EXPLORING THE USE OF DATA FROM NEWER TECHNOLOGIES IN ROAD DESIGN

by

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The following individuals read and discussed the thesis submitted by student Mahamudul Hasan, and they evaluated his presentation and response to questions during the final oral examination. They found that the student passed the final oral examination.

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DEDICATION

To my parents, for their sacrifice and support

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ABSTRACT

The use of Light Detection and Ranging (Lidar) is widespread currently all over the world including the United States. Though on-the-ground surveying and photogrammetric surveying are the more common methods to acquire terrain information, Lidar data is being increasingly used for this purpose due to its various advantages. Various research indicates that the accuracy of Lidar data has increased enough to make its use suitable for diverse applications. One potential application that is explored in this research is the use of terrain models generated from Lidar data in road design. To make such use possible we need to be assured that the accuracy of terrain models developed from Lidar data is comparable to models obtained from traditional land surveying techniques. Such assertions were tested in this research.

Lidar data collected using airplanes, terrestrial vehicles, and Unmanned Aerial Vehicles (UAV) were examined for use in highway geometric design. As current on-the-ground surveying methods take time, are costly, and have other operational constraints, it was worthwhile looking for alternative methods. We used ‘Bentley’s OpenRoads Designer CONNECT Edition’ and ‘ArcMAP’ 10.6 edition from ESRI to process the data. The data were obtained from the Idaho Transportation Department (ITD), District 5 for a section of US 30 through Georgetown, Idaho. Elevations of selected points from aerial Lidar, mobile-terrestrial Lidar, UAV-captured Lidar, and traditional surveying methods were obtained and compared. Other statistical analyses were also performed to compare the four sets of elevations. We also calculated Root Mean Squared Errors (RMSE) for different slopes of

the ground as well as Road-Surface and Non-Road-Surface to find out the accuracy of Lidar on different surfaces. A cost comparison was performed to aid in the selection of the best alternative.

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CHAPTER ONE: INTRODUCTION AND BACKGROUND

Statement of Problem

Since the introduction of motor vehicles, roads have become one of the basic pillars of a modern society. Today many of the citizens in the United States of America (USA) are the owner of their own vehicles. People use their vehicles over road networks for various personal reasons; the road network is also used to move goods to consumers. It is said that for the development of a country, developing the road network is one of the basic steps. This is especially true for less developed countries of the world. Also, during the time of building the roads we need to think about preserving the operability of the road network while considering the safety of the road users. For these reasons, road design is a critical endeavor and we have to be very cautious when we design a road network.

A typical highway project generally takes 5 years or more from the planning phase to the construction phase. A significant amount of this time is spent in getting the terrain information of the project area. Getting accurate terrain information is very important for the success of the project. To acquire highly accurate terrain information, we currently rely on traditional methods such as field surveying and photogrammetry. Despite the fact that these methods provide accurate terrain information, there are a few issues related to these methods. Essentially, these techniques are tedious and need a significant effort. Additionally, in many instances land that needs to be surveyed will not be level. In addition, in places with thickly vegetated areas, it is very difficult to get the required data because when using traditional methods, surveyors will need to go to the site physically to get the information. In unfavorable climate conditions, it is even harder to get the required information using these methods.

Because of the various complexities associated with traditional methods, there has always been a demand for alternative methods for terrain data collection. One of the most promising alternatives is the use of Light Detection and Ranging (LIDAR) for collecting terrain data. LIDAR is one of the most innovative remote sensing terrain mapping technologies. In most of the cases, Digital Surface Model (DSM) represents the earth's surface. DSM is a surface model which contains practically all sort of objects on the surface. For road design we need the information about elevation of the study area. For this, a Digital Terrain Model (DTM) is ideal. A DTM represents the bare surface ground without any kind of objects above the ground like plants, cables or buildings (1). This accurate DTM is a very important source of data for Geographic Information Systems (GIS). It can be used for many studies such as assessing terrain parameters, analyzing the earth’s surface, performing spatial analysis, and also for building other spatial models.

This type of data is used for engineering and environmental analysis purposes. At present, there are quite a few data sources for generating the DTM. The most widely used and most common method is the classical field survey and it is usually done with the use of total stations or Global Navigation Satellite System (GNSS) receivers. The accuracy of the data resulting from this method is high. The method is expensive (2) and time consuming (3). For creating the DTM, LIDAR can be an effective alternative.

As another alternative, we can consider the use of Unmanned Aerial Vehicles (UAV) for Lidar data collecting. The use of UAV with nonmetric digital cameras to recover the terrain information is being investigated so that we can overcome the limitations of the classical techniques. UAV is a relatively newer type of remote-sensing platform which has significant advantages over conventional piloted aircrafts and satellites. The most important advantages of this method are low cost, operational flexibility, and better spatial and temporal resolutions. Primarily drones are used to collect the UAV data. As they can be easily operated, less time will be needed for collecting the data. For these reasons, this method is expected to be the lowest-cost alternative relative to the other alternatives. Our literature review revealed, however, that very few studies were found that compared these alternatives with traditional field surveying, which was quite surprising. Our goal is to find alternatives to the present surveying method, which will not only save time but is also less expensive. In this research, we have evaluated the effectiveness of the alternatives in terms of accuracy and cost.

Background

Three collection methods are presently utilized by many Departments of Transportation (DOT) for large scale elevation data collection:

1. Electronic Distance Measurement methods (Total Station),
2. Real Time Kinematic (RTK) methods
3. Photogrammetry.

Both Electronic Distance Measuring (EDM) and RTK strategies share comparable advantages and disadvantages, including:

Advantages:

- Electronic gathering in field permits quick download of information in office
- In-field nearness enables notes to be taken

- Several units working autonomously take into consideration quick information accumulation, particularly in unobstructed areas (e.g. fields)

Disadvantages:

- Frequent equipment movements
- Permission required to access private property
- Personnel may work in risky territories (for example near roadways, heavy traffic zones)
- Ineffective in zones where signs can be blocked (Forests, urban communities, and so forth.)

Photogrammetry can address a portion of these disadvantages, yet it likewise has a few impediments. The symbolism for photogrammetric information should be taken in leaf-off conditions with no ice superficially. Leaf-off means that there is no foliage or a reduced amount of foliage on the tree. There is likewise a requirement for an appropriate sun edge with no cloud. That implies a compact time frame should be accessible to take the picture, which is not advantageous. Additionally, the procedure for getting heights from the pictures is moderate. Thus, there is a need to find an alternative that is quicker and less costly.

Remote Sensing has been widely used all over the world for various purposes. Lidar is an active remote sensing technique that might be able to create the elevation of earth's surfaces. Departments of Transportation in various states in the United States of America have been working for a long time to use this new technology for engineering applications. Road design could be one of them. Various reports show that nationwide many state DOTs have planned to use LIDAR. This data can be used for asset management, construction, road design, disaster management, infrastructure inspection, environmental monitoring, traffic operations, and surveillance. As current surveying methods are lengthy and costly, various DOTs have been seriously looking for alternatives. In many cases, these alternative data need not have pinpoint accuracy in applications such as traffic operations or environmental monitoring. For utilizing these information sources, we should be cautious about the precision of the data dependent on the areas in which we intend to utilize this information. If the accuracy is not acceptable, then it can become problematic in many ways. For example, inaccurate LIDAR data can give inaccurate elevations for the study area. So, after designing the road when we start construction, we will have to change our design plans because of a wrong DTM for that area. In the worst case scenario it may require us to completely redesign the road or may need some substantial changes in the current design. Besides requiring more time to complete the project it will also increase the cost of the project. That is why we need to be certain about the accuracy of the alternatives before using them.

With improved Lidar frameworks and developing accessibility of Lidar information, investigation on Lidar-based DTM creation is receiving increasing attention. Although some review papers (4, 5, 6, 7) have examined a large body of ground filtering algorithms, these papers did not include the latest developments of Lidar-based DTM generation, Generating DTM from Lidar has so many steps and each step is critical to make the final result acceptable. Any mistake within these steps can affect the overall accuracy. Past research suggests that Lidar data has good accuracy over flat ground but they have a hard time to deliver good accuracy in steep ground. The effect of the steepness of the terrain in road design applications has not been adequately addressed. Hodgson found that LiDAR information exactness changes by land spread conditions (8). It is likewise asserted that LiDAR information exactness in flat zones are twice as precise as those in more steep zones with woodland inclusion (8).The research reported in this thesis tests that assertion by examining the applicability of Aerial Lidar, Mobile Lidar and Lidar data from UAVs as a function of ground slope.

Research Objectives and Tasks

The research hypothesis of this thesis is that Mobile Lidar data is more accurate than Aerial Lidar data. However, none of the Lidar data or UAV-based Lidar data can replace traditional survey data. In this study we try to find the answers to these questions:

- How can we compare the accuracy for different Digital terrain Models (DTM)?
- Up until what stage of road design are data from such newer technologies acceptable?
- Will the alternatives be cost effective and save time?

To validate the hypothesis and to answer the above questions we consider several objectives for our research. They are:

1) Finding alternatives for traditional surveys
2) Comparing the accuracy of the alternatives
3) Statistical comparison of different surfaces
4) Evaluating the effectiveness of the alternatives

Our tasks to accomplish these research objectives and answer our questions are:

i. Ground Survey, Aerial LIDAR, and Mobile Terrestrial LIDAR data were collected for the same study area and processed.

ii. Digital Terrain Models (DTM) were generated from datasets in OpenRoads Designer Software. Also, ground survey points were imported with specific coordinates and elevations for the points were extracted using other data sources; the two sets of elevations were compared.

iii. A similar process was completed using the ArcMAP software. Then Digital Elevation Models (DEMs) were created from these processed files.

iv. Surveying points were imported in our study area and the elevations were again extracted for different files in ArcMAP.

v. The study area was divided into three categories.

vi. Overall accuracy for the study area as well as the accuracy for the sub-areas were estimated.

