Evaluation of Cost-effective Pavement Deformation Detection technologies using LiDAR

AUTHORS

Hani Alzraiee. Ph,D., PE
Ashraf Rahim, Ph.D., PE
Alireza Shams, Ph.D.
Anurag Pande, Ph.D.
Mr. Wiliam Andrews
Mr. Nickolas Cruz

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Evaluation of Cost-Effective Pavement Deformation Detection Technologies using LiDAR

FINAL PROJECT REPORT

By:

Dr. Hani Alzraiee, Civil and Environmental Engineering, Cal Poly
Dr. Ashraf Rahim, Civil and Environmental Engineering, Cal Poly
Dr. Alireza Shams, Environmental and Civil Engineering, Mercer University
Dr. Anurag Pande, Civil and Environmental Engineering, Cal Poly
Mr. Wiliam Andrews Civil and Environmental Engineering, Cal Poly
Mr. Nickolas Cruz Villalobos Civil and Environmental Engineering, Cal Poly

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7. Author(s)

Anurag Pande (ORCID 0000-0002-3456-7932)
Hani Alzraiee (ORCID 0000-0001-6963-785X)
Ashraf Rahim (ORCID 0000-0001-6983-3383
Alireza Shams ((ORCID 0000-0001-5369-1122)
Mr. Wiliam Andrews
Mr. Nickolas Cruz Villalobos

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16. Abstract

Cross slope, the transverse slope with respect to the horizon, is a critical geometric feature of pavement surfaces as it affects safety due to its relationship to the potential of hydroplaning during wet weather. Appropriate cross slopes provide adequate drainage so water will run off the surface to a drainage system such as street gutters (urban streets) or side ditches (rural facilities). An inadequate cross slope could lead to several safety issues, including hydroplaning, loss of control, and run-off-road crashes. This research study compared two methods of data collection, namely a conventional survey and a LiDAR-based survey using a terrestrial laser scanner, to evaluate the roadway surface's cross slopes. Two existing rural farm road segments in San Luis Obispo County (California, USA) were selected for evaluation. A comparison between the results from the two methods showed that the difference follows a normal distribution, indicating no systematic errors during data collection. Also, the two-sided paired t-test between the traditional survey surveying and LiDAR showed no statistically significant differences between the slopes estimated using the two methods. This finding is important since LiDAR could increase the data collection efficiency and support the asset management practices of smaller county agencies. Moreover, the results indicate that the difference between LiDAR-derived cross slopes and field surveying measurements is less than 0.2% at a 95% confidence level. This level of accuracy meets cross-slope accuracy requirements (±0.2%) used by practitioners and demonstrates that LiDAR is a reliable method for cross-slope data collection.

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EXECUTIVE SUMMARY

Cross slope, the transverse slope with respect to the horizon, is a critical geometric feature of pavement surfaces as it affects safety due to its relationship to the potential of hydroplaning during wet weather. Appropriate cross slopes provide adequate drainage so water will run off the surface to a drainage system such as street gutters (urban streets) or side ditches (rural facilities). An inadequate cross slope could lead to several safety issues, including hydroplaning, loss of control, and run-off-road crashes. This research study compared two methods of data collection, namely a conventional survey and a LiDAR-based survey using a terrestrial laser scanner, to evaluate the roadway surface's cross slopes. Two existing rural farm road segments in San Luis Obispo County (California, USA) were selected for evaluation. A comparison between the results from the two methods showed that the difference follows a normal distribution, indicating no systematic errors during data collection. Also, the two-sided paired t-test between the traditional survey surveying and LiDAR showed no statistically significant differences between the slopes estimated using the two methods. This finding is important since LiDAR could increase the data collection efficiency and support the asset management practices of smaller county agencies. Moreover, the results indicate that the difference between LiDAR-derived cross slopes and field surveying measurements is less than 0.2% at a 95% confidence level. This level of accuracy meets cross-slope accuracy requirements (±0.2%) used by practitioners and demonstrates that LiDAR is a reliable method for cross-slope data collection. The report also provides direction for future efforts in this area

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ABSTRACT

Cross slope, the transverse slope with respect to the horizon, is a critical geometric feature of pavement surfaces as it affects safety due to its relationship to the potential of hydroplaning during wet weather. Appropriate cross slopes provide adequate drainage so water will run off the surface to a drainage system such as street gutters (urban streets) or side ditches (rural facilities). An inadequate cross slope could lead to several safety issues, including hydroplaning, loss of control, and run-off-road crashes. This research study compared two methods of data collection, namely a conventional survey and a LiDAR-based survey using a terrestrial laser scanner, to evaluate the roadway surface's cross slopes. Two existing rural farm road segments in San Luis Obispo County (California, USA) were selected for evaluation. A comparison between the results from the two methods showed that the difference follows a normal distribution, indicating no systematic errors during data collection. Also, the two-sided paired t-test between the traditional survey surveying and LiDAR showed no statistically significant differences between the slopes estimated using the two methods. This finding is important since LiDAR could increase the data collection efficiency and support the asset management practices of smaller county agencies. Moreover, the results indicate that the difference between LiDAR-derived cross slopes and field surveying measurements is less than 0.2% at a 95% confidence level. This level of accuracy meets the cross-slope accuracy requirements (±0.2%) used by practitioners and demonstrates that LiDAR is a reliable method for collecting cross-slope data.

Chapter 1: Background and Literature Review

1.1 Problem Statement

Lateral water drainage on roadways is important to ensure safe and efficient operation and structural condition of the pavement. Failure to drain water poses the risk of hydroplaning due to the loss of skid resistance in wet weather. Traditional data collection methods to measure cross slopes and identify pavement sections with deformation, such as rutting, are time-consuming, labor-intensive, and require data collectors to be located on the road, which poses a safety hazard. Local county agencies and States' Department of Transportation (DOTs), and especially local and regional agencies such as the county DOTs, could benefit from the use of Light Detection and Ranging (LiDAR)-based scanning using Terrestrial Laser Scanner (TLS) to collect accurate pavement cross-section data on roads in their jurisdictions. This study will provide a technical and economic evaluation of the TLS system through a comparison of the data collected through TLS with traditional data collection processes. TLS systems can create accurate three-dimensional (3D) coordinates in the form of dense point clouds for large-scale areas in a short period of time, leading to potential cost savings. The research will result in a framework to calibrate, collect, and process pavement cross-section and condition data. The project has significant potential for tech transfer to stakeholder agencies as the TLS data, and related processes will be relevant for several applications using spatial data for asset management.

1.2 Project Objective

Rutting is a major pavement deformation that could lead to failure in draining water from the pavement surface, causing loss of skid resistance in wet weather (Shams et al., 2020). The main concern with rutting has been related to driving safety. A timely collection of data on rut depth and similar deformation is an important safety practice for state and local agencies that maintain roadway infrastructure (Shams et al., 2020). Measuring the cross slope of pavement using a Lidar scan can help identify deformation, such as rutting since rutting is characterized by depression and lateral displacement of pavement materials. Common survey data collection methods for cross-slope measurements are time-consuming and require data collection personnel to be present on the road, which poses a safety hazard. New efficient and economical methods for collecting data are now available using LiDAR mapping and related technologies to capture roadway surface data, a variety of other geometric design characteristics, and roadway assets in general. These new applications can potentially increase productivity, provide users with timely enterprise data, minimize road crew exposure, and create robust information products with multiple use cases (Sarasua et al., 2018). However, before TLS technologies are widely deployed to improve the efficiency of the data collection processes for pavement performance monitoring, they need to be evaluated for the accuracy and usefulness of the data. In our discussions with the key stakeholders, we also learned that how the LiDAR data compares with more traditional data in terms of its accuracy is a critical question to be addressed prior to widespread adoption. The research objectives are:

1. Perform a technical comparison of the alternative LiDAR scanning with traditional data collection approaches for the collection of roadway cross-section data
2. Establish a framework for evaluating Terrestrial LiDAR Scanning (TLS) systems for pavement deformation data

1.3 Background and Significance of Work

The Cross slope is the transverse slope of the pavement with respect to the horizon. On tangent sections of normal crown two-lane roads, the pavement cross section is usually highest in the center and drops off to either side. The cross slope is intended to drain water from the roadway laterally so that water can run off the surface to a drainage system. Cross slopes are essential in enhancing user safety by minimizing the risk of hydroplaning (Shams et al., 2020) and the formation of ice during cold weather (Sarasua et al., 2018). The California Department of Transportation (Caltrans) standards call for a 2.0 percent cross slope to be used for new construction on the traveled way for all types of surfaces. However, on unpaved roadway surfaces, the cross slope could be as high as between 2.5 to 5.0 percent (California Department of Transportation (Caltrans), 2020). Several methods may be used to collect roadway longitudinal grade and cross slope, including the use of as-built plans, traditional surveying, GPS data-logging, and photogrammetry using high-resolution ortho-rectified images (Shams et al., 2018). Conventional surveying yields highly accurate results but is time-consuming (Shams et al., 2022). Furthermore, since it is conducted in the field, conventional surveying requires data collectors to be located on-road, posing a safety risk to data collectors and interrupting the roadway traffic (Esfandabadi, 2018; Rastiveis et al., 2020).

