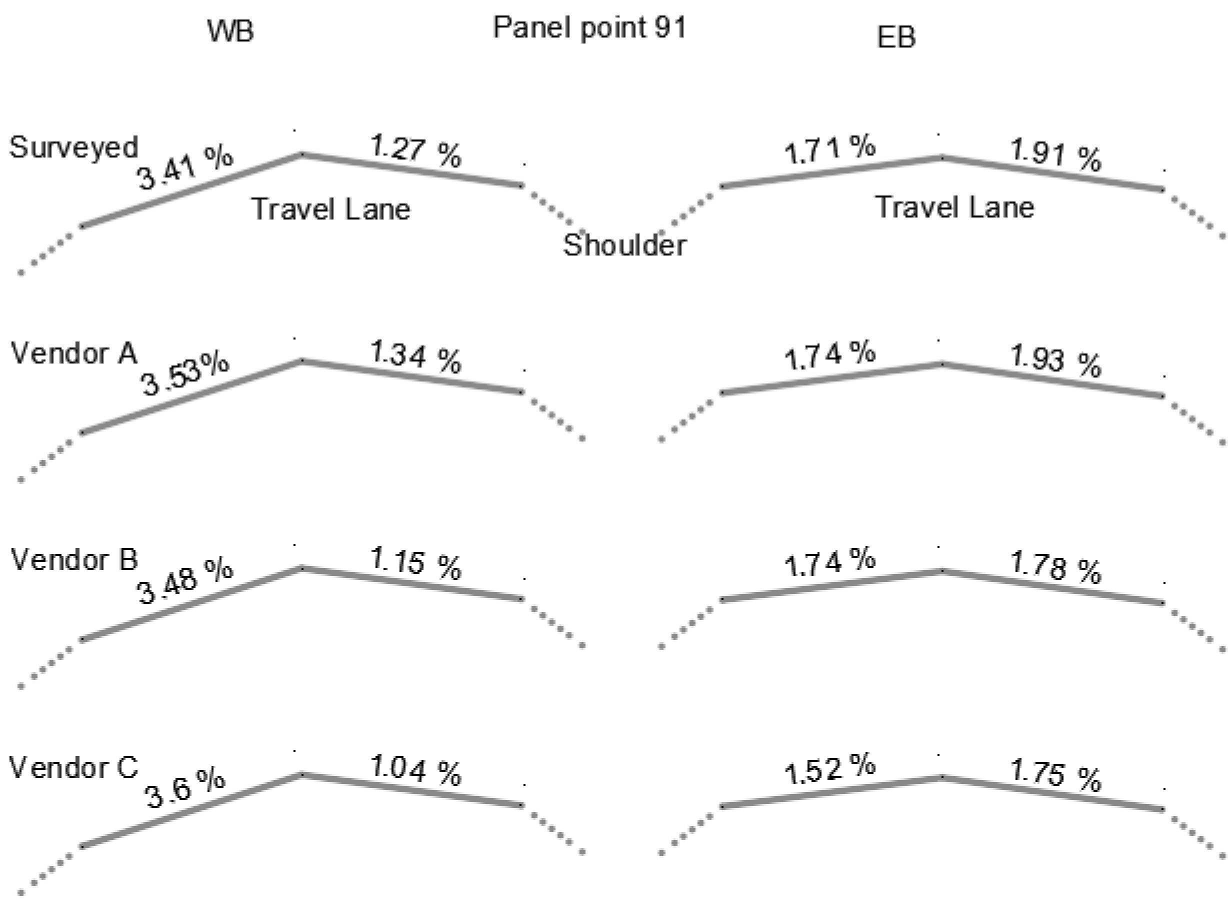
Section 2 – East West Parkway, Anderson, SC



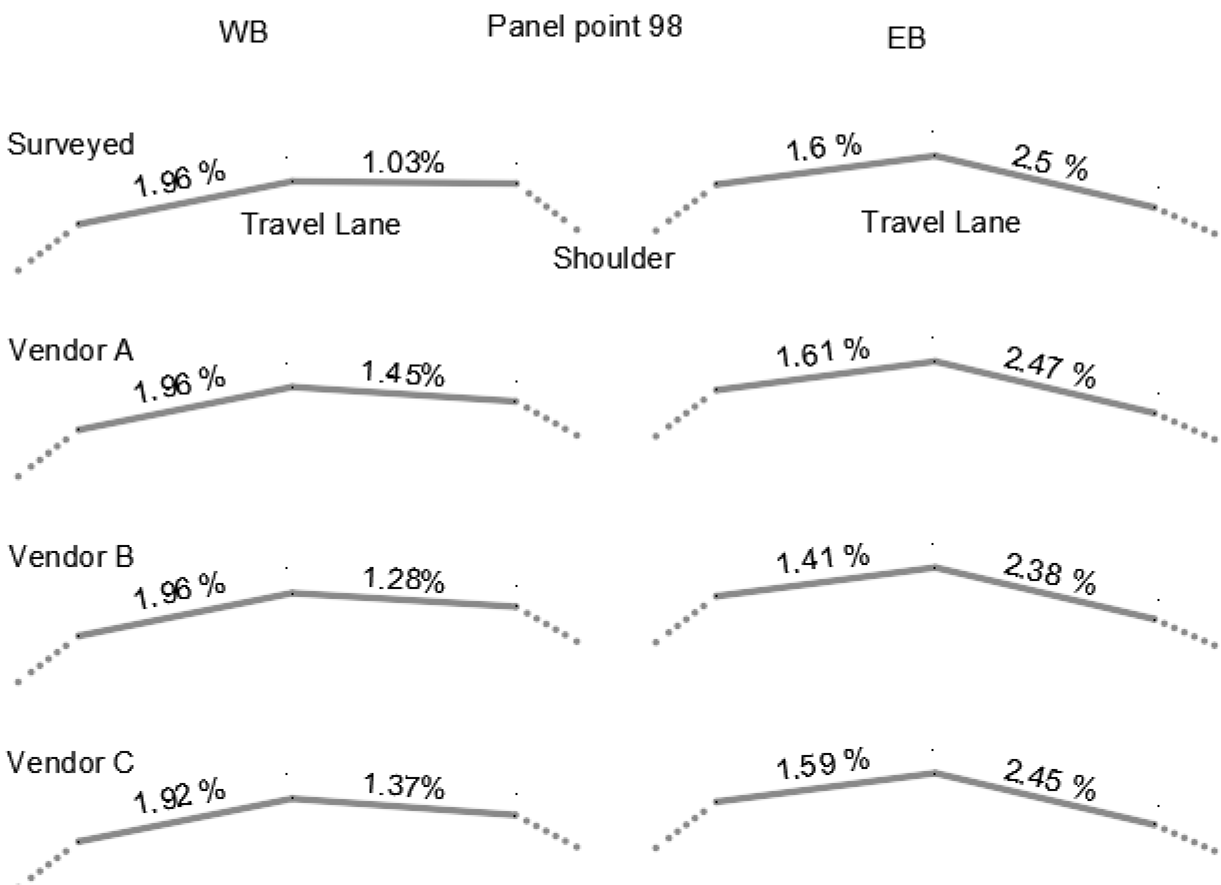
Section 3 – I 85 Business Loop, Spartanburg, SC