Organization of Thesis

This thesis paper consists of an introduction chapter, which is this chapter followed by two chapters containing two separate manuscripts that resulted from this thesis. The two manuscripts are inter-related and provide results related to a common objective. Both manuscripts describe the effectiveness of the alternative data sources taking different factors into consideration. Manuscript one explains the effectiveness of Aerial Lidar, Mobile Lidar, and UAV-Based Lidar data over traditional surveying. Here we used ArcMAP to complete the analysis. Manuscript two has a similar analysis and it describes the accuracy of Lidar data using Bentley's OpenRoads Designer Software. Also, cost comparison analysis is shown here for each data sources here. One of the manuscripts will be submitted to 2020 TRB Annual Meeting. Other will be submitted to another journal.

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CHAPTER TWO: MANUSCRIPT ONE – STATISTICAL ACCURACY COMPARISON OF AERIAL LIDAR, MOBILE-TERRESTRIAL LIDAR, AND UAV PHOTOGRAMMETRIC CAPTURE DATA ELEVATIONS OVER DIFFERENT TERRAIN TYPES

Abstract

Lidar and other remotely sensed data such as UAV photogrammetric data capture are being collected and utilized for roadway design on an increasing basis. These methods are desirable over conventional surveys due to their efficiency and cost-effectiveness over large areas. A high degree of relative accuracy is achievable through the establishment of survey control. In this case study, elevations (z-values) derived from mobile-terrestrial lidar, aerial lidar, and UAV photogrammetric capture collected with survey control are statistically compared to conventionally-surveyed elevations. A cost comparison of the methods is also included. Each set of z-values corresponds to a discrete horizontal point originally part of the conventional survey, collected as cross-sections. These cross-sections were surveyed at three approximate tenth-mile sample locations along US-30 near Georgetown, Idaho. The cross-sections were collected as elevational accuracy verification, and each sample location was selected as an area where the mobile-terrestrial lidar in particular was expected to have more difficulty achieving accuracy off the road surface. Processing and analysis were performed in Esri ArcMap 10.6, and all data were obtained from the Idaho Transportation Department, District 5.

Introduction

Designing new or existing transportation facilities requires accurate surface terrain information (*1*). Conventional survey methods for acquiring accurate terrain surfaces include Real Time Kinematic Global Positioning System (RTK-GPS), Electronic Distance Measurement (Total Station), and photogrammetry. Generally, RTK-GPS and Total Station procedures are time-consuming and costly due to the necessity of workers and equipment needing to physically move across the terrain of an area to achieve satisfactory coverage. Certain operational constraints such as dense vegetation cover must also be considered, and in the case of conventional surveys on existing road design projects, vehicular traffic is a further safety consideration. While large-area terrain information can be collected through these methods, the time and effort needed is significant.

Photogrammetry circumvents some of the limitations of RTK-GPS and Total Station survey but introduces other issues. Imagery used for photogrammetric data must typically be gathered in highly specific conditions, usually when foliage is in a bare, leaf-off state but before the ground is covered by snow and ice (1). Photogrammetry also requires a particular sun angle with no cloud cover present. Once photogrammetric imagery is collected, processing the data and determining elevation is often time-consuming.

Lidar and other remotely-sensed data such as UAV photogrammetric capture are an alternative to these methods, and may be used for road design if their accuracy is within an acceptable range. By supplementing these data with survey control methods, a high degree of accuracy can be achieved. Lidar (light detection and ranging) is an active remote sensing technique that uses laser light to measure distance by illuminating an object and measuring the reflected light with a sensor. Common acquisition methods include mounting a lidar device on an aircraft or ground-based vehicle and moving while the device continuously collects point data. The result is a “point cloud” dataset of lidar point locations, from which elevation models can be created. Compared to the previously described conventional survey methods, lidar is generally considered to offer safer data collection, cost effectiveness, and a high level of detail (2).

Another remote sensing technique is the use of an unmanned aerial vehicle (UAV) to acquire photogrammetric capture data through the collection of a large volume of photographs. This method utilizes a digital structure from motion process with scale invariant feature transform tools. Essentially, this uses the oblique differences between photographs to generate a three-dimensional model of its target. A digital surface terrain model can be generated using this output, as well as a point cloud file or files resembling a lidar point cloud dataset. Although this method has some of the same issues as “traditional” photogrammetry, it is generally considered a less-expensive alternative to both conventional survey and lidar.

The accuracy of lidar data have been compared to conventional survey points in other research. For example, Pourali et al. utilize this general technique to determine vertical accuracy for a test lidar dataset, noting its suitability for purposes requiring an accuracy of up to 0.5 meters (approximately 1.64 feet) for a large area of aerial lidar in Victoria, Australia (3). Hodgson and Bresnahan used a similar approach to test aerial lidar accuracy as part of a large-scale mapping effort for Richland County, South Carolina (4). Lidar accuracy depends on the entire workflow starting from data acquisition through generating the final terrain model. Researchers have noted that high quality digital terrain models (DTMs) can be generated with suitable processing techniques, which take into account a variety of factors including the multiple returns lidar typically produces (5). For example, classifying lidar data allows for differentiating between the ground, foliage, buildings, and water surface in the point cloud. Besides roadway design, lidar is routinely used in a variety of applications including forest inventory and assessment (6, 7), hydrologic channeling (8), and carbon sequestration (9).

Lidar used for roadway design is usually collected expressly for this purpose, and studies (3, 4, 10) have shown a root mean square error (RMSE) of 0.15–0.40m for vertical accuracy and horizontal RMSE of 0.5–1.0 m is achievable with lidar. The accuracy of lidar-derived digital elevation model (DEM) rasters has been researched over a variety of vegetation and terrain types (11). One study indicates that increasing terrain slope leads to lower lidar canopy height estimates because slope has effect on DEM accuracy (12). As part of this study, the effects of both slope and terrain type on lidar vertical accuracy will be examined.

Methods

Study Area

The study area consists of three approximate tenth-mile segments of US-30 in southeastern Idaho near Georgetown, corresponding roughly to mileposts 414, 419, and 422, respectively. Conventional survey cross-section points including elevation were collected for the Idaho Transportation Department (ITD) by Dioptra Geomatics on these segments to verify the accuracy of the mobile-terrestrial lidar featured in this study. Each of these areas was specifically chosen as an area that the mobile-terrestrial lidar may have difficulty with accuracy off of the road surface. In this study, the verification purpose of the conventional survey has been expanded to the aerial lidar and UAV photogrammetric capture data covering the same general areas. All four datasets (aerial lidar, mobile-terrestrial lidar, UAV photogrammetric capture, and traditional survey cross-section points) were obtained from ITD. Figure 2.1 shows the study area.

Study Objectives

Several objectives were considered for this study:

1) Comparing the vertical accuracy of the three test case datasets to traditional survey elevation ground points,
2) Statistically determining whether the elevation differences between the test datasets are potentially acceptable for use in roadway design, and
3) Performing a cost analysis of the different data collection methods.

Figure 2.1 Google Earth image of the study area

Data Collection

Aerial Lidar

The aerial lidar data used in this study was collected between April 7 and October 12, 2016 by Aero-Graphics, as part of an ITD District 5 district-wide aerial lidar and imagery collection project. Aero-Graphics guaranteed the accuracy of these lidar data at "planning grade." In order to achieve a greater degree of horizontal accuracy, survey control targets were strategically placed along collected routes districtwide (14). All data were collected using a custom districtwide coordinate projection, based on NAD 1983 Idaho State Plane East, intended to maintain regional measurement distances without needing to scale the data.

Collection was performed with an Optech ALTM Orion H300 sensor and an Optech CS-10000 aerial camera system, at an average 3,300 feet altitude. The lidar sensor and the camera were paired in a customized mount to improve accuracy and minimize error between datasets (14). Aero-Graphics reported a 30% overlap in the lidar data, yielding 9.6 points per square meter across the project. The pulse rate frequency used for the collection was 225 kHz with scan frequency of 68.7 Hz, and the scan angle was +/- 14.5° from the nadir position (full scan angle 29°). The Orion H300 was equipped with a GPS/IMU unit, recording the XYZ position and roll, pitch, and yaw attitude of the plane throughout the flight. This allowed for the correction of lidar returns that may have been thrown off by the plane's motion during flight (14).

Mobile-Terrestrial Lidar

The mobile-terrestrial lidar data was collected on November 15, 2016 by R.E.Y. Engineers, Inc. The collection device, mounted to a ground-based vehicle, was a RIEGL

VMX-250 mobile scanning system, consisting of two RIEGL VQ-250 line scanners, two RIEGL CS6 5 MPx Cameras, 80°x65° FOV, an Applanix POS LV V5 Model 510 position and orientation system (IMU), a Trimble BD960 GNSS receiver, a Trimble Zephyr Model 2 GNSS Antenna, an Applanix Distance Measurement Indicator (DMI), and a RIEGL Control Unit (CU). For project control, Dioptra Geomatics set 110 control targets using RTK GPS, with the Utah Reference Network "TURN" solution to improve accuracy on most of these targets (15). These lidar data were collected as part of ITD project A019(382), from the Caribou county line to Nounan Road on US-30 in Bear Lake County. As a result, the data were collected using a custom coordinate system, based on NAD 1983 Idaho State Plane East, specific to the project. It should be noted that this coordinate system is different than the districtwide coordinate system used for the Aero-Graphics aerial lidar.

The collection vehicle with the VMX-250 scanning system was driven two times in each direction for data quality purposes, at an average speed of 35 miles per hour, varying between 30 and 40 miles per hour. Each scanner was set for a measurement rate of 300 kHz (600 kHz combined). For each pass at this speed, R.E.Y. reported a point density on the road surface of approximately 340 points/m^2 at 20 feet away from the sensors, to over 2000 points/m^2 along the trajectory line from the sensors as the point density were collected (15). Unlike the aerial lidar data, the mobile-terrestrial lidar data did not have classifications assigned. Ground classification were determined for this study using the Classify LAS Ground tool in Esri ArcMap.