Photogrammetry is also accurate and less time-consuming than traditional surveying. However, collection and ortho-rectification of imagery of sufficient resolution to yield accurate cross-slope estimates (through accurate elevation measurements) are expensive (Sarasua et al., 2018). Florida Department of Transportation (FDOT) allows the use of electronic levels calibrated a minimum of once per day to measure the cross slope. For calibration, the electronic level shall be placed at the center location of a lane and perpendicular to the roadway centerline, and measurements are normally recorded to the nearest 0.1% (Florida Department of Transportation, 2016). Texas DOT uses a level of a 4-ft minimum length or a digital measuring device to measure the cross slope to the nearest 0.1% (Texas Department of Transportation, 2014). The Iowa Department of Transportation (Iowa DOT) uses a slope meter to measure roadway grade and cross slope for input to their geographical information management system (GIMS) database, which contains grades classified by maximum grade for each segment (Sarasua et al., 2018). The Wisconsin Department of Transportation uses a data-log vehicle with a vertical gyroscope, gyro compass, and a distance measuring instrument (DMI) to collect roadway slopes (Sarasua et al., 2018). However, using a slope meter, data-log vehicle, and ARAN (Automatic Road Analyzer) requires the data collection vehicle to physically traverse each lane of the roadway. For the collection of the cross slope, data must be collected in both directions. As a result, data collection for long segments can be time-consuming and expensive (Sarasua et al., 2018). The American Association of State Highway and Transportation Officials (AASHTO) published a provisional standard of practice for measuring the transverse profile of a roadway surface (American Association of State Highway and Transportation Officials, 2014). However, the data collection standard does not specify particular equipment to be used to collect the profile data. In recent years, mobile Light Detection and Ranging (LiDAR) has been increasingly used for roadside inventory, road geometry measurements, and asset data collection (Findley et al., 2011; Mraz & Nazef, 2008; Nhat-Duc et al., 2018; Shokri et al., 2019, 2021; Souleyrette et al., 2003; Zhang, 2010). Souleyrette et al. (2003) attempted to collect grade and cross slope from LiDAR data on tangent highway sections. While the grade was successfully estimated within 0.5% for most sections and 0.87% for all sections, the accuracy of the cross-slope data was much less accurate. The 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. South Carolina Department of Transportation (SCDOT) supplemental specifications of 2009 require the contractor to collect elevation data for the edge of each travel lane at 100-ft stations in tangents and 50-ft stations on curves (Sarasua et al., 2018). The cross slope is calculated by dividing the difference in elevation between the two edges of the travel lane by the lane width.

Tsai et al. used Riegl LMS-Q120i mobile LiDAR system combined with a high-resolution video camera and an accurate positioning system to extract pavement cross slopes in selected highways in Atlanta, GA (Y. Tsai et al., 2013). 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 is typically 0.2% (or 0.1°) during construction quality control. Repeatability results showed standard deviations within 0.05% (0.03°) at fifteen benchmarked locations in three runs (Y. Tsai et al., 2013).

To evaluate pavement cross slopes for existing roadways, the conventional methods are very time-consuming and require lane closures. Therefore, a need exists for methods that accurately measure pavement cross slope while eliminating lane closure requirements. More cost-effective methods may be beneficial to local county agencies, which often lack resources for asset management. Shams et al., (2018) evaluated the use of mobile LiDAR data for collecting cross slopes on paved roadway sections in South Carolina. The cross slopes were extracted from the LiDAR-derived point cloud by corresponding to two separate mesh grid surfaces, including the elevation and intensity of the points. The cross slope was then measured along each travel lane and compared with field-surveyed cross-slope data. The deviations between LiDAR-derived cross slopes and field measurements were less than 0.19%.

1.4 Context and Methodology Overview

Two farm roads in San Luis Obispo county, California, were selected for this study. The data for both road sections using two methods of data collection. First, the research team deployed a TLS to scan the road segments and create the 3D Point clouds. Second, conventional surveying (real-time kinematics) was used to develop ground truth cross slopes for the existing road sections and determine the point location using the global positioning system (GPS). Then, the accuracy of resulted data was measured and compared with the maximum acceptable error.

1.5 Report Overview

This research aimed to investigate whether coordinate and elevation data from stationary LiDAR could be used to accurately estimate the cross slope for a section of existing county roads. The data for the study was collected in San Luis Obispo County, California. The report is organized as follows: The next Chapter provides an overview of relevant literature, followed by a description of the sites and data collection techniques. Data processing and Analyses are described in Chapter 4. Chapter 5 provides the conclusions and future scope of this work.

Chapter 2: Background and Literature Review

2.1 Roadway Section Cross-slope

The Cross slope is the transverse slope with respect to the horizon. On tangent sections of normal two-lane roads, the pavement cross section usually has the highest elevation at the center and drops off to either side (see Figure 1 for typical cross sections on both tangent and curved segments of two-lane highways). The cross slope is intended to drain water from the roadway laterally so that water will run off the surface to a drainage system. Cross slopes are essential for safety by minimizing the risk of hydroplaning and the formation of black ice during cold weather (Shams et al., 2020). In California, Caltrans standards call for a 2 percent cross slope to be used for new construction on the traveled way for all types of surfaces. However, on unpaved roadway surfaces, the cross slope could vary between 2.5 to 5.0 percent (Sarasua et al., 2018).

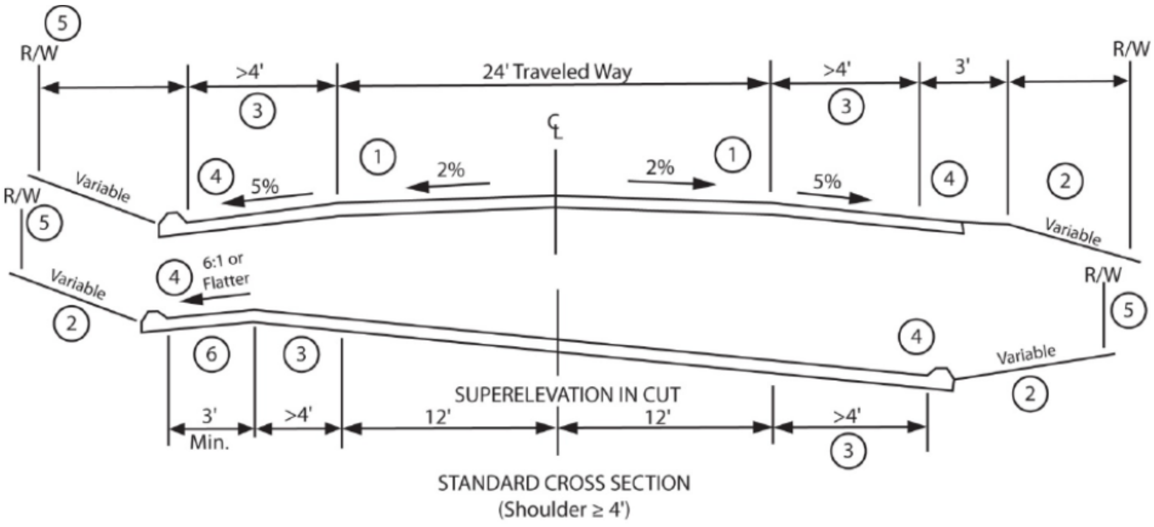


Figure 1. Geometric Cross-Section for Two-lane roadways (New Construction). (Sarasua et al., 2018)

2.2 Cross slope Data Collection Methods

Methods to collect high-accuracy grade or cross-slope data include the use of as-built plans, photogrammetry using high-resolution ortho-rectified images, traditional surveying, GPS, and data logging. Traditional surveying yields highly accurate results but is time-consuming and, since it is conducted in the field, requires data collectors to be located on-road, posing a safety risk to data collectors and interference with traffic. Photogrammetry is also accurate and less time-consuming than traditional surveying. However, collection and ortho-rectification of aerial imagery of sufficient resolution to yield accurate elevation measurements are expensive (Sarasua et al., 2018). Florida Department of Transportation (FDOT) allows the use of electronic levels calibrated a minimum of once per day to measure the cross slope. In that, the electronic level shall be placed at the center location of a lane and perpendicular to the roadway centerline, and measurements are normally recorded to the nearest 0.1% (Florida Department of Transportation, 2016). Texas DOT uses a level of a 4-ft minimum length or a digital measuring device to measure the cross slope to the nearest 0.1% (Texas Department of Transportation, 2014). The Iowa Department of Transportation (Iowa DOT) presently uses a slope meter to measure roadway grade and cross slope for input to their geographical information management system (GIMS) database, which contains grades classified by maximum grade for each segment (Sarasua et al., 2018). The Wisconsin Department of Transportation uses a data-log vehicle, which has a distance measuring instrument (DMI), vertical gyroscope, and gyro compass, to collect roadway grade (Sarasua et al., 2018). However, the use of a slope meter, data-log vehicle, and ARAN requires that the data collection vehicle physically traverse each roadway, and for collection of the cross slope, data must be collected in both directions. As a result, data collection for large areas can be time-consuming and expensive (Sarasua et al., 2018).

The American Association of State Highway and Transportation Officials (AASHTO) published a provisional standard of practice for measuring the transverse profile of pavement (American Association of State Highway and Transportation Officials, 2014). This standard outlines a method for collecting the transverse profile of pavement surface; however, the data collection standard does not specify particular equipment to be used to collect the profile data. In recent years, mobile

LiDAR has been increasingly used for roadside inventory, road geometry measurements, and asset data collection (Findley et al., 2011; Fwa et al., 2016; Mraz & Nazef, 2008; Nhat-Duc et al., 2018; Shokri et al., 2019, 2021; Souleyrette et al., 2003; Zhang, 2010).

Souleyrette et al. attempted to collect grade and cross slope from LiDAR data on tangent highway sections (Souleyrette et al., 2003). 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. The 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.