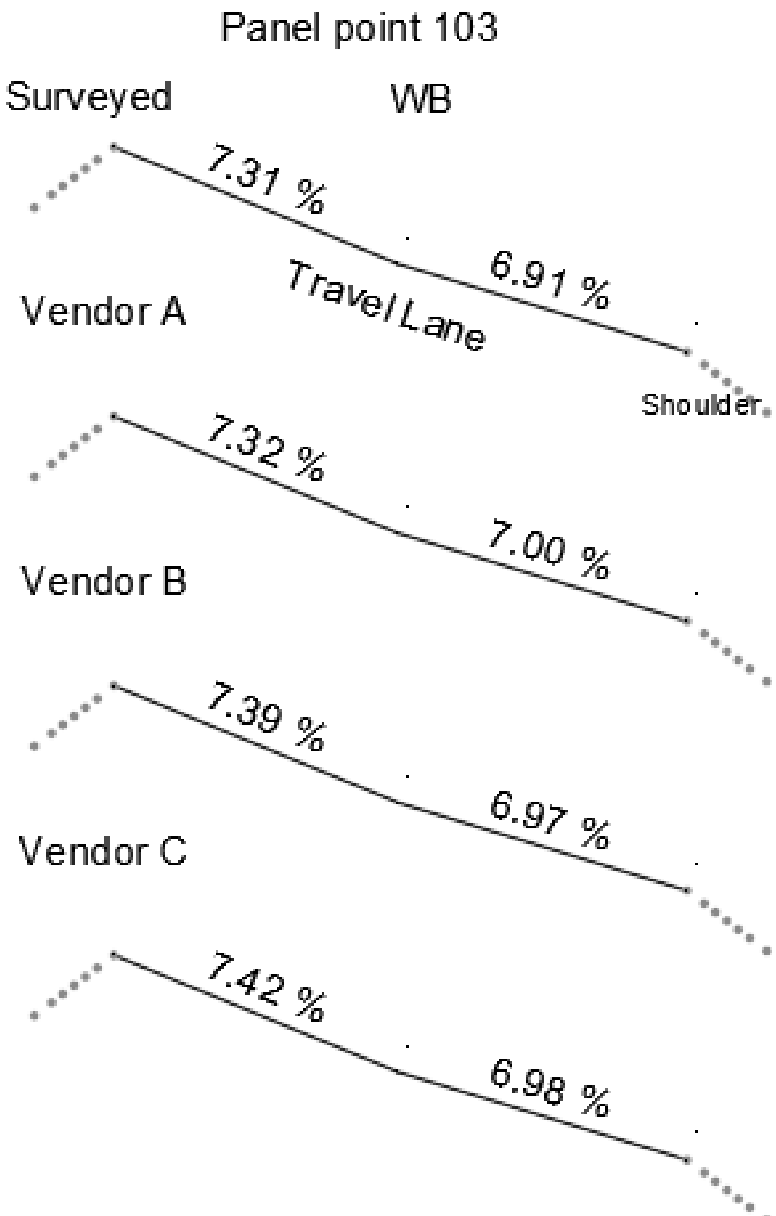
Section 3 – I 85 Business Loop, Spartanburg, SC



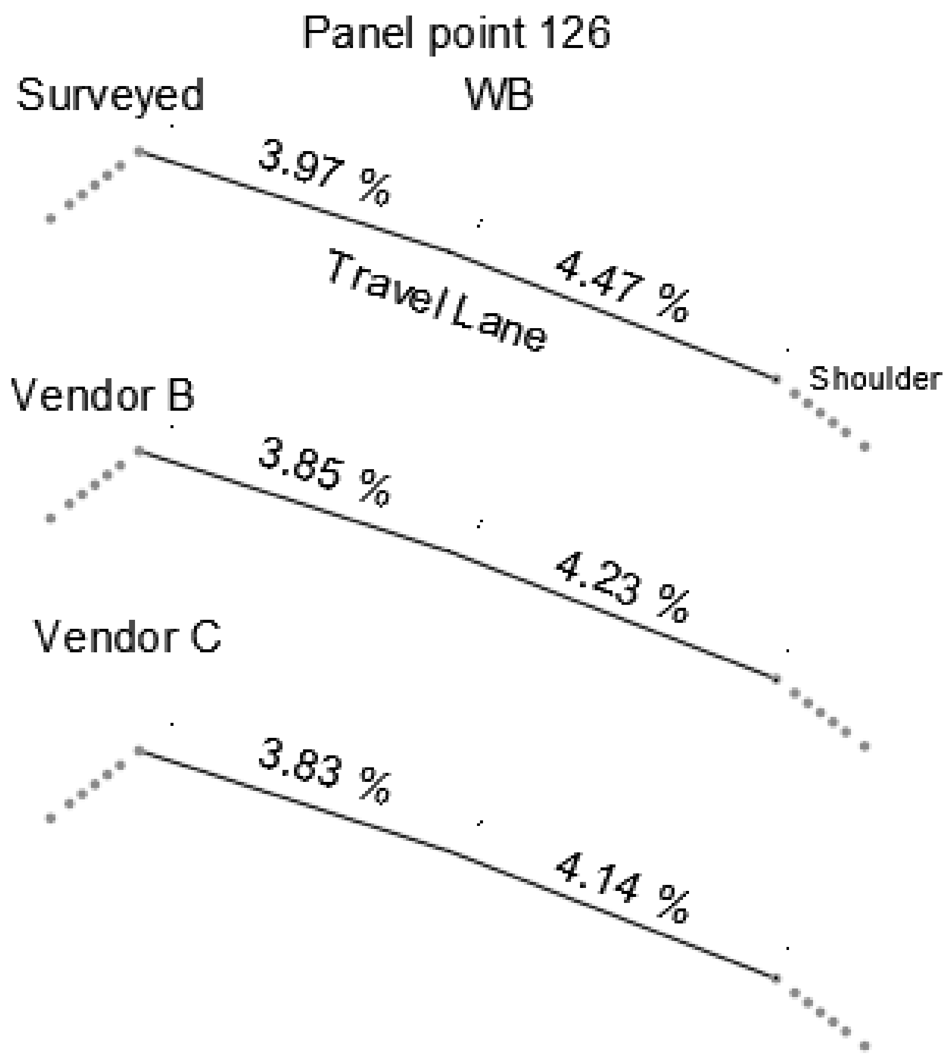
Section 3 – I 85 Business Loop, Spartanburg, SC



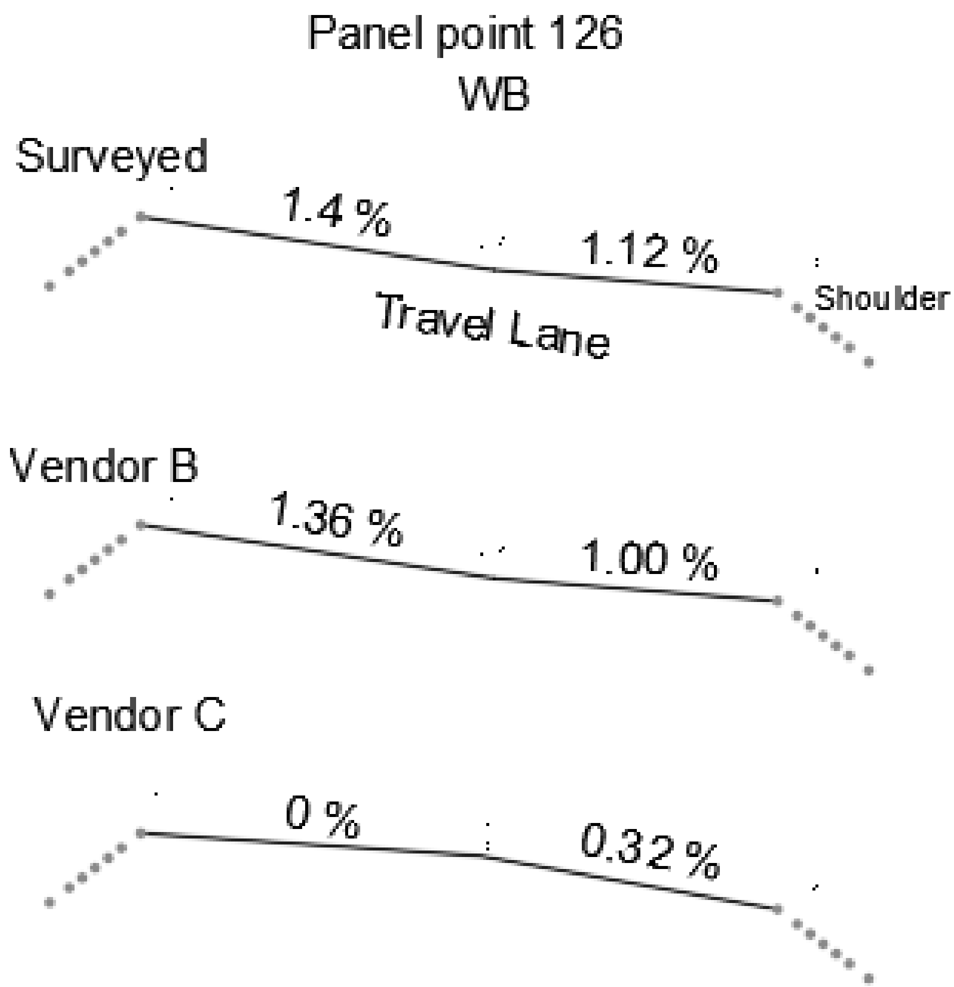
Section 3 – I 85 Business Loop, Spartanburg, SC