UAV Photogrammetric Data Capture

The photogrammetric-engineered dataset was collected October 11, 2018 by ITD District 5 with a DJI Phantom 4 UAV with a 12.4 megapixel RGB sensor. The device was flown at an average elevation of 151 feet above ground level using “terrain awareness” to follow features and create waypoints on the terrain based on a NASA/USGS DEM from Mapbox. The UAV had a relative accuracy GPS/GLONASS system on board and was flown with an iOS mobile command and control application called Map Pilot. Two flights on each section were conducted on either side of the road with 75% front and side overlap and a solar elevation angle at nadir (solar noon) position for the particular date, derived from Spring/Fall NASA values. Approximately 330 aerial images were taken per road section at 3-second intervals. The image metadata Z-values (WGS84 EGM 96 Geoid) were manually adjusted in Microsoft Excel to correct the heights, and then processed in a key point matching process in Pix4D.

Nine aerial targets were set at each site to be used as ground control points, the coordinates of which were determined with a survey-grade RTK-GPS system using the same coordinate system and control point values as the on-the-ground survey data collection. The UAV-collected data was processed in Pix4D (including matching, extraction, densification, meshing, and scaling) utilizing Structure from Motion (SfM) and Scale Invariant Feature Transform (SIFT) tools to acquire a single image composed of the collected images. Using this composite, the program then produced 3D meshes and point clouds for each road section.

These produced data have a ground sampling distance of 1.5 cm/pixel. Pix4D calculated a root mean square error (in U.S. survey feet) of 0.56 for the data at the milepost 414 road section, 0.061 at the milepost 419 section, and 0.52 at the milepost 422 section, representing the difference between the initial and computed positions of the ground control points. Unsupervised point cloud classification was then performed in

Pix4D on the point cloud to filter out points besides the “road” and “ground” points to create a digital terrain model (DTM). A georeferenced DTM LAS point cloud file was then produced and used for the analysis process, exported to unmodified NAD 1983 State Plane Idaho East. No supplemental boundary work was performed on the outer edges of the imagery. It should be noted that the Pix4D unsupervised classification process was limited in its capability to classify the data; a second automated classification of ground returns only was performed using the Classify LAS Ground tool in Esri ArcMap.

Verification Survey

The conventional survey data used in this study to compare the elevational accuracies of the three remote data types was collected by Dioptra Geomatics between April and May 2017 using a Total Station. These cross-section points were collected for the purpose of verifying the accuracy of the mobile-terrestrial lidar and were collected using the same project-specific coordinate system. These verification surveys were used by R.E.Y. to examine the accuracy of the mobile-terrestrial lidar on pavement, at the edge of the pavement, and off-pavement ground using TopoDOT (15).

Analysis

The three test case datasets were provided by ITD as .las files and the conventional survey cross-section points were provided as an Esri Shapefile. The conventional survey points included codes indicating whether their location was on or off the road surface. Esri ArcMap software was used for viewing and working with the lidar data, including deriving bare-earth DEM rasters and preparing the data for statistical analysis. Elevation Z-values for each discrete survey point were derived from the three DEM surfaces to be compared to the conventional survey elevations for each point. The study road sections were subdivided into three categories to evaluate the effect of slope: level, moderate, and steep.

According to the AASHTO "Policy on Geometric Design of Highways and Streets" (commonly referred to as the "Green Book"), terrain with a slope between 0-2% is considered level, 2-5% is considered moderate, and slopes greater than 5% are considered steep. For the purposes of determining areas of level, moderate, and steep terrain for this analysis, degrees were used instead of percentage slope. Slope values less than 1º were categorized as level, between 1º and 5º were categorized as moderate, and more than 5º were categorized as steep. The location of each point was categorized by this slope index. Root mean square error (RMSE) was calculated for all elevation differences between the conventional survey points and their corresponding locations on the test data DEM surfaces. These RMSE values were further divided by study road section, location on or off the road, and slope value.

The .las files were added to a new ArcMap document, and only ground return was selected to produce DEM surfaces. Lidar data typically includes a large number of points for returns other than bare ground, so this is an important step, necessary to produce a model of the ground only. Figure 2.2 shows the properties of the aerial lidar LAS Dataset:

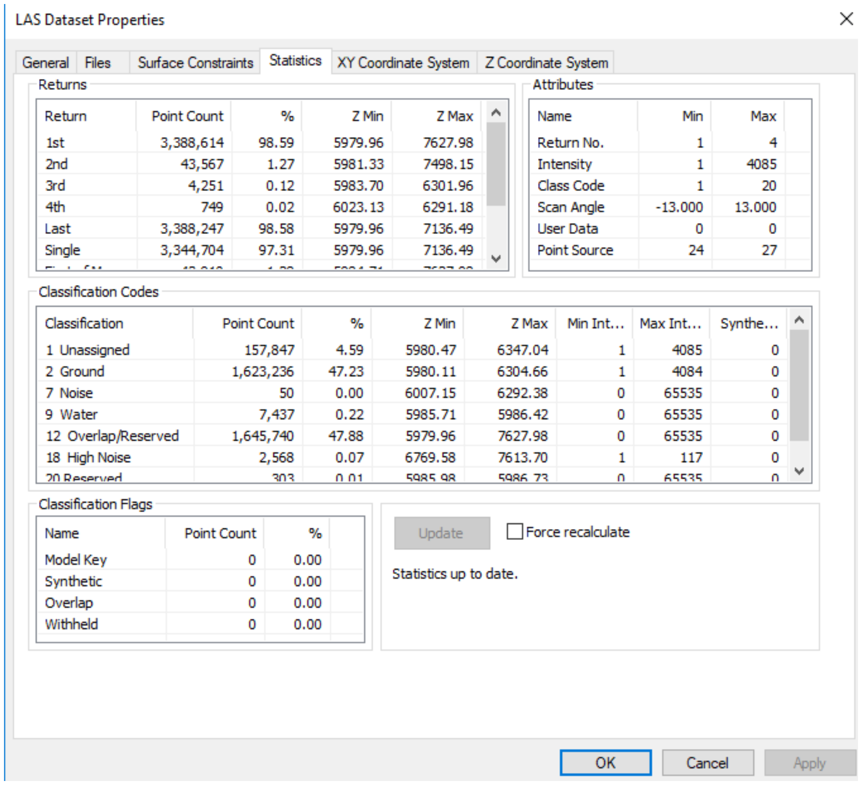

Figure 2.2 Classified aerial lidar data

DEM surfaces were generated from the .las files, and these outputs were visually evaluated to ensure they covered the conventional survey points at each road section. Elevation data was then extracted from each DEM for each covered conventional survey point for aerial, mobile-terrestrial, and UAV data by using the Extract Values to Point (Spatial Analyst) tool. This process allowed for finding the elevations at the same horizontal points for the different data sources to statistically compare them. Figure 2.3 shows the survey points imported in ArcMap for a section of our study area.

As noted previously, the conventional survey data included each point's surveyed elevation with its horizontal XY coordinates, as well as code information indicating location and type. This allowed for determining whether a specific point was a road-surface point or a non-road surface point. Along with the slope classification of each point, this information made it possible to analyze the survey points based on this classification.

RMSE was calculated for the differences between the surveyed elevation values and each DEM elevation value across all point locations. Further, RMSE was calculated for road-surface and non-road-surface points, and for each study road section independently.

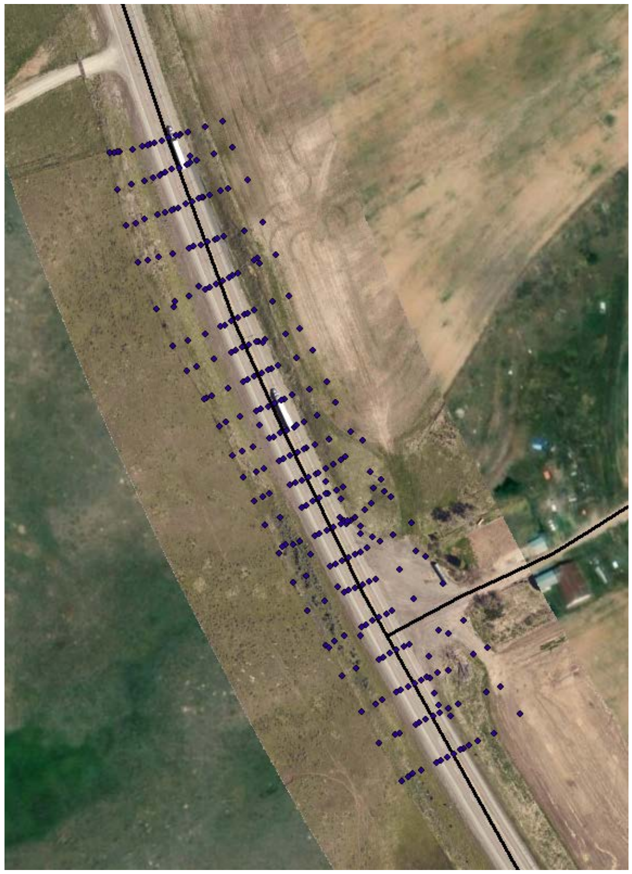

Figure 2.3 Survey points imported in ArcMap

The Slope (Spatial Analyst) and Extract Values to Point (Spatial Analyst) tools in ArcMap were used to determine slope at each point to analyze the effect of slope on the test data vertical accuracy. The DEM raster files for each data type were input to determine slope, using “Degree” as the output measurement and the default method to calculate the slope. After calculating the slopes, they were classified into the three slope categories discussed previously: level, moderate, and steep. The process resulted in a new raster file for each corresponding input raster file, with slope values for the entire terrain covered area. Slope values were then extracted for aerial, mobile-terrestrial, and UAV data at each survey point.