The cross slope is normally calculated by dividing the difference in elevation between the two edges of the travel lane by the lane width. South Carolina Department of Transportation (SCDOT) supplemental specifications of 2009 require the contractor to collect elevation data for the edge of each travel lane at 100-ft stations in tangents and 50-ft stations on curves (Sarasua et al., 2018). Several agencies use similar guidelines, and as a result, conventional methods to evaluate pavement cross slopes for existing roadways are very time-consuming and require closing the lanes for which the cross slope is measured. Therefore, a need exists for a method that accurately measures pavement cross slope while eliminating lane closure requirements, and LiDAR technology can potentially help.

2.3 LiDAR Technology Applications

TLS systems may be a cost-effective alternative to manual surveys with fewer delays in traffic and the need for smaller staffing, site visits, and lead time (K. Yen et al., 2015). Along with the tangible savings of time and lower costs, TLS also can potentially reduce CO_2 emissions, provide more detailed data, and increase the safety of the crew surveying the road (K. Yen et al., 2015; K. S. Yen et al., 2011). TLS surveys can be used for a variety of projects, such as cross slope measurements, pavement surveys, road asset inventories, bridge clearance surveys, Multidisciplinary Crash Investigation Team surveys, and road network surveys, amongst other projects (Ravani et al., 2015; K. Yen et al., 2015, 2018; K. S. Yen et al., 2011). These surveys can also be reused for other projects, such as public hearing presentations and fulfilling survey requests (K. Yen et al., 2018).

TLS can create a 3D point cloud for the pavement asset being surveyed. It allows for a wide variety of features to be extracted from them, such as pavement markings, bridge clearance dimensions, cross-slope, pavement cracking, crosswalks, roughness, rutting, potholes, trees, utility lines, utility poles, curb ramps, overhead signs, vehicles, houses, and other objects (Famili et al., 2021; Fan et al., 2020; Gavilán et al., 2011; Gézero & Antunes, 2019; Guan et al., 2014; H. Guan et al., 2015; Jung et al., 2019, 2019; Kumar et al., 2014, 2015; Rastiveis et al., 2020; Ravani et al., 2015; Shams et al., 2018; Shokri et al., 2019; Soilán et al., 2017, 2018; Tsai J. Y.-C. et al., 2013; Wang et al., 2017; Wen et al., 2019; Yang et al., 2017; K. Yen et al., 2015, 2018; K. S. Yen et al., 2011; Zaboli et al., 2019; Zhu et al., 2020). Table 1 shows the available details from a sample of studies that have demonstrated the process of extracting road features. Table 2 shows how accurate studies have been at extracting pavement distresses.

Table 1: shows the length, accuracy, processing time, and extracted features of LiDAR studies.

Study	Feature Extracted	Segment Length	Processing Time	Reported Accuracy
Guan et al. 2014	Road markings	105 m 63 m	1.11s* 0.89s*	F1 88% Precision 83 % 90% 82%
Kumar et al. 2014	Road markings	140 m each	-	True Positive Rate 88%
Yang et al. 2017	Lane markings and curbs	5.3 km 79.8 km	52.8 minutes 32.4 mins	Curb Precision 87.6% Recall 97.3% 95.4% 98.4% Road marking

				Precision 93.7% Recall 98.3% 97.6 % 98.1%
Soilan et al. 2017	Pedestrian crosswalks and traffic arrows	2.5 km - -	-	Average precision 96% Average F score 94%
Shams et al. 2018	Cross slope	3 mi 3.4 mi 1 mi	3mi/2person-hr	Within required 0.2% of manual survey
Yen et al. 2018	Overhead sign inventory	600 mi 2061 Total lane miles	6 weeks to collect data 41 hr to calculate XYZ coordinates 123 hr to colorize data	-
	Smart intersection mapping	1.9 mi (11 intersections	1 day site reconnaissance 1 day for planning 1 day collection (2 hours total) 3 days for post process	6” error in Z direction 2” error in XY direction 0.5” relative error between points
Soilan et al. 2018	Find pedestrian crossing, safety, and accessibility	2.5 km - -	-	Average precision 96% Average F score 94%
Jung et al. 2019	Improve lane marking extraction	180 m 460 m 2.13 km 4.74 km	Opt. processing 1173s 1415s 1361s** 2609s**	Precision 91.5% F1 90.7% 89.6% 89.1% 94%** 89%** 97%** 97%**
Wen et al. 2019	Use deep learning to find LMs (Original dataset vs. TUM-MLS dataset [25])	400 m 1 km [26]	- -	cGAN Precision 90.15% Recall 86.06% Precision 82.56% Recall 79.40%

				U-Net Precision 95.97% Recall 91.55% Precision 89.12% Recall 85.04%
	Urban and highway roads	300 m 400 m	- -	Precision 93.38% 90.77%
	Parking Structure	2000 m^2		Error rate 3.79%
Zaboli et al. 2019	Classification of objects	600 m	-	Accuracy 90%
Rastiveis et al. 2020	Lane Marking extraction	15.6 km 9.5 km	4.78 hr 2.40 hr	F1 99.4% Accuracy 99.6% 99.4% 99.2%

* Does not include sectioning time

** Average

2.4 Conclusions from Literature Review

The literature review demonstrated that i) agency requirements and specifications for cross slope estimation on exiting roads make the manual data collection quite expensive, and ii) that exploratory research using TLS has been used to extract several road features such as cross slopes and road markings. It is fair to say that these methods are still not fully implemented by the local and regional agencies that are most in need of cost savings that come with the use of TLS. This research focused on demonstrating the process of generating coordinate and elevation data in the form of point clouds generated from the stationary LiDAR and that this process could be used to accurately estimate the cross slope for segments of existing county roads.

Chapter 3: Site Description and Data Acquisition

3.1 Introduction

There are many LiDAR systems available to scan the project site. The most used systems are the Terrestrial Laser Scanner (TLS) and Mobile Laser Scanner (MLS). In the project proposal, the researchers suggested an MLS be used to collect the data required for conducting the research project. However, due to Covid-19 conditions and the cost of acquiring the data through MLS, the researchers used a TLS to collect the project data. It is important to note the difference between mobile and terrestrial scanning is the completeness of scans and overall data quality. TLS takes longer to scan, but the data quality and accuracy are much higher than the data collected using the MLS. The researchers used a FARO® Focus laser scanner to scan the selected road surfaces. This scanner can deliver up to 350m scanning range leading to superior area coverage per scan position. The researchers used FARO® SCENE 3D Point Cloud Software to process the scans, register the scans, and create 3D point cloud models for the cross-slop analysis.

3.2 Site Description

Two farm roads in San Luis Obispo County, California, were selected for this study. Each of the two test segments was approximately 260 feet in length and was selected on tangent roadway sections to avoid horizontal curves so that the cross slope was consistent throughout the segment. The pavement study sections were divided into 20-ft stations and centerline, and the edge of pavement elevations was measured using LiDAR and conventional survey. Second, conventional surveying (real-time kinematics) was used to develop ground truth cross slopes for the existing road sections and determine the point location using the global positioning system (GPS). The two test road segments of Mt. Bishop and Stenner Creek Roads are shown in Figure 3.2.

Figure 2. Road Segments Selected for Laser Scanning

3.3 Field Surveying

The field data collection involved two steps. The first was using conventional real-time Kinematic (RTK) surveying to develop a ground truth cross slope and then using the FARO laser scanner to scan the selected road segment. In the following section, both data collection methods will be explained in detail.

3.3.1 Conventional Survey

The real-time Kinematic (RTK) Surveying method was used to collect site data and create the as-is condition of the road segments (California Department of Transportation (Caltrans), 2012). RTK is a surveying technique that measures the relative positions of the points using two Global Navigation Satellite System (GNSS) antennas, one as a base station and one as a rover, in real-time with higher accuracy. The errors found in GNSS results are corrected using differential correction.

Per Caltrans standards, since the cross slope is constant within each travel lane, the collected points using GPS were collected at road edges and the center of the road for each section to regenerate the normal crown shape of the roads (California Department of Transportation (Caltrans), 2012). Conventional survey points were imported into Autodesk Civil 3d (C3D) as an existing ground point group in which the surface was created. Table 3.1 shows the results of the surveying process.

Table 2: Station Locations at 10’ Intervals for Bishop Road & Stenner Creek Road.