Section 3 – I 85 Business Loop, Spartanburg, SC

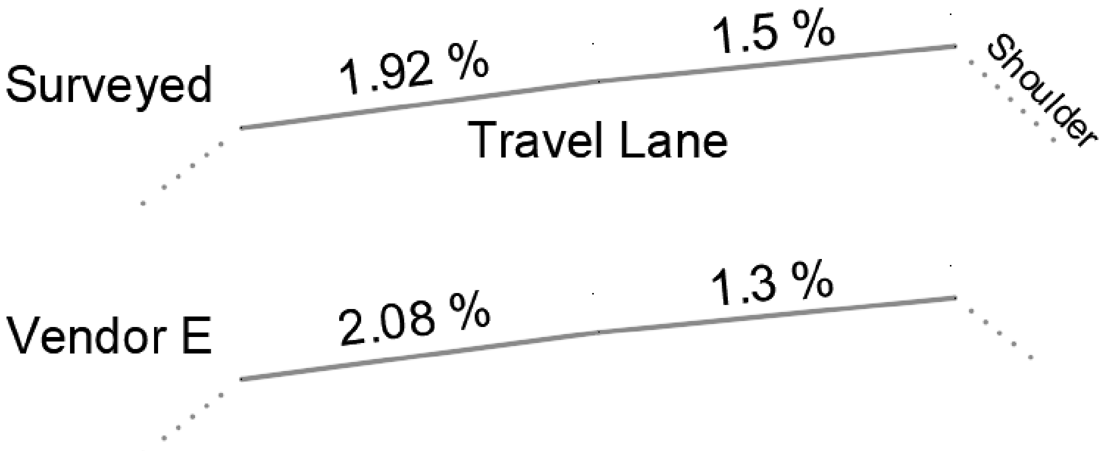


Section 3 – I 85 Business Loop, Spartanburg, SC

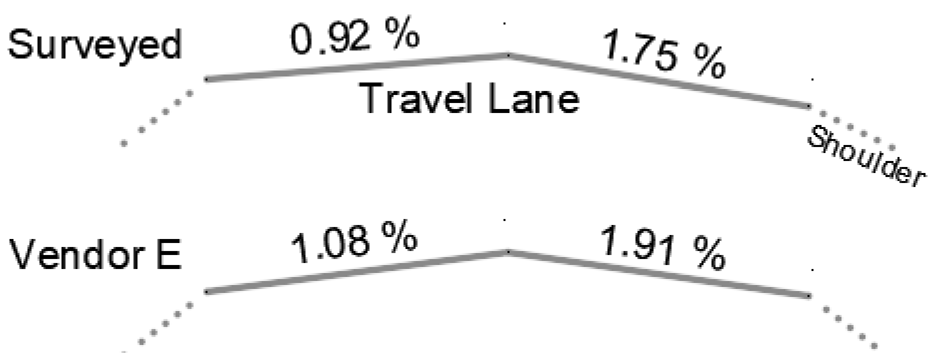


US 123, Easley, SC

Station 34+31
EB

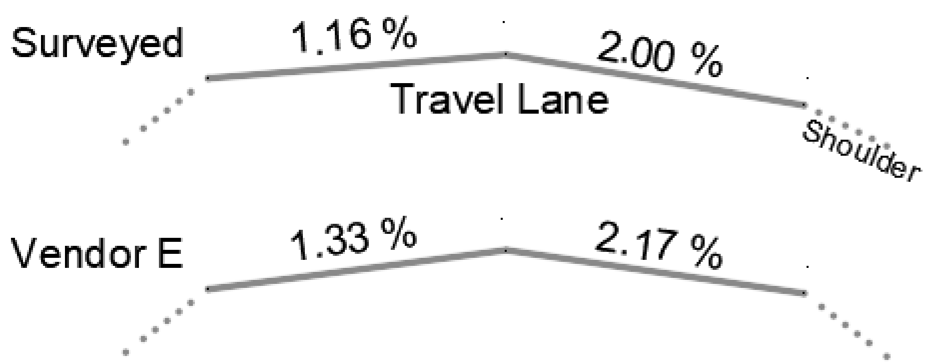


Station 38+52
EB

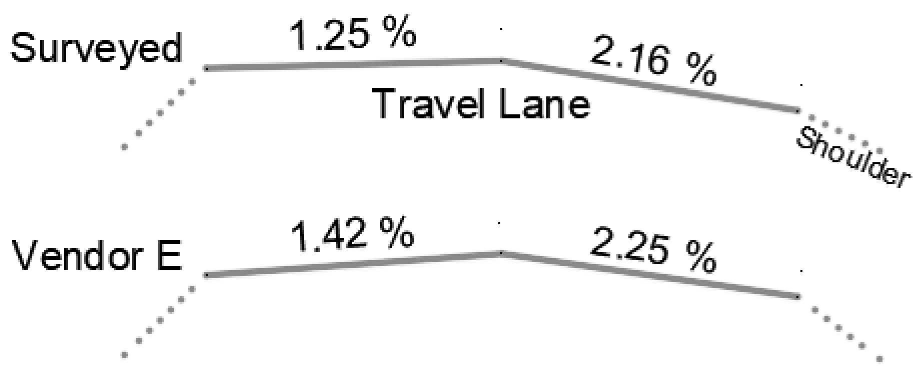


US 123, Easley, SC

Station 44+20
EB

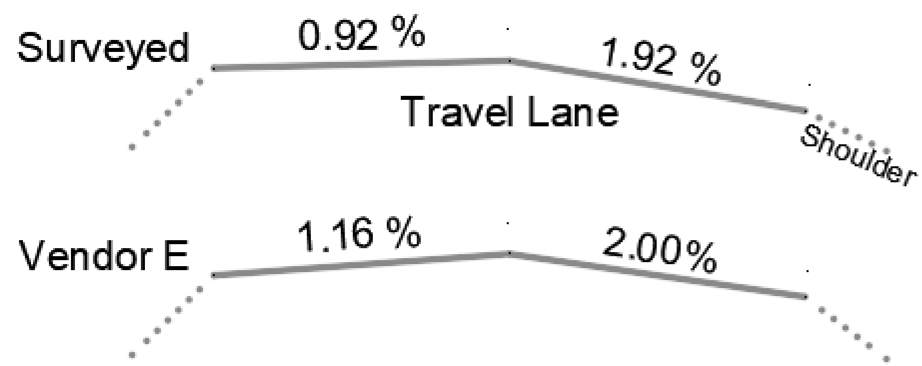


Station 44+68
EB

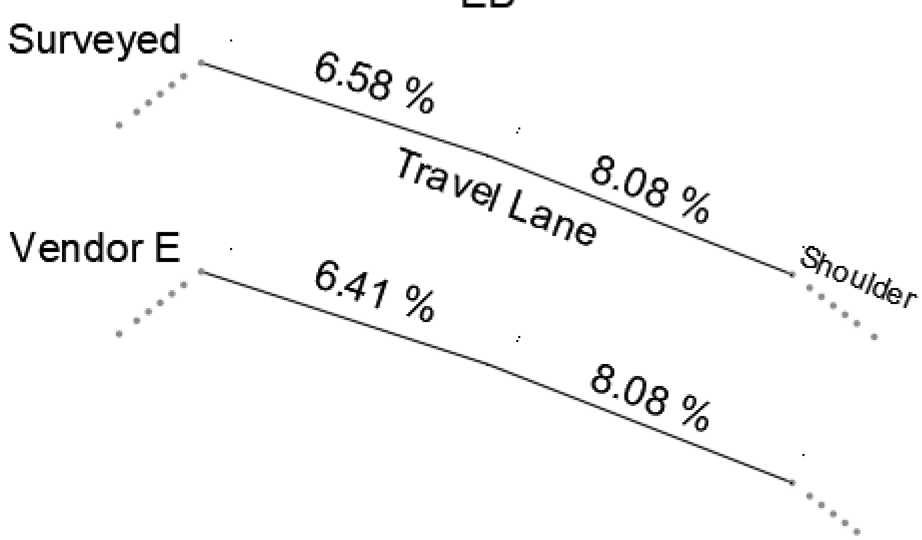


US 123, Easley, SC

Station 45+92
EB