Results

Table 2.1 shows the difference in elevations obtained from the conventional survey and each remote method DEM for all survey point locations using ArcMap. The conventional survey elevations were considered to be the "true" elevations.

Table 2.1 Statistics Related to Difference in Elevations for Different Data Sources

Data Source	Aerial Lidar	Mobile-Terrestrial Lidar	UAV Photogrammetric Capture
RMSE (cm)	9.03	18.40	14.76
Mean Difference (cm)	-7.48	-9.04	-7.79
Standard Deviation Sd(cm)	5.15	17.18	12.57

The difference in elevation represented in Table 2.1 is the conventional survey elevation minus the elevation obtained from one of the three remote sources of data. All elevation differences used in this table were taken into account, regardless of location or slope. The mean difference was found to be negative for all three remote data sources, indicating that on average the remote data sources overestimated the ground elevation. The table shows that the aerial lidar elevations are closer to the surveyed elevations than those from the other two sources. The RMSE for mobile-terrestrial lidar was the highest in this analysis, with similar results for mean difference and standard deviation.

Table 2.2 shows the results for the three road sections in which the verification survey data was collected. In all cases, the RMSE and standard deviation were high in

Table 2.2 Statistics Related to Difference in Elevations for Three Sections

Data Source	Aerial Lidar			Mobile-Terrestrial Lidar			UAV Photogrammetric Capture		
Area type	Section 1	Section 2	Section 3	Section 1	Section 2	Section 3	Section 1	Section 2	Section 3
RMSE(cm)	9.5	9.1	8.4	23.5	11.1	16.3	17.4	13.6	12.9
Mean Difference (cm)	-7.3	-7.5	-6.6	-11.4	-5.3	-8.3	-10.9	-4.5	-7.6
Standard Deviation (cm)	6.1	5.2	3.7	20.5	9.8	13.3	13.6	12.8	9.5

Section 1. This was also true for mean difference except for the aerial lidar elevation differences. The accuracy was higher in Sections 2 and 3 for all remote data sources.

Table 2.3 presents the elevation differences for road- and non-road-surfaces. The RMSE for the road-surface points is much lower than that for the non-road-surface points. The RMSE for road-surface is quite acceptable within the standard accuracy limit stipulated by the Idaho Lidar Consortium (ILC). According to ILC, any RMSE less than 5 cm is within their accuracy standard. For points on the road-surface, mobile-terrestrial lidar gave the most accurate result among the three sources of data, while the aerial lidar had the highest RMSE (5.4 cm). The mean differences and standard deviations were also low for all remote data sources. It can be concluded that on road-surface areas, all these data types are capable of achieving acceptable results.

However, similar results were not observed for non-road-surface areas. The RMSE was high for all the remote data sources, with RMSEs higher than the 5 cm ILC standard for all cases. Aerial lidar achieved the closest result in terms of RMSE, mean difference, and standard deviation. This indicates that vertical accuracy of both the lidar and UAV photogrammetric data is significantly affected by non-road-surface returns for all of the alternatives. To summarize, it can be concluded that lidar and UAV photogrammetric data collected using survey control can achieve high accuracy for areas over a road surface with diminished accuracy for non-road surfaces.

Table 2.3 Statistics Related to Difference in Elevations for Road-Surface and Non-Road-Surface Survey Points

Data Source	Aerial Lidar		Mobile-Terrestrial Lidar		UAV Photogrammetric Capture	
Area type	Road-Surface	Non-Road-Surface	Road-Surface	Non-Road-Surface	Road-Surface	Non-Road-Surface
RMSE (cm)	5.4	11.3	1.9	25.6	4.4	19.7
Mean Difference (cm)	-5.00	-9.4	-0.5	-15.7	-1.8	-12.7
Standard Deviation Sd(cm)	2.0	6.2	1.9	20.0	4.0	15.4

Table 2.4 shows results by slope of the ground using the previously described slope classification. From the table it can be concluded that the RMSE for aerial lidar was noticeably lower for moderate and steep slope areas than for either mobile-terrestrial lidar or UAV photogrammetric data. There were 922 survey points across the three road sections of the study area, and of these only 36 points were identified as level. More than half of the points were considered moderate, a total of 494 points, and 392 points were considered steep. The RMSE for all remote data types was lowest at points considered to be on level terrain. The RMSE for aerial lidar differences at points considered level was 4.91 cm. The aerial lidar data had its highest RMSE in steep areas, at 11.00 cm. Still, this RMSE is much

Table 2.4 Statistics Related to Difference in Elevations for Three Slope Areas

Data Source	Aerial Lidar			Mobile-Terrestrial Lidar			UAV Photogrammetric Capture		
Area type	Flat	Moderate	Steep	Flat	Moderate	Steep	Flat	Moderate	Steep
RMSE (cm)	4.91	7.48	11.00	4.36	10.99	24.57	3.95	9.92	18.94
Mean Difference (cm)	-4.65	-6.54	-8.92	-0.79	-3.42	-15.29	-1.90	-3.68	-12.48
Standard Deviation (cm)	1.58	3.64	6.45	4.34	10.45	19.26	3.56	8.99	13.98

lower compared to those for the other two remote datasets. This, along with its RMSE of 7.48 cm for moderate areas, explains why the overall RMSE, all points considered, was lowest for the aerial lidar.

The RMSE for the mobile-terrestrial lidar was higher than aerial lidar for all types of terrain areas. A total of 920 conventional survey points was available for comparison of the mobile-terrestrial lidar. Of these 920 points, only 39 points were on ground considered level. The highest number of points were considered moderate, a total of 458. The remaining 423 points were considered steep. The mobile-terrestrial RMSE was 4.36 cm for level terrain, which was low compared to that for aerial lidar. The highest RMSE for mobile-terrestrial lidar was obtained in steep areas with an RMSE value of 24.57 cm, while in moderate areas the RMSE was 10.99 cm. The overall RMSE was high, due to the higher RMSE in the steep areas. Similar patterns are apparent in the mobile-terrestrial mean difference and standard deviation for each terrain type. All values were high for steep regions and low for level regions, following a pattern similar to the aerial lidar.

The UAV photogrammetric data had a total of 918 usable survey points. Only 45 points were determined to be on level terrain. Among the three types of remote data, the UAV-based DEM had the highest number of survey points considered level and the RMSE was the lowest among all of them, with an RMSE for level terrain of 3.95 cm. RMSE of the points considered to be on moderate terrain was 9.92 cm. This RMSE was higher than that for the mobile-terrestrial lidar but lower than for aerial lidar, with 436 survey points considered on moderate terrain. A similar number of points were obtained for steep areas, 437 in total. The RMSE for steep areas was 18.94 cm, which was the highest among the three types of terrain areas. Notably, the UAV data for steep areas was closer in accuracy than the mobile-terrestrial lidar. The mean difference and standard deviation for the UAV data appear to generally follow the same patterns as for the aerial lidar and mobile-terrestrial lidar.

In Figure 2.4, the RMSEs for the aerial lidar, mobile-terrestrial lidar and UAV photogrammetric data are shown for the different areas including the overall RMSE for these data sources. The figure illustrates that the aerial lidar elevations were generally the closest to the conventional survey elevations, although the RMSE for level areas was higher than the other two data types. However, this difference is relatively minimal. The UAV data had the second-closest elevational accuracy compared to the conventional survey, and mobile-terrestrial lidar had the least accurate RMSE, in large part due to steep areas and those away from the road surface. As noted previously, the verification survey locations were intentionally chosen as areas where the mobile-terrestrial lidar collection was likely to have difficulty with terrain away from the roadway.

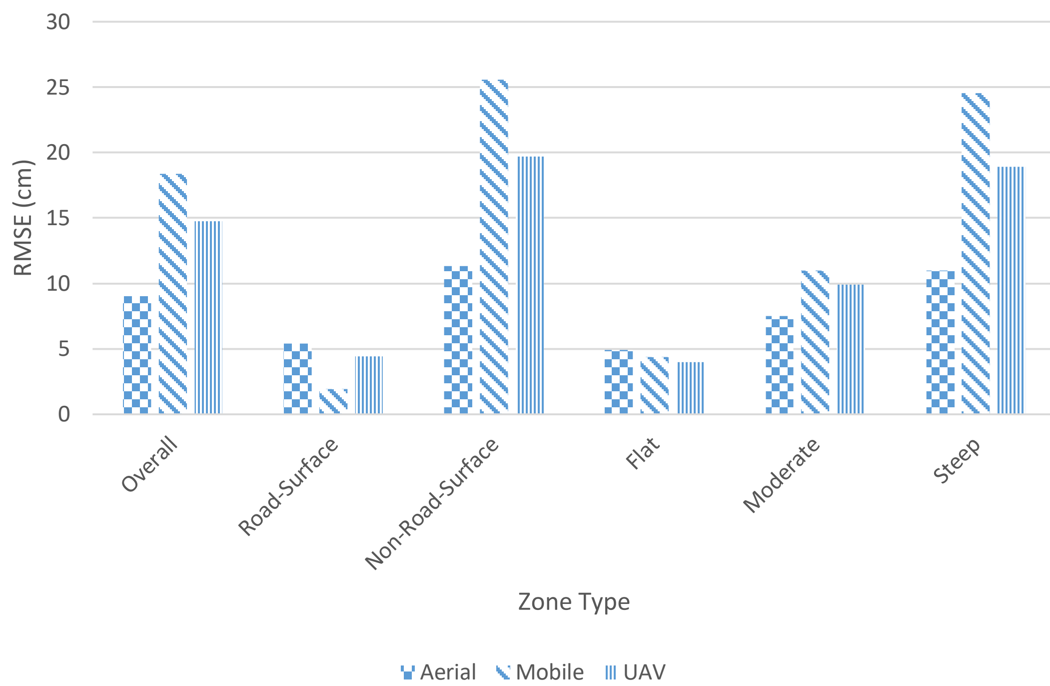

Figure 2.4 RMSE comparison by data type, location on/off road surface, and terrain slope

<u>Statistical Analysis</u>

Two tailed z-tests were performed for these for pairs of elevations. The null hypothesis (H_0) was that the difference in the two elevations are within the ILC vertical accuracy standard of 5 cm or 0.164 ft, and the alternative hypothesis (H_a) was that they are not equal. One of the two elevations is the elevation for one of the alternative data sources, the other is the ground-survey elevation, which is considered to be the "true" elevation.