Bishop				Stenner			
Pt ID	**Northing**	**Easting**	**Elevation**	**Pt ID**	**Northing**	**Easting**	**Elevation**
300	2,309,769.19	5,762,466.55	349.39	400	2,310,000.42	5,762,038.74	364.00
301	2,309,778.97	5,762,482.77	349.07	401	2,309,998.80	5,762,047.51	364.16
302	2,309,752.90	5,762,470.55	348.73	402	2,309,998.41	5,762,056.59	363.85
303	2,309,738.31	5,762,486.66	348.49	403	2,309,978.13	5,762,055.77	363.14
304	2,309,747.66	5,762,502.48	348.61	404	2,309,978.06	5,762,046.67	363.41
305	2,309,723.60	5,762,518.74	348.43	405	2,309,978.40	5,762,037.90	363.18
306	2,309,712.48	5,762,501.84	348.25	406	2,309,959.12	5,762,037.21	362.46
307	2,309,685.22	5,762,519.86	347.95	407	2,309,958.65	5,762,046.99	362.67
308	2,309,696.13	5,762,536.66	348.22	408	2,309,958.33	5,762,055.25	362.36
309	2,309,676.07	5,762,549.64	348.19	409	2,309,942.41	5,762,054.56	361.81
310	2,309,665.05	5,762,534.91	348.08	410	2,309,942.46	5,762,045.65	362.11
311	2,309,644.47	5,762,570.72	348.29	411	2,309,942.97	5,762,036.95	361.88
312	2,309,633.16	5,762,556.20	348.22	412	2,309,929.42	5,762,036.49	361.38
313	2,309,613.80	5,762,591.38	348.62	413	2,309,928.92	5,762,045.48	361.60
314	2,309,601.95	5,762,575.70	348.53	414	2,309,928.34	5,762,054.45	361.26
315	2,309,579.71	5,762,612.31	348.90	415	2,309,917.40	5,762,053.72	360.85
316	2,309,570.64	5,762,594.48	348.43	416	2,309,916.61	5,762,044.32	361.13
317	2,309,774.34	5,762,474.75	349.48	417	2,309,916.56	5,762,035.81	360.86
318	2,309,762.45	5,762,492.97	348.78	418	2,309,904.39	5,762,035.67	360.49
319	2,309,756.91	5,762,485.58	348.92	419	2,309,904.05	5,762,044.39	360.72
320	2,309,750.79	5,762,477.36	348.77	420	2,309,903.58	5,762,053.35	360.38
321	2,309,725.06	5,762,495.29	348.33	421	2,309,889.13	5,762,052.80	359.87
322	2,309,730.21	5,762,502.62	348.47	422	2,309,888.72	5,762,043.12	360.17
323	2,309,735.39	5,762,510.81	348.51	423	2,309,888.38	5,762,034.93	359.95
324	2,309,700.26	5,762,510.14	347.99	424	2,309,874.68	5,762,034.65	359.52
325	2,309,705.60	5,762,518.88	348.38	425	2,309,874.13	5,762,043.42	359.62
326	2,309,710.18	5,762,527.53	348.28	426	2,309,873.79	5,762,052.60	359.33
327	2,309,690.84	5,762,528.74	348.19	427	2,309,858.83	5,762,052.06	358.85
328	2,309,673.48	5,762,528.20	347.99	428	2,309,858.93	5,762,042.20	359.01
329	2,309,679.30	5,762,535.89	348.21	429	2,309,858.57	5,762,034.09	358.92
330	2,309,684.70	5,762,544.14	348.20	430	2,309,841.88	5,762,033.35	358.17
331	2,309,669.95	5,762,542.29	348.23	431	2,309,841.94	5,762,043.04	358.34
332	2,309,647.41	5,762,546.23	348.16	432	2,309,841.41	5,762,051.50	358.17
333	2,309,652.46	5,762,553.59	348.28	433	2,309,825.49	5,762,050.90	357.56
334	2,309,657.90	5,762,561.65	348.20	434	2,309,825.74	5,762,041.95	357.73
335	2,309,637.85	5,762,563.61	348.32	435	2,309,825.66	5,762,032.74	357.50
336	2,309,613.94	5,762,567.29	348.46	436	2,309,807.92	5,762,032.21	356.77
337	2,309,620.11	5,762,575.40	348.48	437	2,309,807.63	5,762,041.62	357.01
338	2,309,625.61	5,762,583.45	348.47	438	2,309,807.57	5,762,050.63	356.92
339	2,309,606.40	5,762,584.04	348.55	439	2,309,784.92	5,762,049.20	356.07
340	2,309,588.02	5,762,585.45	348.56	440	2,309,784.89	5,762,039.94	355.98
341	2,309,592.79	5,762,593.41	348.68	441	2,309,785.84	5,762,031.44	355.89
342	2,309,598.19	5,762,602.19	348.76	442	2,310,049.48	5,762,027.98	365.42
343	2,309,742.66	5,762,494.60	348.59	443	2,310,049.49	5,762,028.04	365.42
344	2,309,717.10	5,762,511.10	348.41				

3.4 LiDAR Scanning

The research team used FARO Focus 350 laser scanner to scan the road segments (*FARO Focus Laser Scanner | FARO*, 2022). The scanner is classified as TLS and can capture object details at a 350-meter maximum distance. The site location was visited before the scan to create the scan plan. This is an important step toward acquiring scan point clouds that are accurate and represent the as-built condition. Further, in the scan planning, the scan settings, such as quality and resolution, should be determined for each scan. Both parameters (quality and resolution) control the time of scan and the details captured.

3.4.1 Scan Planning and Settings

Minimizing scanner positions will reduce scanning time and ensure point data is captured adequately. This can be achieved in the scan planning phase. Figure 3 shows the scanner location for the selected road segments, along with a map of the roadway segment. The scan locations were selected based on the site condition with the consideration of not causing traffic disruption and compromising scan data quality. The scanner was set to capture the area within 360 degrees horizontal by 270 degrees vertical field of view. Scan resolution (1/4) refers to the number of data points collected and the distance between those points. Resolution is chosen based on the level of detail needed and the distance to the object of interest. The second important parameter is called scan quality. The scan quality (3x) refers to the number of measurements the scanner makes to confirm point data. Increasing this setting increases scan accuracy but also increases scan time. Figure 4 shows the scanner settings used to collect the data.

a) Bishop RD Scan Location

b) Stenner RD Scan Location

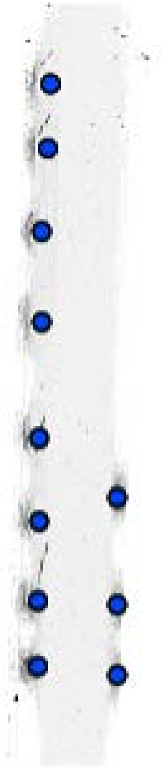


Figure 3. Selected Road Segments and scanned roadway locations

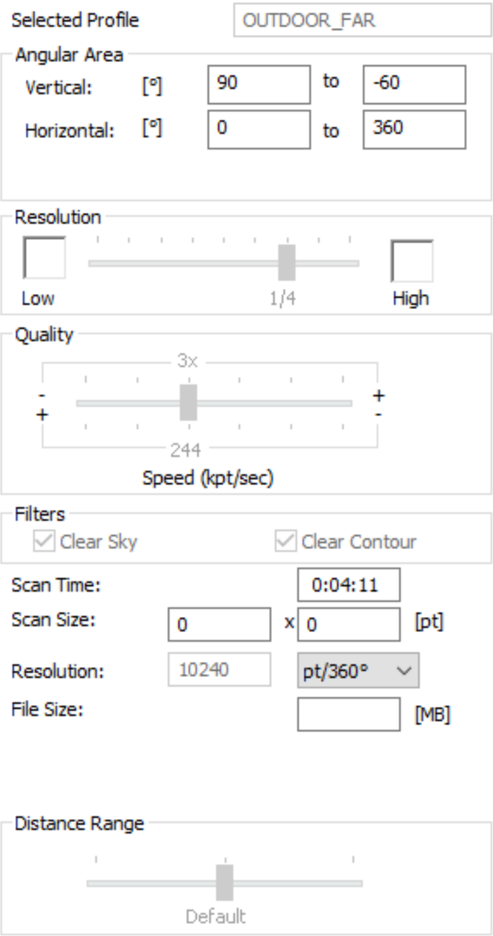

Selected Profile: OUTDOOR_FAR
Angular Area
Vertical: [°] 90 to -60
Horizontal: [°] 0 to 360
Resolution: 1/4
Quality: 3x
Speed (kpt/sec): 244
Filters
☑ Clear Sky
☑ Clear Contour
Scan Time: 0:04:11
Scan Size: 0 x 0 [pt]
Resolution: 10240 pt/360°
File Size: [MB]
Distance Range: Default

Figure 4. Scanner Settings

3.4.2 Scan processing, Registration, and 3D Point Cloud Models

The scans were processed using FARO SCENE software. Once the scans successfully pass the processing stage, they will move to the registration stage. Registration is the most important phase, and it means aligning multiple scans in a parent coordinate system using reference positions common between scans. We used the artificial targets to be the common objects between the scans. During the scan, artificial targets (spheres) of 200 mm in diameter were placed to facilitate the scan registration process. Figure 4 shows an example of the spheres used during scanning the Stenner Road segment.

Figure 5. Artificial Target (Spheres) Locations

The raw files of the scans were imported to SCENE software for processing and registration. Figure 3.5 and Figure 3.6 show an example of the 3D point cloud models created for both segments using the scan data. The 3D point cloud models were georeferenced using surveying data to align the scans with real-world coordinates.

Figure 6. Lidar Point Cloud of Bishop Road Segment

Figure 7. Lidar Point Cloud of Stenner Road Segment

The next chapter describes the process of analyzing these point clouds for cross-slope estimation and then comparing the results from the conventional surveying approaches.