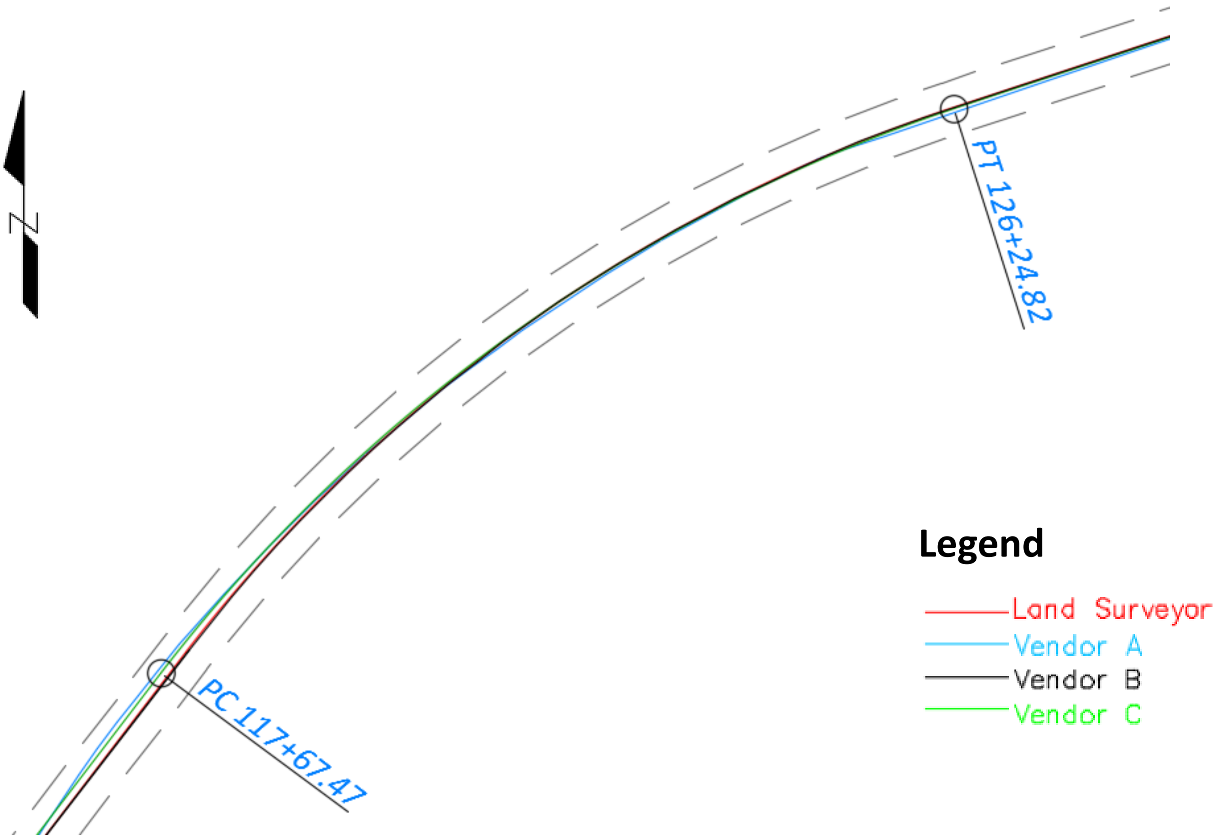
Station 57+39
EB



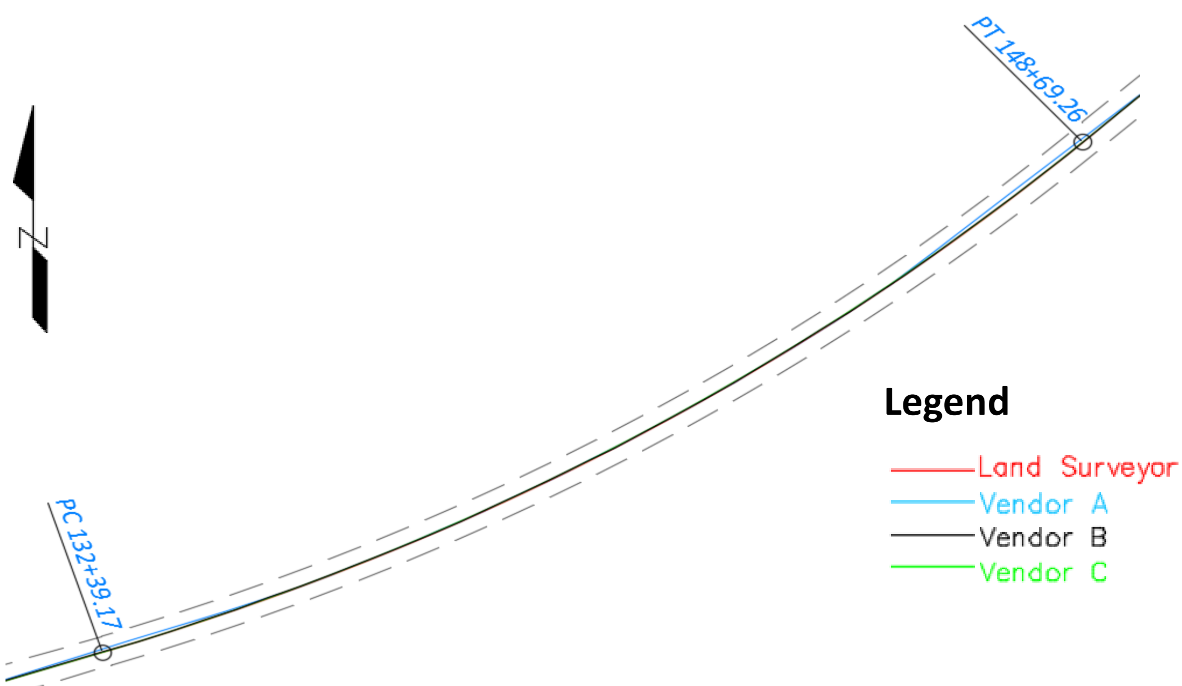
APPENDIX F

SECTION 2 SUPERIMPOSED CENTERLINES

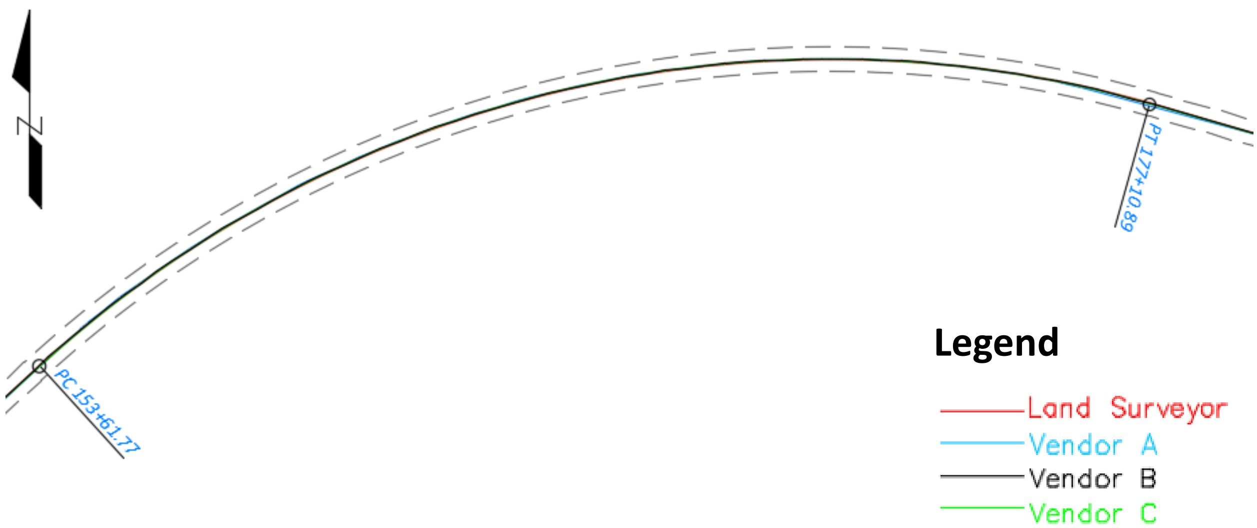
Centerlines superimposed – Curve 1



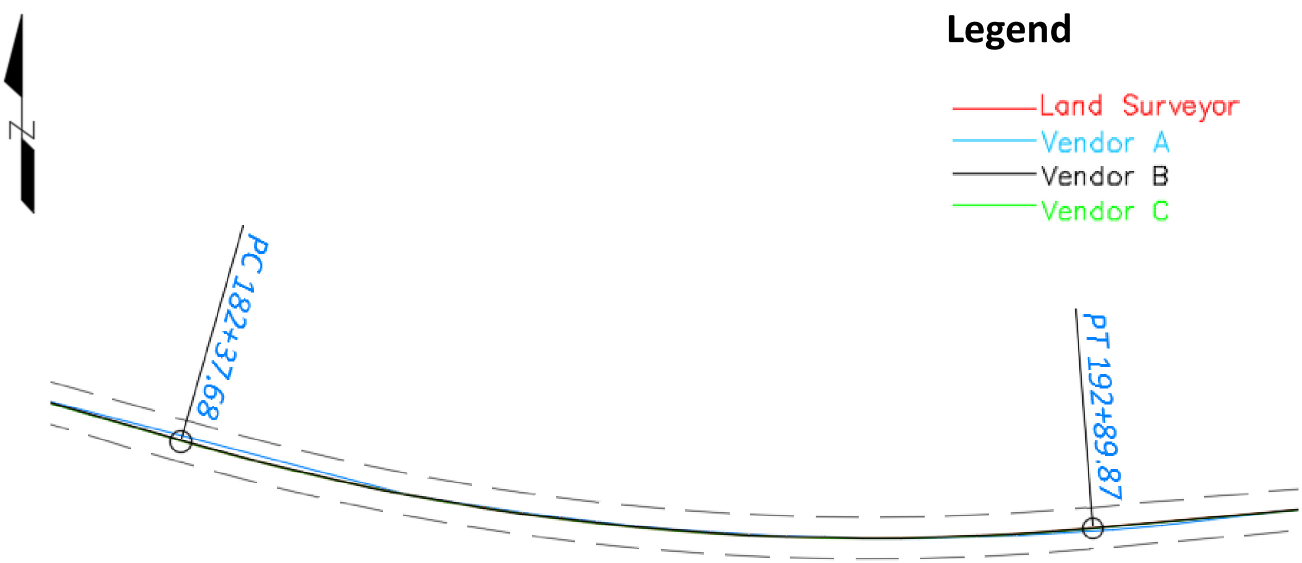
Centerlines superimposed – Curve 2



Centerlines superimposed – Curve 3

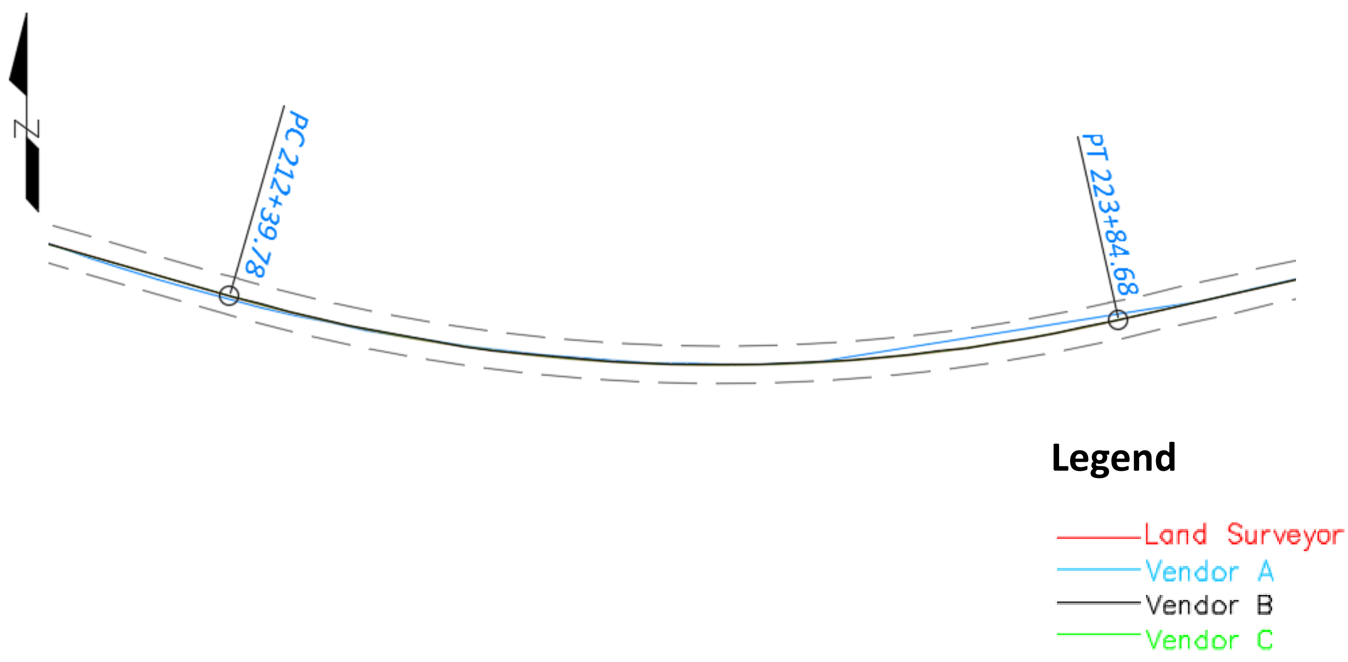


Centerlines superimposed – Curve 4

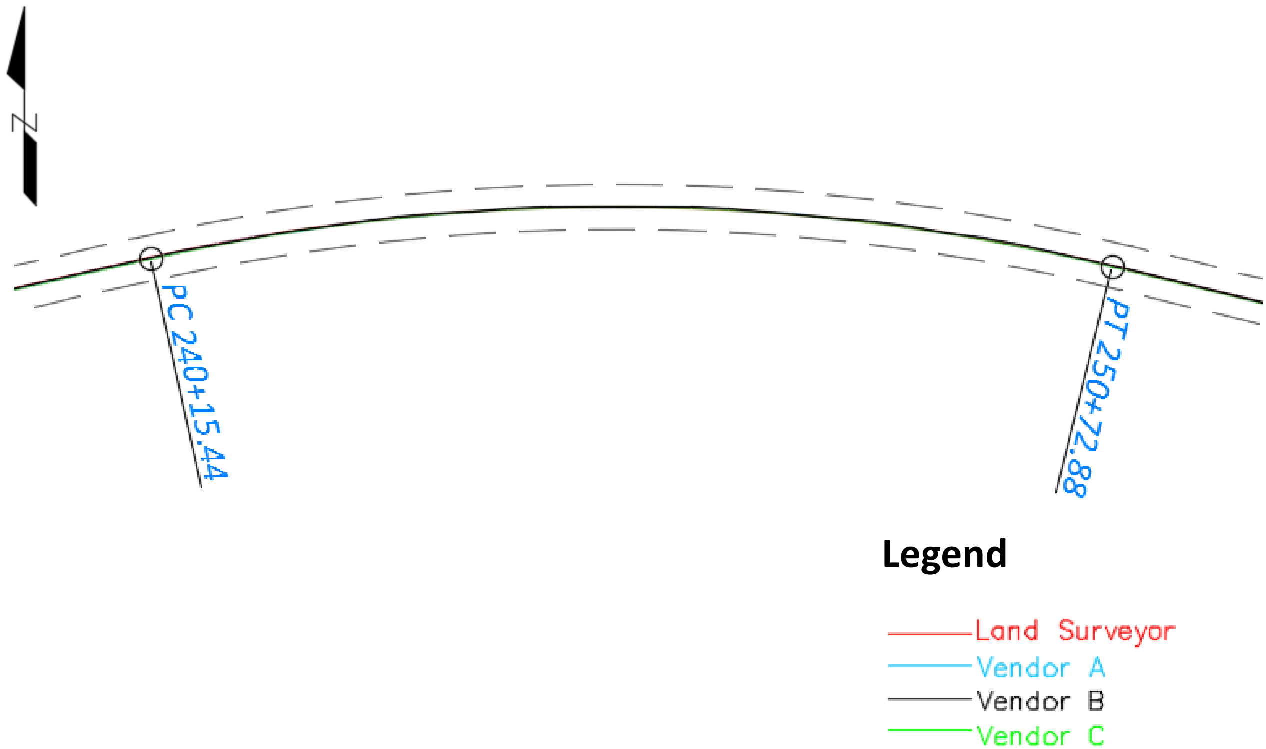


Centerlines superimposed – Curve 5

Centerlines superimposed – Curve 6



Centerlines superimposed – Curve 7



APPENDIX G

SECTION 2 HORIZONTAL AND VERTICAL CURVE DATA

ADDITIONAL CURVE DATA WITH COMPARISONS

Horizontal Alignment

Horizontal Curve 3

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Survey/AS-BUILT (Baseline)	3	Curve	2349.11	2291.83	1289.48	153+61.77	166+51.25	177+10.89
Vendor A	3	Curve	999.91	2311.49	507.90	154+99.92	160+07.82	164+99.83
Vendor B	3	Curve	2345.85	2291.89	1287.33	153+65.03	166+52.36	177+10.88
Vendor C	3	Curve	2325.00	2280.00	1274.94	153+79.86	166+54.80	177+04.86