Define,

μ_d= Mean elevation difference between the datasets;

H_0: $\mu_d = 0.164$

H_a: $\mu_d \neq 0.164$

Aerial Lidar and Survey data

H_0: $\mu_d = 0.164$

H_a: $\mu_d \neq 0.164$

We found z= -73.6

For α=0.05, our obtained P value<0.00001

So, the null hypothesis, H_0, can be rejected at the 5% level of significance. The difference in elevations between the two sets of elevations are statistically not within the ILC standard.

Mobile Lidar and Survey data

H_0: $\mu_d = 0.164$

H_a: $\mu_d \neq 0.164$

We found z= -24.8075

For α=0.05, our obtained P value<0.00001

So, the null hypothesis, H_0, can be rejected at the 5% level of significance. The two sets of elevations are statistically not within the ILC vertical accuracy standard.

UAV-Based Lidar and Survey data

H_0: $\mu_d = 0.164$

H_a: $\mu_d \neq 0.164$

We found z= -30.9

For α=0.05, our obtained P value<0.00001

So, the null hypothesis, H_0, can be rejected at the 5% level of significance. Again, the two sets of elevations are statistically not within the ILC vertical accuracy standard.

From this analysis it can be concluded that the elevations from the aerial lidar, mobile-terrestrial lidar and UAV photogrammetric data are statistically not close enough to the survey elevations using the ILC vertical accuracy standard.

Cost Comparison

For the cost comparsion, the twelve miles of US-30 between mileposts 413 and 425 where the mobile-terrestrial lidar was collected in Bear Lake County are considered. Table 2.5 lists the costs of collecting and processing each data type for a roadway project of this magnitude:

Table 2.5 Cost comparison of each data source type

Data Source	Conventional Survey	Aerial Lidar, Districtwide Collection	Aerial Lidar, Comparable Single-Project	Mobile-Terrestrial Lidar	UAV Photogrammetric Capture (Estimated)
Cost (12 Miles)	$145,256.60	$8,145.25	$123,992.58	$88,646.40	$25,000.00
Cost (per Mile)	$12,104.72	$720.44	$10,332.72	$7387.20	$2,083.33

The conventional survey cost refers to the use of a Total Station to record optical data observations. This methodology was used in the conventional survey verification cross-sections, used as the basis for all accuracy comparisons in this study. ITD paid Dioptra Geomatics $6,877.68 for the approximate 3,000 feet of cross-sections of highway surveyed for project A019(382) to produce the three verification cross-section areas. The above cost was derived as follows:

5,280 feet x 12 miles = 63,360 feet/3,000 feet = 21.12 cross-sections x $6,877.68 = $145,256.60

The planning-grade aerial lidar used in this study is part of a districtwide collection effort, including 716 linear miles of roadway. Economies of scale are important to note in determining the cost of such an extensive project. The total cost of the project, including ground survey control by AeroGraphics' survey crew, as well as the collection of aerial imagery by Aero-Graphics, Inc., orthorectified imagery, DEM raster surfaces, and other data processing, was $486,000, from which the 12-mile and single-mile figures are derived.

However, if a consultant collected aerial lidar on a more limited basis at design-grade (as the mobile-terrestrial lidar was), rather than districtwide at planning-grade, the cost would likely be significantly more. This may in large part be due to the necessity of mobilizing the collection aircraft. To approximate this cost, a comparable aerial lidar collection effort such as that for ITD project keys 14002 and 13106, flown in 2014, could be used for comparison. The invoiced amount of the combined lidar collection for these projects was $123,992.58.

It should be noted that the comparison here is not perfectly analogous to the US-30 project area, as it is for a different part of the highway system, multiple stretches of highway, and includes numerous side roads, which may make for a more complex flight pattern. However, the total highway distance with these two roads is similar to the US-30 study area and should make for a reasonable comparison with the US-30 study area data costs.

The total invoice for the mobile-terrestrial lidar collected by R.E.Y. Engineers, including control, supplemental survey data, and conventional verification data by Dioptra

Geomatics, was $88,646.40. This collection spanned 12 highway miles between MP 413-425 on US-30. Finally, because the UAV photogrammetric data was collected and processed in-house by ITD, the cost in the table is an approximate estimate of the cost by a consultant.

Conclusions

Although all three remote data sources deviated from the conventionally-surveyed elevations, the mobile-terrestrial lidar was particularly close on the road surface. The aerial lidar, while guaranteed at planning-grade, also proved promisingly close on the road surface, as did the UAV photogrammetric data. For this reason, the UAV photogrammetric data capture method may be a cost-effective alternative to the other two remote data types. All three remote data types may be suitable for certain design purposes, particularly preliminary design and those dealing primarily with an existing road surface.

The accuracy of each data type degraded at higher steepness and off-pavement. Spaete et al. noted that vegetation and slope areas have a statistically significant impact on the accuracy of lidar-derived DEMs (13). This study indicates that the aerial lidar provided the most accurate terrain information in these areas. Considering the vantage point of the aerial lidar with its capability of multiple returns, this makes sense. The mobile-terrestrial lidar is understandably limited by its ground vantage point, especially in areas with steep slopes.

The three conventional verfication areas were deliberately selected to be areas likely difficult for the mobile-terrestrial to achieve accuracy away from the pavement. The UAV photogrammetric capture, while having an aerial vantage point, is limited by being based on photographic images. This means foliage is likely to have a major impact on its accuracy. Another possible consideration is the processing method each remote .las dataset received. The aerial lidar received some manual processing, while the mobile-terrestrial and UAV data both relied on an automated ground-classifying process in ArcMap. Manual processing of the mobile-terrestrial lidar and UAV photogrammetric data may improve the accuracy of these data types in off-road and steeper areas.

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CHAPTER THREE: MANUSCRIPT TWO – ROAD DESIGN USING ALTERNATIVE DATA SOURCES

Abstract

For relocating existing infrastructure facilities and designing new infrastructure with final design plans, we need accurate surface terrain information. At present traditional surveying and photogrammetric mapping are the common methods in use due to their high accuracy. However, both methods are time-consuming and resource intensive. So, it would be beneficial to find alternative methods for collecting accurate surface terrain information**.** Light Detection and Ranging (Lidar) data collected using airplanes, mobile terrestrial vehicles, or unmanned aerial vehicles (UAV) may provide an alternative technology to obtain terrain information. These technologies are in use currently in the United States and many other countries of the world. Various research show that the accuracy of Lidar data is good enough to use it for multiple applications. However, the accuracy for Lidar data in Road Design has not been tested that much. This research does that by examining the applicability of Aerial Lidar, Mobile Lidar and Lidar data from UAVs. The data used in this research were obtained from the Idaho Transportation Department (ITD), District 5. We used OpenRoads Designer software from Bentley to do this analysis. Root mean square errors (RMSE) for various datasets were calculated. Statistical analysis was also performed to compare the four sets of elevations. Cost Comparison was also done to find out the effectiveness of the alternatives. In all cases, RMSE was very high and we cannot use these data sources as alternatives of traditional survey.

Introduction

We use different types of transportation modes in our daily life. Transport modes are the means by which passengers and freight achieve mobility. Roads, rails, waterways, and airways are the most common modes of transportation. Among all modes, roads play a vital role in the development of a country. Roads are vital for economic development of a country and provide many social benefits to the citizens. They are essential for a country's development. In underdeveloped and developing countries especially, providing access to work and various social, health, and educational services makes roads a critical element in battling against destitution. Roads provide access to remote areas and spur economic and social development. Consequently, development and management of a road infrastructure system is one of the most significant resources of every country. That is why construction and maintenance of highways is very important for all countries in the world.

For road design and construction, we need terrain information for the area through which the road is planned to traverse. To get terrain information, we currently use the spatial polar method (1), GNSS method, laser scanning (2), photogrammetric methods (3), and remote sensing. To obtain terrain information most agencies currently depend on traditional methods such as field surveying and photogrammetry. Though these methods provide highly accurate terrain information, there are some disadvantages associated with these methods. Primarily, these methods are time consuming and are labor-intensive. In non-flat terrain these problems are enhanced. This is also true for areas with dense vegetation. In adverse weather conditions, it becomes difficult to get data using these methods. So, the time window for data collection can be limited using current methods. Due to the potential shortcomings of traditional methods, there has been always a need to look for the alternative methods. One of the most promising alternatives is the use of Light Detection and Ranging (LIDAR) technology for data collection.

LIDAR is a remote sensing technology that is being increasingly used for various purposes all over the world. Departments of Transportation (DOT) in various states in the United States of America (US) have used or have been looking to use this new technology for engineering applications. Road design is one of the potential application areas. Various reports show that nationwide many state DOTs have planned to use LIDAR. To use LIDAR data digital models of the earth are needed. A Digital Surface Model (DSM) refers to the earth's surface and it contains almost all kind of objects on it. But for road design purposes we just need the information of locations on the ground which includes the elevations of the location. For this purpose, a Digital Terrain Model (DTM) is what is needed. A DTM represents the bare surface ground without any kind of objects above the ground like plants, cables, or buildings (4).

Aerial LIDAR data for many regions of the US are publicly available and many agencies currently use these data for different purposes. If it can be determined that such data are accurate enough for road design, agencies can easily obtain them. If publicly available data are not accurate enough for road design, then DOTs will have to arrange to collect the data either in-house or through outside agencies. Not all DOTs may have the resources to collect such data in-house. Irrespective of how the data is collected, the first step will be to determine the level of accuracy of such data. That is the objective of this research. For this purpose, DTMs were created using different LIDAR data sources and elevations obtained from these DTMs were compared with those from a DTM created from data obtained through traditional surveys. Directly measured survey point elevations were also used in the comparison. A high quality DTM can be obtained from Lidar data by applying appropriate processing techniques (5).