Chapter 4: Data Processing and Analyses

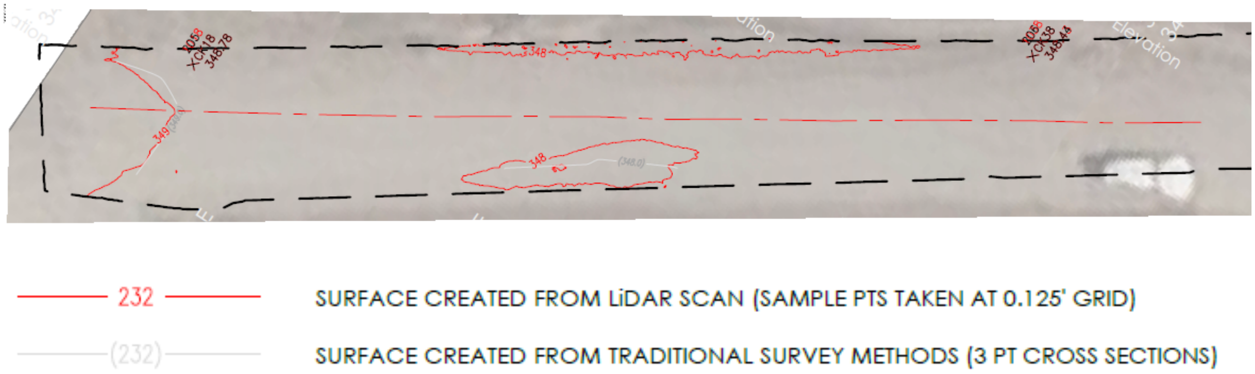
4.1 Introduction

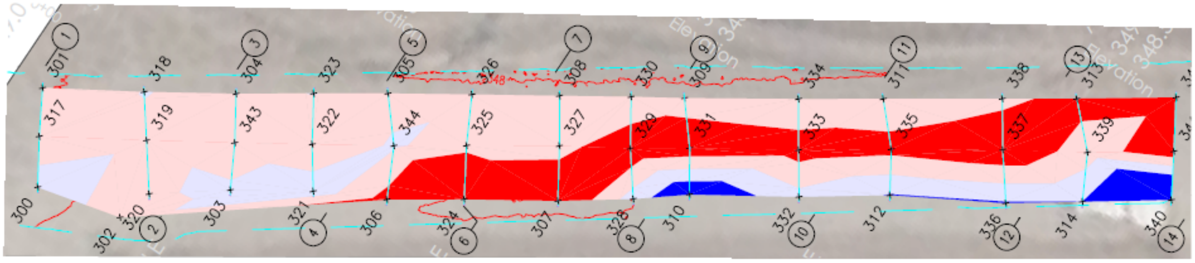
This Chapter discusses the process of creating the as-built road geometry from the conventional survey data and the 3D point cloud models. Both datasets were then used to create the cross-slope sections and the road profiles.

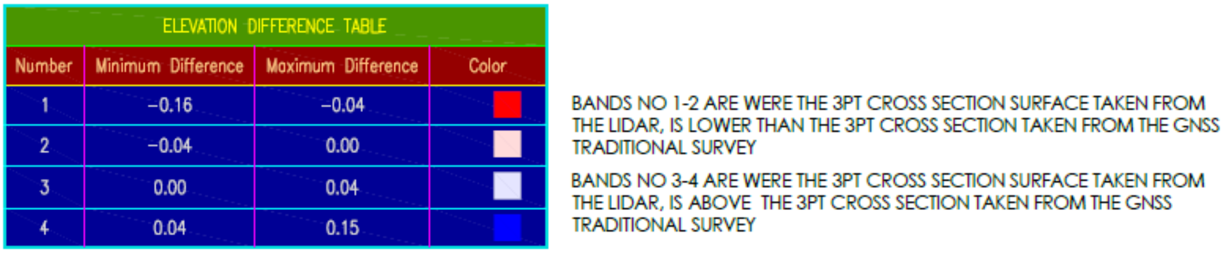
4.2 Surface Modeling

Conventional survey data were imported into Autodesk Civil 3d (C3D) as an existing ground point group in which the surface was created. Since the cross slope is constant within the travel lane, the survey points were collected at road edges and the center of the road for each section, as a result, the cross-section looks like a normal crown, triangle in shape.

The point cloud model was imported as a .las file into Trimble Business Center (TBC) to subsample points and create and surface needed to work in C3D. The point clouds were classified in TBC to extract ground features such as poles, vegetation, and other unknown points. The classification step was run three times to filter out and exclude any potential noise within the point cloud. Once the classification process outcome is satisfactory, the next stage involved using the surface creation tool within TBC to create the road surface from the point cloud (see Figure 1). The surface is created based on triangulating all the points in the point clouds. The final surface was exported from TBC as a .xml file and then imported into C3D. The Coordinate Geometry (COGO) points tool with C3D was used to create points from the TBC. COGO points, in addition to coordinate data (x, y, and z), have a variety of properties associated with them, including point number, point name, raw (field) description, and full description.







ELEVATION DIFFERENCE TABLE			
Number	Minimum Difference	Maximum Difference	Color
1	-0.16	-0.04	🟥
2	-0.04	0.00	⬜
3	0.00	0.04	⬜
4	0.04	0.15	🟦

BANDS NO 1-2 ARE WERE THE 3PT CROSS SECTION SURFACE TAKEN FROM THE LIDAR, IS LOWER THAN THE 3PT CROSS SECTION TAKEN FROM THE GNSS TRADITIONAL SURVEY

BANDS NO 3-4 ARE WERE THE 3PT CROSS SECTION SURFACE TAKEN FROM THE LIDAR, IS ABOVE THE 3PT CROSS SECTION TAKEN FROM THE GNSS TRADITIONAL SURVEY

Figure 8. Roadway surfaces created using LiDAR Scan and Traditional Survey Methods

4.3 Profile view and Cross Sections

These new Cogo points were created and added to a new surface that would mimic the initial surface, being a three points cross-section but with the elevations collected from the point cloud instead of the conventional survey. Using point on edge of the pavements, defining the boundary of surface, and collected points on the crown helps on triangulation and creating the 3D surface. Then an elevation along a reference line (between two points at same station but on opposite side of the road) resulted in cross section view showing the cross slope of travel lane at specific station on each travel lane. The sections allow us to visually gauge the differences between each surface and if they were within tolerance. A volumetric TIN surface (a composite of points in a base surface and comparison surface) was created by using the base surface as the conventional surface created using the three points cross section and then the comparison surface was the surface defined by the three points cross-section that used the elevation from the scanner.

The point cloud data sets were then imported into Autodesk Civil 3D software. The as-built cross-slop and profile were created from the point clouds as shown in Figure 9. Sample of the Road Cross-Slop Profiles Extracted from the 3D point Cloud model

2 and 3.

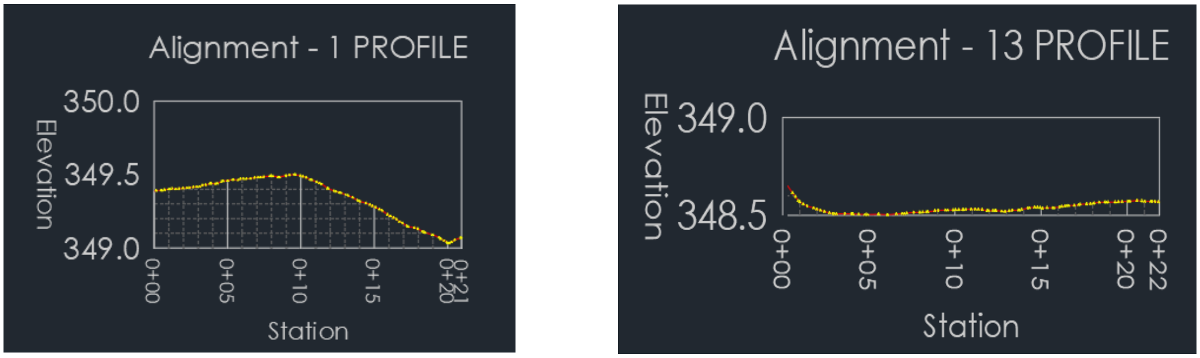


Figure 9. Sample of the Road Cross-Slop Profiles Extracted from the 3D point Cloud model

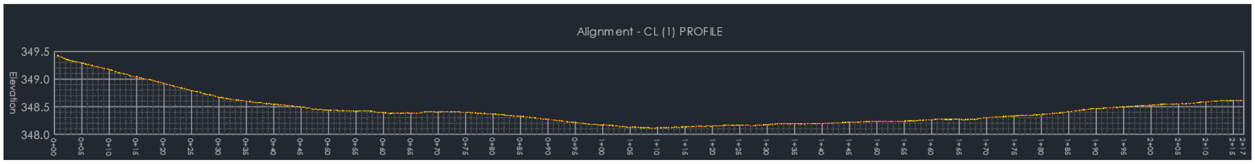
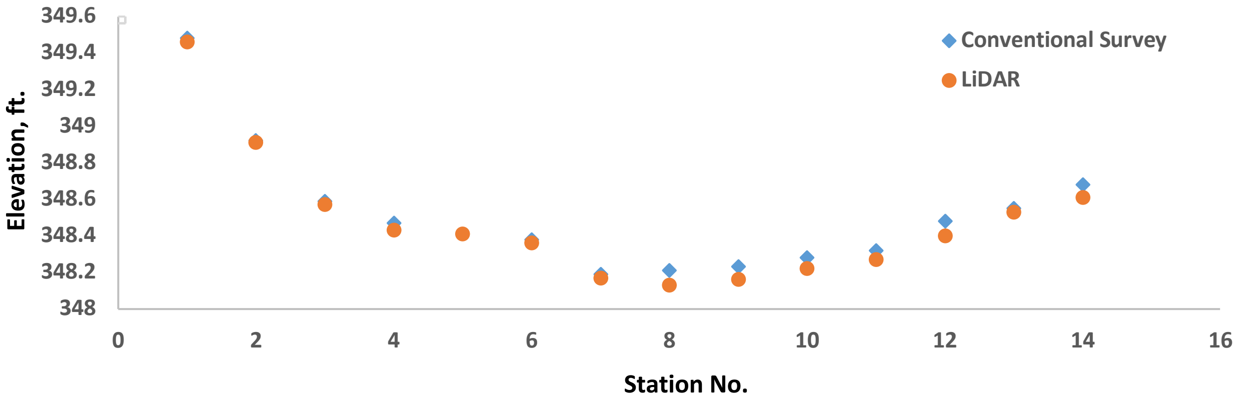