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Vendor A	3	Curve	-1349.2	19.7	-781.6	138.2	-643.4	-1211.1
Vendor B	3	Curve	-3.3	0.1	-2.1	3.3	1.1	0.0
Vendor C	3	Curve	-24.1	-11.8	-14.5	18.1	3.5	-6.0

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Vendor A	3	Curve	57.43%	0.86%	60.61%	0.90%	3.86%	6.84%
Vendor B	3	Curve	0.14%	0.00%	0.17%	0.02%	0.01%	0.00%
Vendor C	3	Curve	1.03%	0.52%	1.13%	0.12%	0.02%	0.03%

Horizontal Curve 4

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Survey/AS-BUILT (Baseline)	4	Curve	1052.19	2864.79	532.09	182+37.68	187+69.77	192+89.87
Vendor A	4	Curve	999.85	2297.29	507.97	164+99.83	170+07.80	174+99.68
Vendor B	4	Curve	1052.19	2863.23	523.10	182+38.90	187+71.00	192+91.10
Vendor C	4	Curve	1064.05	2900.00	538.07	182+31.14	187+69.21	192+95.19

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Vendor A	4	Curve	-52.3	-567.5	-24.1	-1737.9	-1762.0	-1790.2
Vendor B	4	Curve	0.0	-1.6	-9.0	1.2	1.2	1.2
Vendor C	4	Curve	11.9	35.2	6.0	-6.5	-0.6	5.3

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Vendor A	4	Curve	4.97%	19.81%	4.53%	9.53%	9.39%	9.28%
Vendor B	4	Curve	0.00%	0.05%	1.69%	0.01%	0.01%	0.01%
Vendor C	4	Curve	1.13%	1.23%	1.12%	0.04%	0.00%	0.03%

Horizontal Curve 5

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Survey/AS-BUILT (Baseline)	5	Curve	698.66	1909.86	353.28	199+96.61	203+49.89	206+95.27
Vendor A	5	Curve	1000.03	3132.17	504.31	184+99.96	190+04.26	194+99.98
Vendor B	5	Curve	698.66	1908.05	353.29	199+95.71	203+48.99	206+94.37
Vendor C	5	Curve	683.95	1875.00	345.82	200+00.46	203+46.28	206+84.41

`	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Vendor A	5	Curve	301.4	1222.3	151.0	-1496.7	-1345.6	-1195.3
Vendor B	5	Curve	0.0	-1.8	0.0	-0.9	-0.9	-0.9
Vendor C	5	Curve	-14.7	-34.9	-7.5	3.8	-3.6	-10.9

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Vendor A	5	Curve	43.14%	64.00%	42.75%	7.48%	6.61%	5.78%
Vendor B	5	Curve	0.00%	0.09%	0.00%	0.00%	0.00%	0.00%
Vendor C	5	Curve	2.11%	1.83%	2.11%	0.02%	0.02%	0.05%

Horizontal Curve 6

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Survey/AS-BUILT (Baseline)	6	Curve	1144.89	2291.83	584.66	212+39.78	218+24.44	223+84.68
Vendor A	6	Curve	1000.18	2360.71	507.71	200+00.02	205+07.73	210+00.20
Vendor B	6	Curve	1144.90	2291.41	584.66	212+39.40	218+24.07	223+84.30
Vendor C	6	Curve	1156.43	2319.99	590.49	212+35.15	218+25.64	223+91.58

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Vendor A	6	Curve	-144.7	68.9	-76.9	-1239.8	-1316.7	-1384.5
Vendor B	6	Curve	0.0	-0.4	0.0	-0.4	-0.4	-0.4
Vendor C	6	Curve	11.5	28.2	5.8	-4.6	1.2	6.9

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Vendor A	6	Curve	12.64%	3.01%	13.16%	5.84%	6.03%	6.18%
Vendor B	6	Curve	0.00%	0.02%	0.00%	0.00%	0.00%	0.00%
Vendor C	6	Curve	1.01%	1.23%	1.00%	0.02%	0.01%	0.03%

Horizontal Curve 7

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Survey/AS-BUILT (Baseline)	7	Curve	1057.44	2291.83	538.31	240+15.44	245+53.74	250+72.88
Vendor A	7	Curve	1000.24	2574.22	506.51	210+00.20	215+06.71	220+00.45
Vendor B	7	Curve	1057.44	2278.25	538.42	240+17.17	245+55.59	250+74.60
Vendor C	7	Curve	1035.96	2250.00	527.33	240+23.49	245+50.81	250+59.44

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Vendor A	7	Curve	-57.2	282.4	-31.8	-3015.2	-3047.0	-3072.4
Vendor B	7	Curve	0.0	-13.6	0.1	1.7	1.8	1.7
Vendor C	7	Curve	-21.5	-41.8	-11.0	8.1	-2.9	-13.4

	Number	Type	Curve Length	Radius	Tangent	PC Station	PI Station	PT Station
Vendor A	7	Curve	5.41%	12.32%	5.91%	12.56%	12.41%	12.25%
Vendor B	7	Curve	0.00%	0.59%	0.02%	0.01%	0.01%	0.01%
Vendor C	7	Curve	2.03%	1.83%	2.04%	0.03%	0.01%	0.05%

Vertical Alignment

Vertical Curve 3

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Land Surveyor (Baseline)	3	Sag	269.42	118+92.62	770.33	120+27.33	765.71	121+62.04	763.34	-3.43%	-1.76%	1.67%
Vendor A	3	Sag	291.33	118+85.18	768.38	120+30.84	763.16	121+76.51	760.51	-3.58%	-1.82%	1.76%
Vendor B	3	Sag	265	118+72.06	768.52	120+04.56	763.66	121+37.06	761.28	-3.67%	-1.79%	1.87%
Vendor C	3	Sag	289.96	118+74.79	768.66	120+19.78	763.46	121+64.76	760.81	-3.59%	-1.83%	1.76%

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation
Vendor A	3	Sag	21.91	-7.44	-1.95	3.51	-2.55	14.47	-2.83
Vendor B	3	Sag	-4.42	-20.56	-1.81	-22.77	-2.05	-24.98	-2.06
Vendor C	3	Sag	20.54	-17.83	-1.67	-7.55	-2.25	2.72	-2.53

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Vendor A	3	Sag	8.13%	0.06%	0.25%	0.03%	0.33%	0.12%	0.37%	4.37%	3.41%	5.39%
Vendor B	3	Sag	1.64%	0.17%	0.24%	0.19%	0.27%	0.21%	0.27%	6.90%	1.90%	12.17%
Vendor C	3	Sag	7.62%	0.15%	0.22%	0.06%	0.29%	0.02%	0.33%	4.66%	3.98%	5.39%

Vertical Curve 4

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Land Surveyor (Baseline)	4	Crest	835.11	123+50.53	760.03	127+68.08	752.70	131+85.64	732.22	-1.76%	-4.90%	-3.15%
Vendor A	4	Crest	805.27	123+68.09	757.02	127+70.73	749.68	131+73.36	729.72	-1.82%	-4.96%	-3.14%
Vendor B	4	Crest	765	123+81.93	756.89	127+64.43	750.03	131+46.93	731.02	-1.79%	-4.97%	-3.18%
Vendor C	4	Crest	775.38	123+81.34	756.85	127+69.03	749.76	131+56.72	730.54	-1.83%	-4.96%	-3.13%