The accuracy of Lidar data depends primarily on the entire workflow from data acquisition through generating the final terrain model. So, for Lidar data to be useful processing is very important for all applications (6). Lidar data accuracy is also dependent on the ground type, mainly on the separation of ground and non-ground points. There is agreement in most of the research that the accuracy of Lidar is good in flat regions, less vegetation, and low altitudes (7). In Lidar data there will typically be a lot of multiple returns from the ground, buildings, or vegetation. If we cannot differentiate the returns between ground and non-ground, then the resulting terrain model will be inaccurate. Several studies have used ground-elevation data to estimate the accuracy of Lidar measurements (8, 9). Digital Elevation Model (DEMs) generation is also very important for getting elevations from Lidar data. DEMs refers to a quantitative model in a digital form for a topographic surface. It is a bare-earth raster grid which will refer to a vertical datum. Of the many factors that affect the accuracy of DEMs, the accuracy, density and distribution of the obtained data, the interpolation techniques, and the DEM resolution are the main factors (10, 11, 12, 13).

Lidar data is saved in LAS format. This is a type of file which can store Lidar data as an industry-standard binary format. Few softwares can handle the heavy processing of this type of data. One of the softwares that can handle the processing of LAS files is ArcMAP from ESRI. We do not know the effectiveness of using Bentley software for handling Lidar data. We used OpenRoads Designer software from Bentley to process the data and generate the terrain model used in our analysis. The ‘ground truth’ data we used in our analysis was traditional survey data with elevations for specific points on three segments in our study area. We obtained elevations from terrain models based on Lidar data for designed roads at specific stations so that we could compare the datasets. We chose to do this analysis using OpenRoads Designer since many state Departments of Transportation use this software for road design. For the analysis using OpenRoads Designer we used DTMs as the terrain models.

The primary goal of this research was to analyze the ground elevation differences (vertical accuracy) for aerial, mobile-terrestrial, and UAV-captured Lidar data relative to elevations obtained from traditional surveys. As all sources of data collection used the same horizontal control, horizontal accuracy analysis was not performed.

Study Area

The study area is in Southeastern Idaho. It covers a segment of US30 through Georgtown from MP 414 to MP 425. Georgetown is a small farming community in Bear Lake County, Idaho with the Bear River on one side and mountains to the east. The terrain includes flat and sloped areas. The segment covered in this research is from Georgetown Summit to Nounan Road. Figure 3.1 shows a Google Earth image of the study area. Terrestrial mobile Lidar data was collected from 1st to 7th Streets in Georgetown. Dioptra, a consulting company, collected the land survey data. The airborne Lidar data was collected by Aero-graphics. All data used in this research were obtained from the ITD**.** The Mobile Lidar data was acquired towards the end of 2016. The Aerial Lidar data was collected between April 7 and October 12, 2016. The survey data was collected the following year. The UAV data was collected more recently, in 2018. Though the Lidar data covered around 6 miles of US 30, we could not use all of the data. That is because the verification data collected using traditional land survey covered only 0.6 miles of US 30 in three separate segments spread across the 6-mile study area.

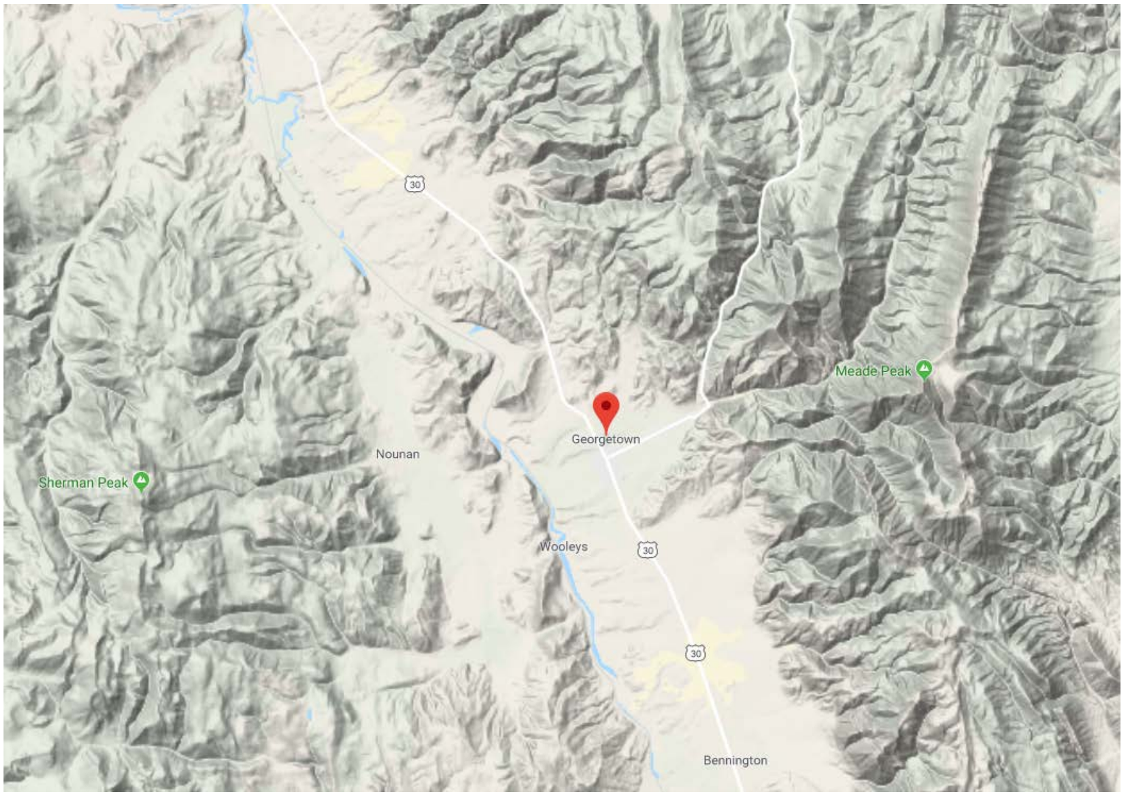

Figure 3.1: Google Earth Image of the Study Area

Study Objectives

The questions addressed in this study are the following:

1) How do you compare different DTMs?
2) Will the alternative terrain models have similar accuracy for different terrains?
3) Will the alternative methods save cost and time?

We identified the following objectives for our research based on the questions listed above.

i. Use statistical methods to compare elevations obtained from different DTMs for points with the same x-y coordinates.

ii. Use methods identified in Objective 1 to compare accuracies of DTMs for different sections of areas.

iii. Evaluate the cost effectiveness of the alternatives

Methodology

1. Collect data
2. Compare and analyze
3. Conclude

Data Collection

<u>Airborne Lidar</u>

The Aerial Lidar data was collected by Aero-Graphics, a company located in Salt Lake City, Utah. This data was collected between April 7 and October 12, 2016. From the "Technical Project Report- D5 Aerial Photography and Lidar" report made by Aero-graphics, we were informed that it was performed with an Optech ALTM Orion H300 Lidar sensor and an Optech CS-10000 aerial camera system. The Lidar Sensor and the camera were paired in a custom mount to increase accuracy. Aero-Graphics flew at an average altitude of 3300 feet above ground level (AGL) and made appropriate adjustments to compensate for topographic relief. The imagery was acquired at a 0.25' (7.5cm) ground sampling distance with 30% overlap, collecting 6,788 images over 411 flight lines. Lidar acquisition was performed with 30% overlap and yielded an average 9.6 points per square meter throughout the project area. The PRF (pulse rate frequency) used for collection was

225 kHz, scan frequency 68.7 Hz, and scan angle +/- 14.5° from the nadir position (full scan angle 29°).

Terrestrial Mobile Lidar

The Mobile Lidar data was collected between November 8 and 15, 2016. It was collected by R.E.Y. Engineers, Inc. a company from Folsom, California. From the Mobile Scan Survey Report made by R.E.Y. Engineers, we learned that a mobile scanning system named RIEGL VMX-250 was used to collect the data. The data was collected two times as the data collection vehicle was driven two times in each direction. The average speed of the vehicle was 35 mph. Each scanner was set for a measurement rate of 300 kHz (600 Khz combined). The horizontal control was NAD83 (2011) Idaho State Plane East (1101). The vertical datum is North American Vertical Datum of 1988 (NAVD88) (GEOID12B). With this speed approximately 340 points/m^2 at 20 feet to overall 2000points/m^2 along the trajectory line from the sensors as the point density were collected.

UAV

Data was collected by an intern from ITD.

All the data from Aerial and Mobile Lidar were provided to us as LAS files.

Validation Survey

The conventional survey data was collected by Dioptra Geomatics. This company is in Pocatello, Idaho. The Survey was conducted between April-May 2017**.** For this survey, only two control points at each location were used to reduce varying control point elevation differences in each area. This conventional survey methodology refers to the use of a total station to record optical data observations. This methodology was used in the conventional survey verification cross-sections, which were used as the basis for all accuracy comparisons in this study.

Analysis

OpedRoad Designer

We had the Lidar data, as previously mentioned, in LAS file format and survey data in excel file format. We could import LAS files to Open Roads Designer directly, but we needed to do some processing of these files. The software transforms LAS files into POD files; a POD file is the Bentley native file format for point cloud. A point cloud is a set of data points which can measure many points on the external surfaces. In OpenRoads Designer the Reality Modeling workflow was used to process the POD files. After processing the files, we got our desired terrain models. We used feet as a unit to measure the elevation. The terrain models were saved as 3D DGN files after processing. This processing is described in more detail below.