Figure 10. The road profile Extracted from the 3D point Cloud Model

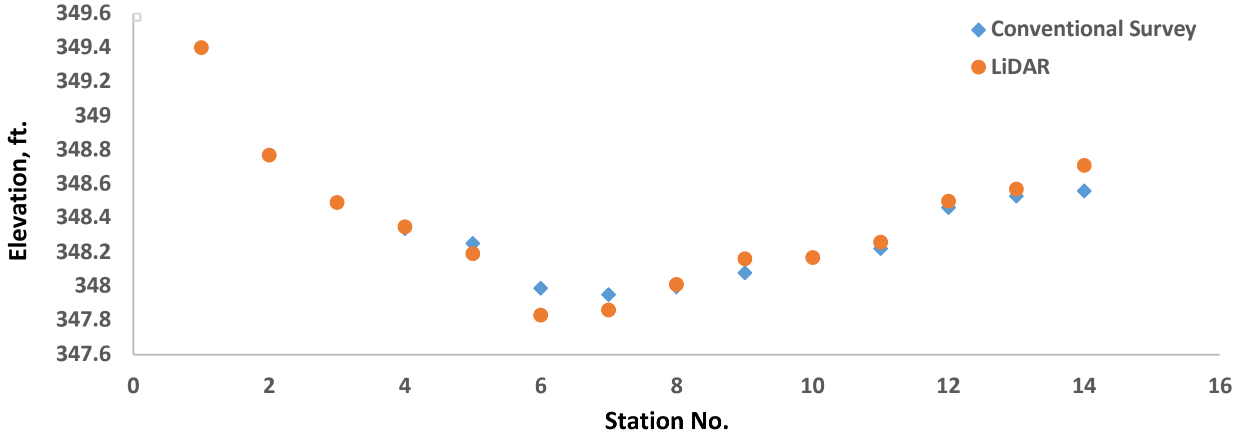
4.4 DATA ANALYSES

4.4.1 Roadway Vertical Profile

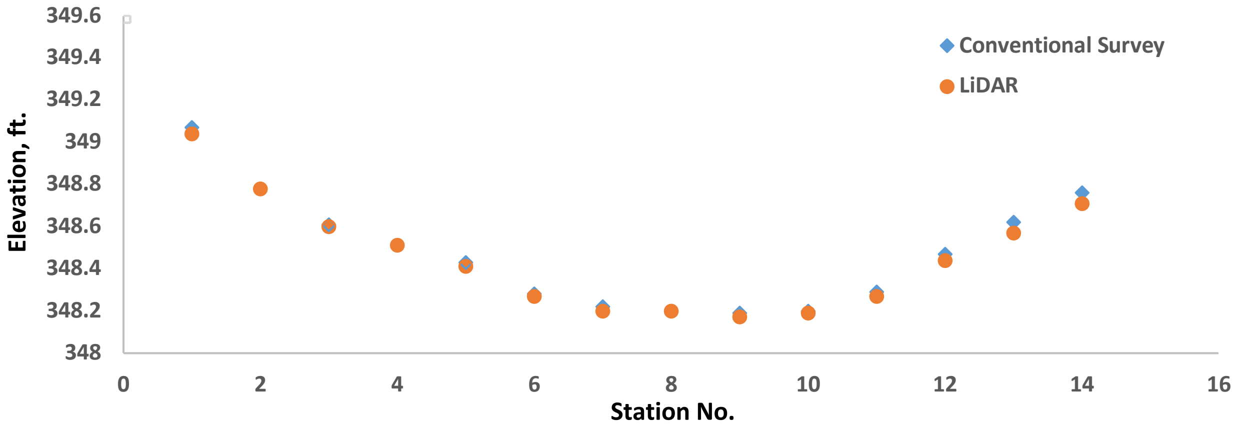
The point elevations obtained from the LiDAR scanning and conventional surveys were used to plot the cross section view of the roadway centerline and edge of travel ways (ETWs) as seen in Figures 4.4 and 4.5. Figure 4.4 shows the comaprison between cross sections generated from data collected by the two survey methods. It is noted, from these plots, that both survey methods resulted in almost identical profiles.



a) Centerline

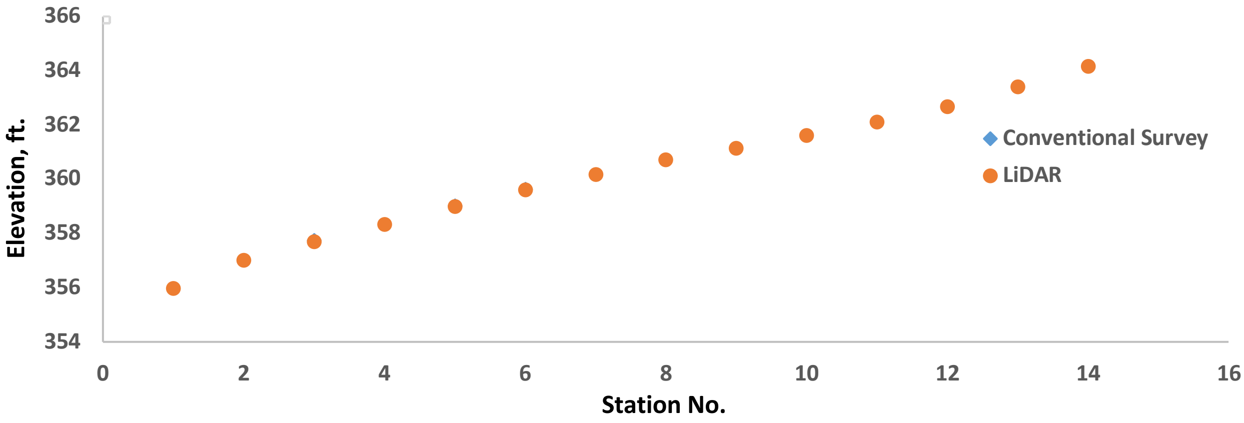


b) Northbound ETW

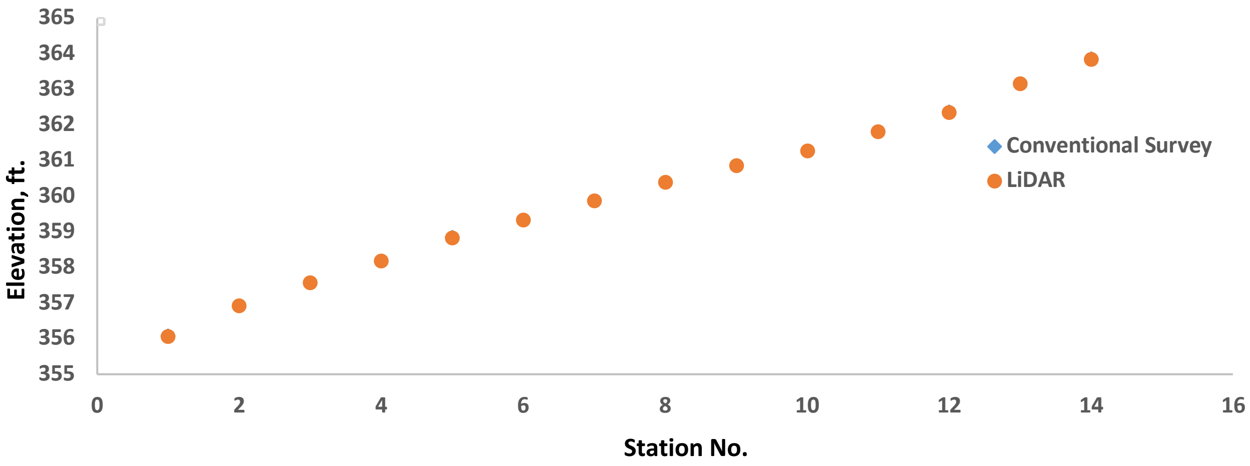


c) Southbound ETW

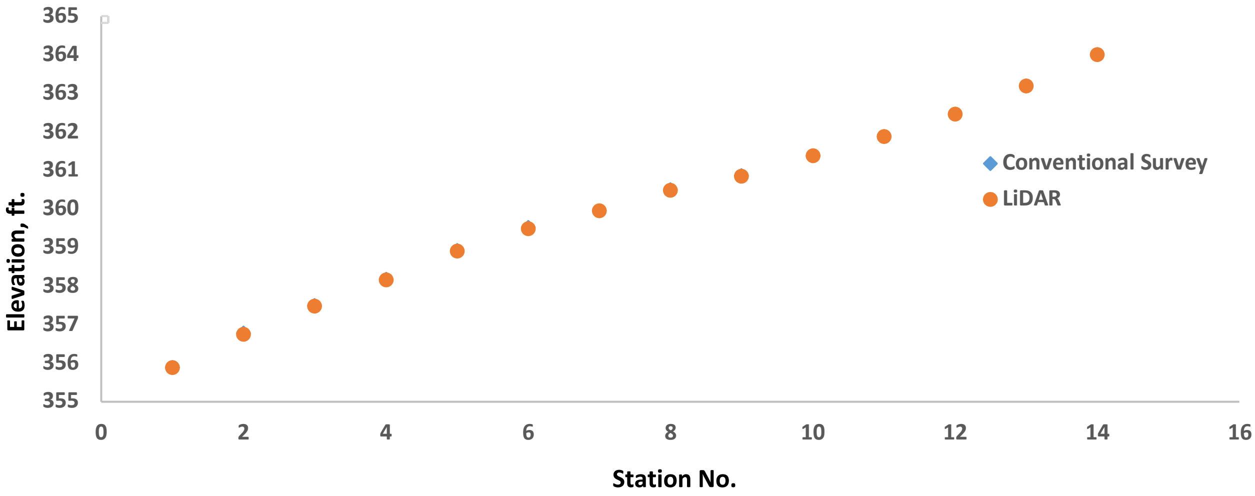
Figure 11. . Comparison of Roadway Profiles Generated from Conventional and LiDAR Surveys for Mt. Bishop Road.



a) Centerline



b) Eastbound ETW



c) Westbound ETW

Figure 12. Comparison of Roadway Profiles Generated from Conventional and LiDAR Surveys for Stenner Creek Road

4.4.2 Roadway Cross-Slope

The boxplot of extracted cross slope estimates using conventional surveying and LiDAR data showed no outliers, even as the LiDAR survey had a slightly wider distribution of estimates (Figure 4.6). The Q-Q plots show that both LiDAR and survey data cross slope estimates follow a normal distribution (Figure 4.7).