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation
Vendor A	4	Crest	-29.84	17.56	-3.01	2.65	-3.02	-12.28	-2.50
Vendor B	4	Crest	-70.11	31.40	-3.14	-3.65	-2.67	-38.71	-1.20
Vendor C	4	Crest	-59.73	30.81	-3.18	0.95	-2.94	-28.92	-1.68

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Vendor A	4	Crest	3.57%	0.14%	0.40%	0.02%	0.40%	0.09%	0.34%	3.41%	1.22%	0.32%
Vendor B	4	Crest	8.40%	0.25%	0.41%	0.03%	0.35%	0.29%	0.16%	1.90%	1.42%	0.83%
Vendor C	4	Crest	7.15%	0.25%	0.42%	0.01%	0.39%	0.22%	0.23%	3.98%	1.22%	0.63%

Vertical Curve 5

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Land Surveyor (Baseline)	5	Sag	1501.46	135+86.58	712.56	143+37.31	675.73	150+88.04	710.69	-4.90%	4.66%	9.56%
Vendor A	5	Sag	1487.43	135+00.49	713.49	142+44.21	676.61	149+87.92	709.49	-4.96%	4.42%	9.38%
Vendor B	5	Sag	1410	135+36.89	711.64	142+41.89	676.61	149+46.89	707.75	-4.97%	4.42%	9.39%
Vendor C	5	Sag	1436.81	135+26.42	712.22	142+44.82	676.62	149+63.23	708.40	-4.96%	4.42%	9.38%

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation
Vendor A	5	Sag	-14.03	-86.09	0.93	-93.10	0.88	-100.12	-1.20
Vendor B	5	Sag	-91.46	-49.69	-0.92	-95.42	0.88	-141.15	-2.94
Vendor C	5	Sag	-64.65	-60.16	-0.34	-92.49	0.89	-124.81	-2.29

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Vendor A	5	Sag	0.93%	0.63%	0.13%	0.65%	0.13%	0.66%	0.17%	1.22%	5.15%	1.88%
Vendor B	5	Sag	6.09%	0.37%	0.13%	0.67%	0.13%	0.94%	0.41%	1.42%	5.21%	1.81%
Vendor C	5	Sag	4.31%	0.44%	0.05%	0.65%	0.13%	0.83%	0.32%	1.22%	5.15%	1.88%

Vertical Curve 6

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Land Surveyor (Baseline)	6	Crest	1427.99	157+70.11	742.44	164+84.11	775.68	171+98.10	759.76	4.66%	-2.23%	-6.89%
Vendor A	6	Crest	1320.6	157+82.42	744.62	164+42.72	773.81	171+03.02	758.60	4.42%	-2.30%	-6.72%
Vendor B	6a	Crest	1120	157+90.09	744.99	163+50.09	769.73	169+10.09	761.69	4.42%	-1.43%	-5.85%
Vendor B	6b	Crest	200	169+80.00	760.69	170+80.00	759.26	171+80.00	756.88	-1.43%	-2.38%	-0.94%
Vendor C	6	Crest	1328.79	157+82.09	744.63	164+46.48	774.02	171+10.88	758.47	4.42%	-2.34%	-6.76%

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation

Vendor A	6	Crest	-107.39	12.31	2.18	-41.39	-1.87	-95.08	-1.16
Vendor B	6a	Crest	-307.99	19.98	2.55	-134.02	-5.95	-288.01	1.93
Vendor B	6b	Crest	-1227.99	1209.89	18.25	595.89	-16.42	-18.10	-2.88
Vendor C	6	Crest	-99.20	11.98	2.19	-37.63	-1.66	-87.22	-1.29

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Vendor A	6	Crest	7.52%	0.08%	0.29%	0.25%	0.24%	0.55%	0.15%	5.15%	3.14%	2.47%
Vendor B	6a	Crest	21.57%	0.13%	0.34%	0.81%	0.77%	1.67%	0.25%	5.21%	35.65%	15.06%
Vendor B	6b	Crest	85.99%	7.67%	2.46%	3.61%	2.12%	0.11%	0.38%	130.79%	6.70%	86.29%
Vendor C	6	Crest	6.95%	0.08%	0.29%	0.23%	0.21%	0.51%	0.17%	5.15%	4.93%	1.89%

Vertical Curve 7

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Land Surveyor (Baseline)	7	Sag	917.53	174+41.17	754.34	178+99.94	744.12	183+58.70	765.99	-2.23%	4.77%	7.00%
Vendor A	7	Sag	999.38	172+67.50	754.81	177+67.19	743.30	182+66.88	767.24	-2.30%	4.79%	7.09%
Vendor B	7a	Sag	750	172+60.57	754.96	176+35.57	746.04	180+10.57	757.83	-2.38%	3.15%	5.52%
Vendor B	7b	Sag	200	181+02.34	760.72	182+02.34	763.87	183+02.34	768.79	3.15%	4.92%	1.77%
Vendor C	7	Sag	993.35	172+61.10	754.96	177+57.77	743.34	182+54.45	766.86	-2.34%	4.74%	7.08%

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation
Vendor A	7	Sag	81.85	-173.67	0.47	-132.75	-0.82	-91.82	1.25
Vendor B	7a	Sag	-167.53	-180.60	0.62	-264.37	1.92	-348.13	-8.16
Vendor B	7b	Sag	-717.53	661.17	6.38	302.40	19.75	-56.36	2.80
Vendor C	7	Sag	75.82	-180.07	0.62	-142.17	-0.78	-104.25	0.87

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Vendor A	7	Sag	8.92%	1.00%	0.06%	0.74%	0.11%	0.50%	0.16%	3.14%	0.42%	1.29%
Vendor B	7a	Sag	18.26%	1.04%	0.08%	1.48%	0.26%	1.90%	1.06%	6.70%	34.06%	21.07%
Vendor B	7b	Sag	78.20%	3.79%	0.85%	1.69%	2.65%	0.31%	0.37%	241.04%	3.13%	74.66%
Vendor C	7	Sag	8.26%	1.03%	0.08%	0.79%	0.10%	0.57%	0.11%	4.93%	0.63%	1.14%

Vertical Curve 8

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Land Surveyor (Baseline)	8	Crest	1409.01	185+78.98	776.49	192+83.48	810.08	199+87.99	806.87	4.77%	-0.46%	-5.22%
Vendor A	8	Crest	1478.12	184+92.46	778.05	192+31.52	813.45	199+70.58	806.25	4.79%	-0.97%	-5.76%
Vendor B	8	Crest	1400	184+90.23	778.03	191+90.23	812.46	198+90.23	805.32	4.92%	-1.02%	-5.94%
Vendor C	8	Crest	1447.16	185+04.64	778.71	192+28.22	812.98	199+51.79	806.44	4.74%	-0.90%	-5.64%

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation
Vendor A	8	Crest	69.11	-86.52	1.56	-51.96	3.37	-17.41	-0.62
Vendor B	8	Crest	-9.01	-88.75	1.54	-93.25	2.38	-97.76	-1.55
Vendor C	8	Crest	38.15	-74.34	2.22	-55.26	2.90	-36.20	-0.43

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Vendor A	8	Crest	4.90%	0.47%	0.20%	0.27%	0.42%	0.09%	0.08%	0.42%	110.87%	10.34%
Vendor B	8	Crest	0.64%	0.48%	0.20%	0.48%	0.29%	0.49%	0.19%	3.13%	121.85%	13.79%
Vendor C	8	Crest	2.71%	0.40%	0.29%	0.29%	0.36%	0.18%	0.05%	0.63%	95.65%	8.05%

Vertical Curve 9

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Land Surveyor (Baseline)	9	Sag	403.03	202+88.56	805.50	204+90.07	804.58	206+91.59	806.88	-0.46%	1.14%	1.60%
Vendor A	9	Sag	407.30	201+16.50	804.83	203+20.15	802.85	205+23.79	805.87	-0.97%	1.48%	2.45%
Vendor B	9	Sag	250	200+90.60	803.28	202+15.60	802.00	203+40.60	803.60	-1.02%	1.28%	2.30%
Vendor C	9	Sag	383.83	201+22.60	804.89	203+14.52	803.16	205+06.43	805.66	-0.90%	1.30%	2.21%