We used the reality modeling mode of Bentley's OpenRoads Designer Software to import the LAS files. The software converted the LAS files to POD files, which we could then attach in the software for further processing. Next, we did the ground extraction with automatic seed mode. Automatic Seed mode created the reference points which were used during the ground extraction process. These reference points then could be evaluated and edited to get the final terrain model. After completing the extraction process, we needed to save a triangulated irregular network (TIN) file and the Scalable Terrain Model (STM) created by OpenRoads Designer. The software needed some time for processing and saved the STM with the reference points.

Next, we selected the STM and turned on the contours and turned off the triangles to see whether any unusual features were created in this process. This was done by examining the resulting terrain model. Unexpected spikes that appeared in the front view of the model were removed. There were some spikes in almost all the files due to non-ground returns from trees and buildings. Though the software's ground extraction process did an adequate job for the most part, some manual editing was also needed. This was an iterative process dependent on the user's judgement.

After completing the editing, we created the final terrain model. To do this we needed to delete the STM and only the POD file remained attached. The ground extraction process was repeated with the previously extracted points. This process created a final TIN file with another STM. This TIN file was used to create the final terrain model.

For creating the final terrain model, we used an edge method with the maximum edge length of 1000 feet. Next, we changed the workflow to 'Openroads Modeling' and imported the TIN file to create the terrain model. We used existing contours as the feature definition and imported the terrain only. During the importing we used the following coordinate system: ID83/2011-EF-NAD83/2011 Idaho State Planes, East Zone, US Foot. After completing these steps, we saved the file as a 3D DGN file for further work. This process was repeated for all 3D DGN files created for our analysis.

A 2D file was then created in OpenRoads Designer using the same coordinate system as the one used when creating the terrain file. The terrain file was then referenced, and a test road alignment was drawn in the area of interest. A vertical profile for the test alignment was created using an appropriate terrain model and elevations at selected points along the alignment were read from the vertical alignment report for the alignment. We generated these reports for four different terrain files (based on the Survey, Aerial Lidar, Mobile Lidar and UAV-captured Lidar data). Elevations for the same points along the test roads sections were compared using the elevations from the Survey data as the "true" elevations. We also drew test road alignments over the existing road surface area and the non-road surface area. Then we created vertical alignment reports for these roads based on different datasets. From those reports we extracted elevations for specific stations. This process allowed us to get elevations of the same points for different datasets. Next we checked the RMSE of the Lidar data for road-surface and non-road-surface considering ground-survey elevations as our true data. It is noted here that the terrain models used in this analysis were generated using the elevations for each survey point using ArcMAP.

We would like to note that at first, we tried to create the terrain model using MATLAB software. We tried to read the LAS files in MATLAB and then saved the x, y, and z coordinate values for each point in a text file. This was a straight-forward process and we could import that text file to OpenRoads Designer software and create the terrain model. But we found that in that process we could not edit our terrain and we could not remove the spikes related to the non-ground points from the files. A terrain model created in this manner would not be an accurate representation of the actual terrain. Hence the MATLB-based process was discarded in favor of the Bentley software. The Bentley software allowed for the removal of the non-ground points and other spikes even though the internal workings of the software were not clear to us.

In Figure 2.2, we can see the Survey Points imported in OpenRoads Designer including the terrain models created from the Survey, Aerial Lidar, and Mobile Lidar data. It can be noted from this figure that not all boundaries of the terrain models are perfectly rectangular even though a rectangular shape was drawn when importing the Lidar data. As mentioned earlier, the extent of the Lidar data was much more extensive than the area covered by the on-the-ground survey, and hence, only a subset of the Lidar data was imported when creating terrain models from the Lidar data. During this process the well-defined rectangular shape of the Lidar data was not retained in the final terrain model that OpenRoads Designer created.

Figure 3.2 Survey Points Imported in OpenRoads Designer for One Section of Our Study Area

Results and Discussion

Results from different data sources are shown in Table 3.1, Table 3.2, and Table 3.3. For all of these tables we drew test roads and got elevations of stations at 25 feet interval by using different data sources including the Survey Terrain. In our analysis elevations from Survey Terrain were considered to be the "true" elevations.

Table 3.1 Statistics Related to Overall Difference in Elevations for Different Data Sources

Data Source	Aerial Lidar	Mobile-Terrestrial Lidar	UAV-Captured Lidar
RMSE (cm)	68.5	70.1	66.2
Mean Difference (cm)	-18.3	-25.2	-22.6
Standard Deviation Sd (cm)	66.1	65.5	66.2

From Table 3.1, we can conclude that overall RMSE for UAV-Captured Lidar was lower, but their difference was not that much. The RMSE was much higher. According to the Idaho Lidar Consortium (ILC), any RMSE less than 5 cm is within their accuracy standard. So, in any cases it did not fall within the standard limit. For Mean difference, Aerial Lidar data had the lowest Mean Difference and that was also true for Standard Deviation.

We had survey data for three sections. Every section was 0.2-mile long and they were located in MP 414, MP 419 and MP 422. From Table 3.2, we can see that Section 1 had the highest RMSE for all the alternatives with similar RMSE values. Mean Difference was the lowest for the Aerial Lidar and Standard Deviation was lowest for Mobile-Terrestrial Lidar. Section 2 had the lowest RMSE for all the data sources. In this case Aerial Lidar had the lowest RMSE, UAV had the lowest Mean Difference and Aerial Lidar had the lowest Standard Deviation. For, Section 3, RMSE was higher than Section 2 but lower than Section 1. In this case Mobile-Terrestrial Lidar had the lowest Standard Deviation and Aerial Lidar had the lowest RMSE and Mean Difference.

Table 3.2 Statistics Related to Difference in Elevations for Three Sections

Data Source	Aerial Lidar			Mobile-Terrestrial Lidar			UAV-Captured Lidar		
Area type	Section 1	Section 2	Section 3	Section 1	Section 2	Section 3	Section 1	Section 2	Section 3
RMSE(cm)	86.7	44.3	69.8	87.2	46.6	72.4	86.9	45.0	73.1
Mean Difference (cm)	-8.1	-17.9	-28.9	-23.7	-17.2	-35.4	-18.3	-16.6	-33.3
Standard Deviation (cm)	86.7	40.7	63.8	84.3	43.4	63.4	85.3	41.9	65.4

In Figure 3.3, RMSE for the Aerial Lidar, Mobile-Terrestrial Lidar and UAV data is shown for all sections as well as overall RMSE for these data sources. From this figure, we can see that Aerial Lidar gave the best result among all of them, but all the RMSE was way above our standard limit.

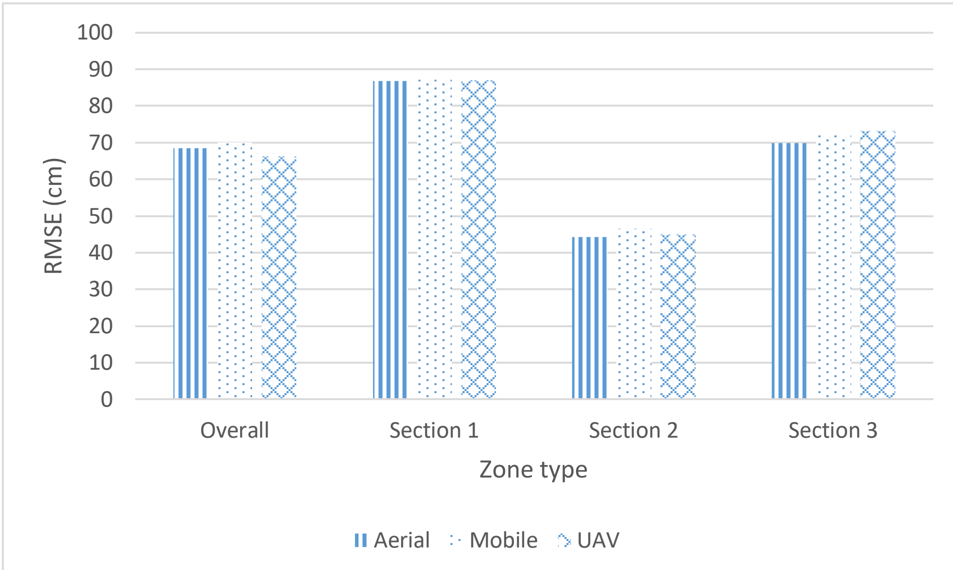

Figure 3.3 RMSE For Different Types of Datasets Based on Different Sections

Table 3.3 Statistics Related to Difference in Elevations for Road-Surface and Non-Road-Surface Stations for Test Roads.

Data Source	Aerial Lidar		Mobile-Terrestrial Lidar		UAV-Captured Lidar	
Area type	Road-Surface	Non-Road-Surface	Road-Surface	Non-Road-Surface	Road-Surface	Non-Road-Surface
RMSE (cm)	73.8	65.2	74.7	67.5	74.7	67.0
Mean Difference (cm)	-1.3	-27.5	-1.3	-38.2	-3.0	-33.2
Standard Deviation Sd(cm)	74.13	59.3	74.6	55.7	74.7	58.3

Table 3.3 presents elevation data for Road and Non-Road-Surfaces. We drew test roads in Road-Surface and Non-Road-Surface area. After that we got elevations from specific stations of the roads by using different data sources including the survey data. From the table, we see that the RMSE for the Road-Surface points was much higher than that for the Non-Road-Surface road stations. The RMSE for Road-Surface was not acceptable based on the standard accuracy limit stipulated by the Idaho Lidar Consortium (ILC). According to ILC, any RMSE less than 5 cm is within their accuracy standard. For Road-Surface and Non-Road-Surface, all the datasets had similar RMSE and Standard Deviation. But for Road-Surface test roads, mean difference was much lower than the Non-Road-Surface test roads. Based on these results, we can conclude that Lidar data does not have good accuracy for areas over a Road-Surface and Non- Road-Surface.