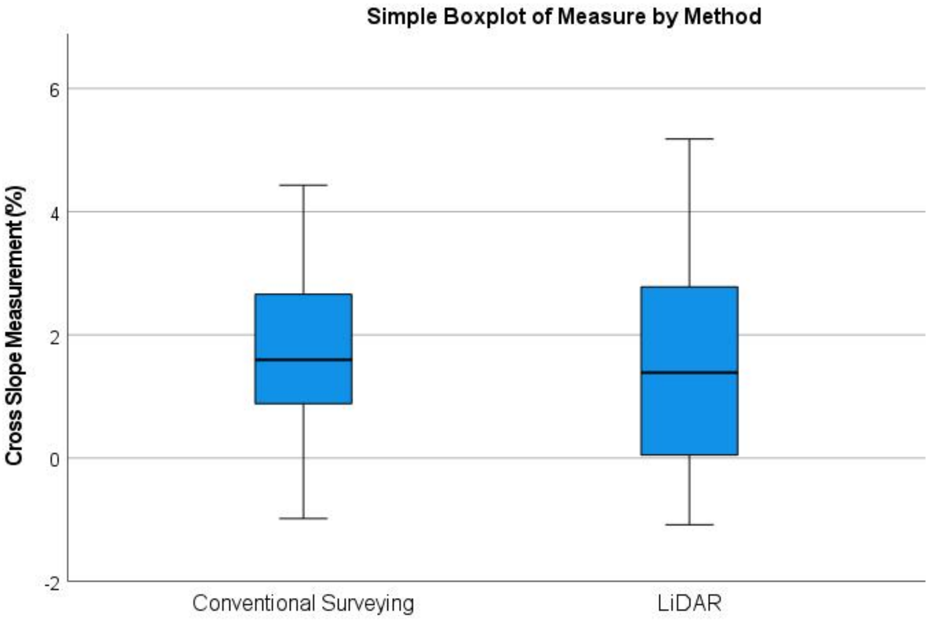


Figure 13. Box plot for cross slope estimates using conventional survey and LiDAR survey

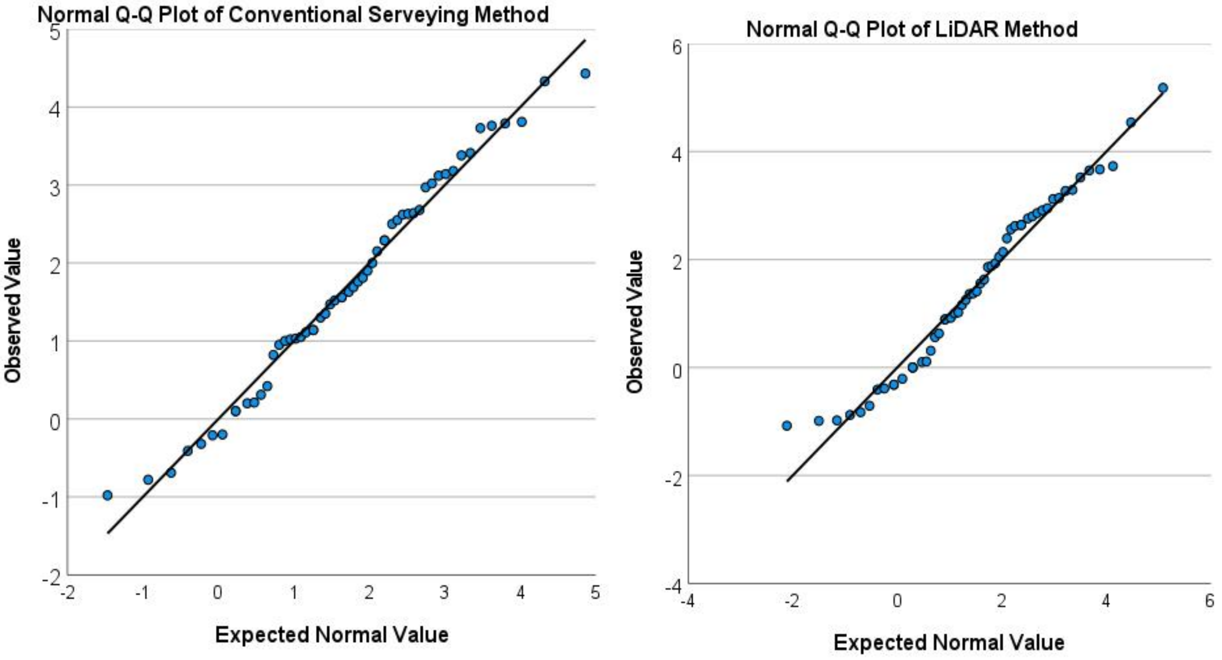


Figure 14. Normal Q-Q plots of Conventional and LiDAR survey estimates

One source of error in any surveying data collection is systematic error which is typically due to equipment imperfection. The systematic error magnitude and sign remain the same, which is depicted by a skew in the collected data. Random or accidental errors are due to imperfections in surveyors' senses, which magnitude and sign could change for each measurement. Based on the Q-Q plots shown in Figure 4.5 for both measurement techniques, we can conclude that the errors follow a normal distribution, and it is reasonable to assume that they are random and not systematic.

The use of LiDAR to extract pavement cross slope on the two roadway segments was compared against cross slope measurements collected using conventional surveying for the two road segments. The cross slope typically is a uniform transverse slope from the crown line on each side of the road. Each cross slope for a single travel lane falls within two GPS collected points (i.e.

edge of pavement marking and centerline). To extract cross slope at travel lanes a linear regression was used to determine best fitted line between points which represents average cross slope. The use of linear regression to extract cross slope estimates has been used in other LiDAR studies (Shams et al., 2018).

The survey data collected using the conventional and LiDAR methods and the comparison between cross slopes are shown in Tables 4.1 and 4.2 for Mt. Bishop and Stennet Creek Roads, respectively.

Table 4.1: Comparison of cross slopes from Conventional Survey and LiDAR for Mt. Bishop Rd.

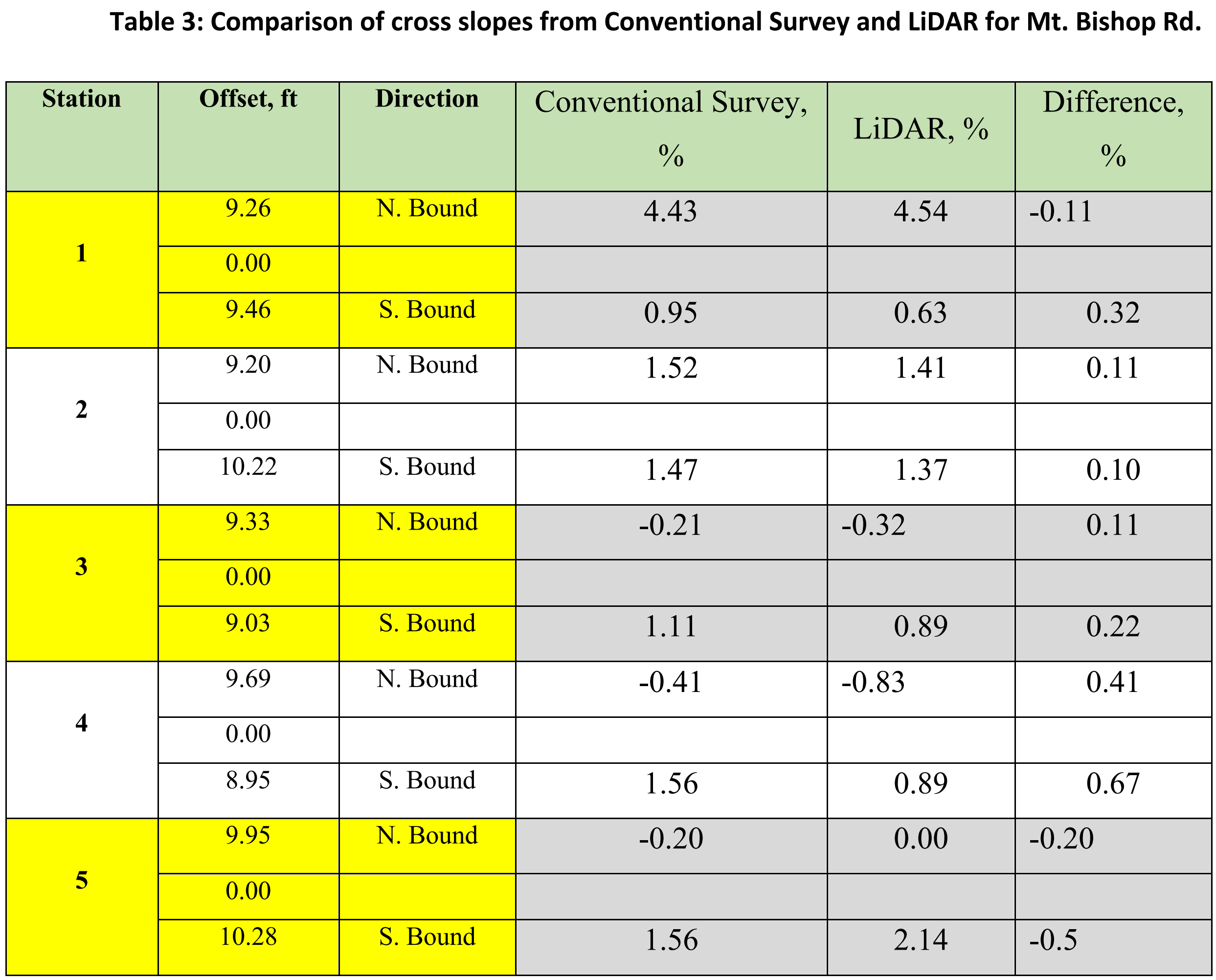


Table 3: Comparison of cross slopes from Conventional Survey and LiDAR for Mt. Bishop Rd.