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation
Vendor A	9	Sag	4.27	-172.06	-0.67	-169.92	-1.73	-167.80	-1.01
Vendor B	9	Sag	-153.03	-197.96	-2.22	-274.47	-2.58	-350.99	-3.28
Vendor C	9	Sag	-19.20	-165.96	-0.61	-175.55	-1.42	-185.16	-1.22

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Vendor A	9	Sag	1.06%	0.85%	0.08%	0.83%	0.22%	0.81%	0.13%	110.87%	29.82%	53.13%
Vendor B	9	Sag	37.97%	0.98%	0.28%	1.34%	0.32%	1.70%	0.41%	121.85%	12.29%	43.79%
Vendor C	9	Sag	4.76%	0.82%	0.08%	0.86%	0.18%	0.89%	0.15%	95.65%	14.04%	38.13%

Vertical Curve 10

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Land Surveyor (Baseline)	10	Crest	569.62	207+84.96	807.94	210+69.77	811.19	213+54.57	805.91	1.14%	-1.85%	-2.99%
Vendor A	10	Crest	665.02	205+97.24	806.95	209+29.75	811.88	212+62.26	805.56	1.48%	-1.90%	-3.38%
Vendor B	10	Crest	590	206+56.49	807.64	209+51.49	811.42	212+46.49	805.73	1.28%	-1.93%	-3.21%
Vendor C	10	Crest	600.10	206+41.97	807.42	209+42.03	811.33	212+42.08	805.77	1.30%	-1.85%	-3.16%

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation
Vendor A	10	Crest	95.40	-187.72	-0.99	-140.02	0.69	-92.31	-0.35
Vendor B	10	Crest	20.38	-128.47	-0.30	-118.28	0.23	-108.08	-0.18
Vendor C	10	Crest	30.48	-142.99	-0.52	-127.74	0.14	-112.49	-0.14

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Vendor A	10	Crest	16.75%	0.90%	0.12%	0.66%	0.09%	0.43%	0.04%	29.82%	2.70%	13.04%
Vendor B	10	Crest	3.58%	0.62%	0.04%	0.56%	0.03%	0.51%	0.02%	12.29%	4.18%	7.27%
Vendor C	10	Crest	5.35%	0.69%	0.06%	0.61%	0.02%	0.53%	0.02%	14.04%	0.00%	5.69%

Vertical Curve 11

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Land Surveyor (Baseline)	11	Sag	439.02	215+52.01	802.26	217+71.52	798.19	219+91.03	800.27	-1.85%	0.95%	2.80%
Vendor A	11	Sag	474.77	214+58.55	801.83	216+95.93	797.32	219+33.32	799.61	-1.90%	0.96%	2.86%
Vendor B	11	Sag	400	215+04.64	800.75	217+04.64	796.90	219+04.64	799.14	-1.93%	1.12%	3.05%
Vendor C	11	Sag	572.76	214+18.87	802.49	217+05.25	797.18	219+91.63	800.28	-1.85%	1.08%	2.94%

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation
Vendor A	11	Sag	35.75	-93.46	-0.43	-75.59	-0.87	-57.71	-0.66
Vendor B	11	Sag	-39.02	-47.37	-1.51	-66.88	-1.29	-86.39	-1.13
Vendor C	11	Sag	133.74	-133.14	0.23	-66.27	-1.01	0.60	0.01

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Vendor A	11	Sag	8.14%	0.43%	0.05%	0.35%	0.11%	0.26%	0.08%	2.70%	1.05%	2.14%
Vendor B	11	Sag	8.89%	0.22%	0.19%	0.31%	0.16%	0.39%	0.14%	4.18%	18.01%	8.87%
Vendor C	11	Sag	30.46%	0.62%	0.03%	0.30%	0.13%	0.00%	0.00%	0.00%	13.68%	5.00%

Vertical Curve 12

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Land Surveyor (Baseline)	12	Sag	593.77	225+77.94	805.84	228+74.83	808.65	231+71.72	818.94	0.95%	3.47%	2.52%
Vendor A	12	Sag	753.84	224+00.36	804.11	227+77.28	807.74	231+54.19	822.02	0.96%	3.79%	2.82%
Vendor B	12	Sag	525	225+42.93	806.30	228+05.43	809.24	230+67.93	818.69	1.12%	3.60%	2.48%
Vendor C	12	Sag	588.71	225+39.16	806.21	228+33.52	809.40	231+27.88	820.92	1.08%	3.91%	2.83%

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation
Vendor A	12	Sag	160.07	-177.58	-1.73	-97.55	-0.91	-17.53	3.08
Vendor B	12	Sag	-68.77	-35.01	0.46	-69.40	0.59	-103.79	-0.25
Vendor C	12	Sag	-5.06	-38.78	0.37	-41.31	0.75	-43.84	1.98

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Vendor A	12	Sag	26.96%	0.79%	0.21%	0.43%	0.11%	0.08%	0.38%	1.05%	9.22%	11.90%
Vendor B	12	Sag	11.58%	0.16%	0.06%	0.30%	0.07%	0.45%	0.03%	18.01%	3.73%	1.66%
Vendor C	12	Sag	0.85%	0.17%	0.05%	0.18%	0.09%	0.19%	0.24%	13.68%	12.68%	12.30%

Vertical Curve 13

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Land Surveyor (Baseline)	13	Crest	1205.61	234+78.32	829.58	240+81.12	850.48	246+83.93	849.88	3.47%	-0.43%	-4.28%
Vendor A	13	Crest	1296.92	232+98.63	827.49	239+47.10	852.05	245+95.56	849.61	3.79%	-0.38%	-4.16%
Vendor B	13	Crest	1225	234+12.70	831.10	240+25.20	853.15	246+37.70	849.70	3.60%	-0.56%	-4.16%
Vendor C	13	Crest	1335.71	232+53.95	825.86	239+21.81	852.00	245+89.66	849.68	3.91%	-0.35%	-4.26%

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation
Vendor A	13	Crest	91.31	-179.69	-2.09	-134.02	1.57	-88.37	-0.27
Vendor B	13	Crest	19.39	-65.62	1.52	-55.92	2.67	-46.23	-0.18
Vendor C	13	Crest	130.10	-224.37	-3.72	-159.31	1.52	-94.27	-0.20

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Vendor A	13	Crest	7.57%	0.77%	0.25%	0.56%	0.18%	0.36%	0.03%	9.22%	11.63%	2.80%
Vendor B	13	Crest	1.61%	0.28%	0.18%	0.23%	0.31%	0.19%	0.02%	3.73%	31.09%	2.73%
Vendor C	13	Crest	10.79%	0.96%	0.45%	0.66%	0.18%	0.38%	0.02%	12.68%	18.60%	0.47%

Vertical Curve 14

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Land Surveyor (Baseline)	14	Sag	506.00	247+43.08	849.82	249+96.08	849.58	252+49.08	852.49	-0.43%	1.72%	2.15%
Vendor A	14	Sag	373.78	247+99.67	848.85	249+86.56	848.14	251+73.45	851.38	-0.38%	1.73%	2.11%
Vendor B	14	Sag	250	248+43.78	848.53	249+68.78	847.83	250+93.78	850.02	-0.56%	1.75%	2.32%
Vendor C	14	Sag	571.60	247+07.53	849.27	249+93.33	848.28	252+79.13	853.22	-0.35%	1.73%	2.07%

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation
Vendor A	14	Sag	-132.22	56.59	-0.97	-9.52	-1.44	-75.63	-1.11
Vendor B	14	Sag	-256.00	100.70	-1.29	-27.30	-1.75	-155.30	-2.47
Vendor C	14	Sag	65.60	-35.55	-0.55	-2.75	-1.30	30.05	0.73

	No.	Profile Curve Type	Length	PVC Station	PVC Elevation	PVI Station	PVI Elevation	PVT Station	PVT Elevation	Grade In	Grade Out	Grade Change
Vendor A	14	Sag	26.13%	0.23%	0.11%	0.04%	0.17%	0.30%	0.13%	11.63%	0.58%	1.86%
Vendor B	14	Sag	50.59%	0.41%	0.15%	0.11%	0.21%	0.62%	0.29%	31.09%	1.88%	7.72%
Vendor C	14	Sag	12.96%	0.14%	0.06%	0.01%	0.15%	0.12%	0.09%	18.60%	0.58%	3.72%