Station	Offset, ft	Direction	Conventional Survey, %	LiDAR, %	Difference, %
1	9.26	N. Bound	4.43	4.54	-0.11
	0.00				
	9.46	S. Bound	0.95	0.63	0.32
2	9.20	N. Bound	1.52	1.41	0.11
	0.00				
	10.22	S. Bound	1.47	1.37	0.10
3	9.33	N. Bound	-0.21	-0.32	0.11
	0.00				
	9.03	S. Bound	1.11	0.89	0.22
4	9.69	N. Bound	-0.41	-0.83	0.41
	0.00				
	8.95	S. Bound	1.56	0.89	0.67
5	9.95	N. Bound	-0.20	0.00	-0.20
	0.00				
	10.28	S. Bound	1.56	2.14	-0.5

6	9.74	N. Bound	1.03	0.92	0.10
	0.00				
	10.23	S. Bound	3.81	5.1	-1.37
7	9.39	N. Bound	-0.32	-0.32	0.00
	0.00				
	10.50	S. Bound	2.29	2.95	-0.67
8	9.85	N. Bound	0.10	-0.71	0.81
	0.00				
	9.63	S. Bound	2.28	1.25	1.04
9	9.53	N. Bound	0.42	-0.10	0.52
	0.00				
	8.86	S. Bound	1.69	*	*
10	9.73	N. Bound	0.82	0.31	0.51
	0.00				
	8.92	S. Bound	1.35	0.56	0.78
11	9.61	N. Bound	0.31	0.00	0.31
	0.00				
	8.76	S. Bound	1.14	0.11	1.03
12	9.75	N. Bound	0.10	-0.41	0.51
	0.00				
	10.15	S. Bound	0.20	*	*
13	10.15	N. Bound	-0.69	-0.39	-0.30
	0.00				
	9.43	S. Bound	0.21	-0.42	0.64
14	10.23	N. Bound	-0.78%	-0.98	0.20
	0.00				
	9.26	S. Bound	1.30%	1.08	0.22

- Data Not Available

Table 4: Comparison of Cross Slopes from Conventional Survey and LiDAR for Stenner Creek Rd.

Station	**Offset, ft**	**Direction**	Conventional Surve, %	LiDAR, %	Difference, %
1	9.23	E. Bound	-0.98	-0.87	-0.11
	0.00				
	8.55	W. Bound	1.05	1.17	-0.12
2	9.01	E. Bound	1.00	1.00	0.00
	0.00				
	9.41	W. Bound	2.55	2.76	-0.21
3	8.95	E. Bound	1.90	1.56	0.34
	0.00				
	9.21	W. Bound	2.50	2.39	0.11
4	8.52	E. Bound	2.00	1.88	0.12
	0.00				
	9.66	W. Bound	1.76	1.86	-0.10
5	9.84	E. Bound	1.63	1.63	0.00
	0.00				
	8.83	W. Bound	1.02	1.02	0.00
6	9.23	E. Bound	3.14	3.14	0.00
	0.00				
	8.76	W. Bound	1.14	1.37	-0.23
7	9.61	E. Bound	3.12	3.12	0.00
	0.00				
	8.20	W. Bound	2.68	2.80	-0.12
8	8.98	E. Bound	3.79	3.67	0.11
	0.00				
	8.72	W. Bound	2.64	2.64	0.00

9	9.28	E. Bound	3.02	2.91	0.11
	0.00				
	8.51	W. Bound	3.17	3.29	-0.12
10	9.05	E. Bound	3.76	3.65	0.11
	0.00				
	9.00	W. Bound	2.44	2.56	-0.11
11	8.88	E. Bound	3.38	3.27	0.11
	0.00				
	8.70	W. Bound	2.64	2.64	0.00
12	8.32	E. Bound	3.73	3.73	0.00
	0.00				
	9.77	W. Bound	2.15	2.05	0.10
13	9.09	E. Bound	2.97	2.86	0.11
	0.00				
	8.78	W. Bound	2.62	2.62	0.00
14	9.09	E. Bound	3.41	3.52	-0.11
	0.00				
	8.83	W. Bound	1.81	1.93	-0.12

In evaluating the cross slopes at reference station locations, the highest difference between the two measurement techniques was on two Bishop Rd stations, where the slopes measured differed by -1.37% and +1.04%, as shown in Tables 4.1 and 4.2 (with red text highlighting the difference in estimated slope). A p-value of 0.076 for a two-sided paired t-test for conventional surveying and LiDAR data collection indicated that there was no statistical difference between the mean difference of the LiDAR-derived slopes and field surveying (see Table 3) at the 95% confidence level.

Table 5. Paired t-test – Comparing mean cross slope between Conventional surveying and LiDAR methods.

	Conventional Surveying	**LiDAR**
Mean	1.69%	1.59%
Variance	0.02%	0.02%
Observations	54	54
Pearson Correlation	0.968587	
Hypothesized Mean Difference	0	
Df	53	
t Stat	1.808572	
P(T<=t) two-tail	0.076192	
t Critical two-tail	2.005746	

With regards to the SHRP2 guide specification, a slope tolerance value of ± 0.2% of the design value is deemed acceptable for final measurement after project completion (Hunt et al., 2011). One may observe that, on average, the difference between slope measurements using the two techniques is only 0.097% (1.688-1.591), which is lower than the threshold specified by SHRP2 research. Furthermore, the absolute value of the difference between the estimated slopes using the two methods was less than or equal to 0.2% for 31 out of 54 stations (61.1.% of measurement locations). Also, another statistical test comparing the absolute difference in slope estimates from the two techniques to 0.2% yielded a p-value of 0.058. It also indicated that the null hypothesis of the absolute difference being the two sets of estimates being less than 0.2% could not be rejected. Based on these findings, the authors infer that the LiDAR survey provides similarly accurate estimates of the cross slope compared to conventional surveys.

Chapter 5: Conclusion and Recommendations

5.1 Summary and Conclusions

Cross slope, the transverse slope with respect to the horizon, is a geometric feature of pavement surfaces, and it is an important safety factor. The inadequate cross slope could lead to several safety issues, including hydroplaning, loss of control, and run-off-road crashes. Traditional surveying is usually applied to evaluate cross slopes and yields highly accurate results but is time-consuming, expensive, and results in worker safety issues. County agencies, in particular, need a more efficient pavement cross-slope survey due to the budget concerns they face. This research investigated the use of TLS to extract cross slopes on two 2-lane farm road segments in San Luis Obispo County, CA. We obtained coordinates and elevation data from LiDAR as well as through conventional surveys to assess if LiDAR data could be used to accurately determine the cross slope for the section. The result of statistical analysis indicated the average deviation between TLS data and conventional surveying using RTK GPS was less than the minimum acceptable accuracy level (± 0.2%). Therefore, according to the analysis documented in the research, the authors conclude that:

1. LiDAR technology is an effective alternative for collecting roadway elevation data for cross-slope estimation.
2. Roadway profiles developed from data collected using conventional, and LiDAR surveys are sufficiently similar even on county-maintained roads that are likely to go through maintenance cycles less frequently than the state DOT-maintained roads.

These conclusions point to LiDAR being a viable technology to evaluate cross slopes for roadways with good pavement surface conditions. Furthermore, it appears that the LiDAR point cloud may be able to capture several pavement distress types (observed in Figure 4), and this capability is worth exploring further by the resource-constrained public works departments in local jurisdictions.

5.2 Recommendations and Future Scope

This research provides a technical evaluation of TLS systems with respect to the accuracy and precision of collected cross-slope data and procedures to collect and process data. The research approach covered various data elements and variables, including profile view, cross-section comparisons, and ground proofing using conventional survey methods. The use of TLS can improve safety in work zones by considerably reducing the time surveyors and other personnel are exposed to risks associated with working close to the traveling public. Evidence from research results demonstrates that TLS can be an effective method for collecting accurate cross-slope data. The time required for data collection indicates that TLS is a cost-effective method for measuring cross slopes continuously along a roadway. Researchers recommend that TLS be implemented as the preferred means of producing data for the Caltrans pavement slope/cross slope verification program. An even greater return on investment can be achieved by using the TLS 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 technical as well as human resources.

Generally, LiDAR scanning devices can only collect data within line of sight. Therefore, other forms of LiDAR data collection, for example, Mobile Terrestrial Laser Scanning (MTLS), are also recommended. Similar to TLS, MTLS is capable of collecting an entire cross-section, with an exception at steep side slopes. Moreover, a vehicle-mounted LiDAR device can collect data at highway speeds, which increases the time efficiency data collection procedure.

The point density (and accuracy) diminishes as distance increases from the LiDAR scanner. Therefore, multiple benchmarks should be used to set up the scanner in order to not exceed the optimum range for data collection. Due to the tremendous number of points within the resultant point cloud, the manual extraction of data is tedious; automating those processes can improve cost-effectiveness. Therefore, automated/semi-automated techniques for filtering, segmentation, and classification of point clouds to extract roadway objects are desirable. As data processing and computing capabilities expand, commercial software product space in the automated extraction of information from LiDAR point clouds is worth watching.

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