Statistical Analysis

Two Tailed Z-Tests

We also did two tailed z-tests for these for pairs of elevations. The null hypothesis(H_0) is that the two elevations have no RMSE difference bigger than 5 cm, the alternative hypothesis(H_a) is the opposite.

Define,

μ_d= Mean elevation difference between the datasets;

H_0: $\mu_d = 0.164$

H_a: $\mu_d \neq 0.164$

Here, we consider the 5 cm standard from ILC as our standard. So, we consider if the mean elevation difference between the two data sets are equal to or less than 5 cm (0.164 feet) then we can conclude that both the datasets are statistically the same.

Aerial Lidar and Survey Data

H_0: $\mu_d = 0.164$

H_a: $\mu_d \neq 0.164$

We found z= -6.98

For α=0.05, our obtained P value<0.00001

So, the null hypothesis, H_0, can be rejected at the 5% level of significance. The two sets of elevations are statistically different from each other.

Mobile Lidar and Survey data

H_0: $\mu_d = 0.164$

H_a: $\mu_d \neq 0.164$

We found z= -9.14

For $\alpha=0.05$, our obtained P value<0.00001

So, the null hypothesis, H_0, can be rejected at the 5% level of significance. The two sets of elevations are statistically different from each other.

UAV-Based Lidar and Survey data

H_0: $\mu_d = 0.164$

H_a: $\mu_d \neq 0.164$

We found z= -8.24

For $\alpha=0.05$, our obtained P value<0.00001

So, the null hypothesis, H_0, can be rejected at the 5% level of significance. Again, the two sets of elevations are statistically different from each other.

From this analysis we can not conclude that the data from Aerial Lidar, Mobile Lidar and UAV data are statistically different from the Survey data.

Cost Comparison

We estimated the cost of collecting the different data types. The costs for each data type are shown in Table 3.4.

Table 3.4 Cost comparison of different data sources

Data Source	Survey	Aerial Lidar	Mobile-terrestrial Lidar	UAV
Cost ($/Mile)	$12104.72	$720.44	$7387.2	$2250

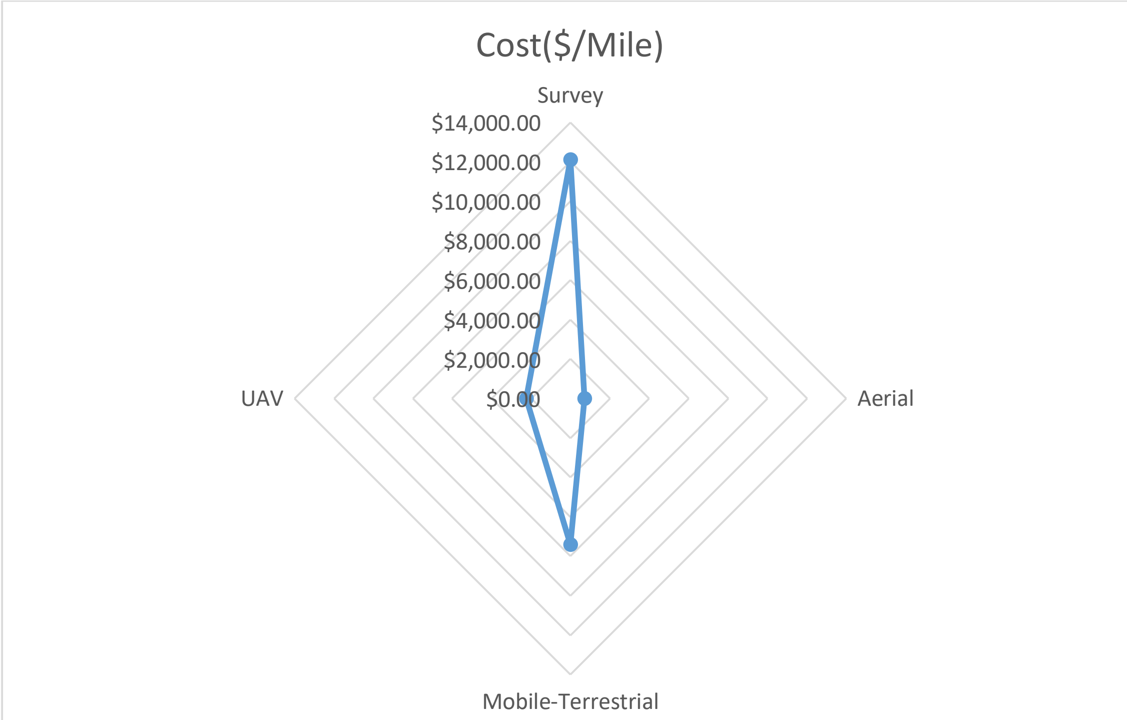

Figure 3.4 Costs for Different Data Sources

From Table 3.4 and Figure 3.4, we can see that Aerial Lidar cost the least and Mobile Lidar cost the most among the three alternatives. The cost for traditional ground survey was the highest. One of the motivations for this study was to find alternatives for traditional surveying because of perceived high cost. Our research supports that perception.

Conclusions and Recommendations

This study focuses on the process of obtaining terrain information from Mobile-Terrestrial, Aerial and UAV Lidar data. It compares the accuracy of these data sources with traditional land survey data. There is some standard for the accuracy of Lidar data in Idaho. According to The Idaho Lidar Consortium (ILC), any RMSE of less than 5cm is considered accurate for using the Lidar data for various purposes. From this study, we can conclude that Aerial Lidar provided the closest terrain information based on our analysis using OpenRoads Designer. Also, Aerial Lidar costs us less compared to other alternatives. It still can not fully replace traditional surveying because the RMSE was way above our standard limit. For further work in this area, we recommend using other software systems for the analysis.

Limitations of the Study

There are some limitations to this study. They are:

1. We had too few survey points. We obtained the best results in the study region, but due to a low number of observation points, we have less confidence in the result.
2. Our collected survey data had information for only a small portion of the study area. If it covered more of the study area, we could possibly get better and more reliable results.
3. This comparison was done with OpenRoads Designer software. So, a comparison using other software would be desirable.

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CHAPTER FOUR: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary and Conclusions

The pragmatic applications of Lidar are expanding. This research demonstates the way toward acquiring terrain infromation from Lidar and contrasting it with data obtained from customary land survey techniques. According to the Idaho Lidar Consortium (ILC), a Root Mean Square Error (RMSE) of less than 5cm will satisfy their vertical accuracy standard. From this study we can conclude that Aerial Lidar provided the closest terrain information based on anlysis using the ArcMAP software. For overall RMSE, Aerial Lidar had an RMSE value of 9.03 cm, while Mobile-terrestrial Lidar had the worst RMSE with a value of 18.40 cm. Also, for Non-Road-Surface areas, Aerial Lidar had the best RMSE, while Mobile-terrestrial Lidar had the highest RMSE for each data sources. For Road-Surface areas Mobile-terrestrial Lidar gave the best result with 1.9 cm RMSE. In this case, Aerial Lidar gave the worst result with a RMSE value of 5.4 cm. Though Mobile-terrestrial Lidar had a good RMSE on Road-Surface but had a high RMSE on Non-Road-Surface areas, which made the overall RMSE high. This is an important conclusion from this research.

For road design we need to have good accuracy for all types of surfaces as roads have to be designed for all kinds of terrains. In fact, in the case of a new road, the design will be for an undeveloped area over Non-Road-Surface areas. Again, for Road-Surface analysis, all RMSEs fell within the ILC standard limit or were very close to the standard limit. The mean differences and standard deviations were also low for all of these data sources. We can conclude that on Road-Surface areas all these data sources give acceptable results. The RMSE was not acceptable for Non-Road-Surface areas and this affected the overall RMSE. These conclusions were also supported by statistical analysis.

But for OpenRoads Designer analysis, we found that overall RMSE for UAV-Captured Lidar was the lowest. For points along the road surface, Mobile-Terrestrial Lidar showed better result. For non-road surface points, Aerial Lidar had the best RMSE. They did not follow any trend and also the RMSE was very high in all cases. We can conclude from this result that either this software can not deal properly with Lidar data or that terrain models generated using Lidar data does not represent the actual ground surface accurately enough for road design purposes.

For Slope Analysis, we can infer that Aerial Lidar resulted in the closed terrain model based on our examination utilizing ArcMAP. Additionally, Aerial Lidar costs us less in comparison with the other data sources. But it still can not fully replace traditional surveying. We found that just on Flat zones it meets the standard for accuracy stipulated by ILC. For Moderate and Steep slope areas the results are not within the acceptable accuracy range. For Moderate and Steep slope regions it is not accurate enough. For UAV-captured Lidar data we can also make the same conclusions, however it is more costly than Aerial Lidar. Mobile-terrestrial Lidar RMSEs were much higher in Moderate and Steep slope areas. But it can achieve the desired accuracy in Flat regions. In any case, it is the costliest strategy after traditional surveying.

From the statistical analysis we could not infer that the mean difference between elevations obtained from the alternative data sources and the ground survey was within the ILC standard for vertical accuracy. From this finding we can conclude that we cannot fully replace Traditional Surveying at this time. We may be able to use the alternative data sources for preliminary design purpose, but for the final design the alternative sources cannot produce terrain models of sufficient accuracy for all terrain types typically encountered in practical settings.

Recommendations for Future Research

Based on the limitations of these study there are some important recommendations for future research. They are:

1. The survey data contains information for only a small portion of the study area. Survey data that covers all of the study area would provide a more conclusive result. In this study we had the survey data for about 0.6 mile long areas. But we had Lidar data for 12 miles. We could not use the remaining 13.4 miles of Lidar data in our analysis. In future studies, survey data over a bigger area would be preferable.
2. We had too few survey points in the flat zone. We obtained the best results in the flat region, but due to a low number of observation points, we have less confidence in the result. So, survey data containing good coverage over all kinds of terrrain areas would be preferable.
3. Bentley's Openroads Designer software analysis has produced results different from ArcMAP analysis. So, comparison using other software would be desireable.
4. We only consider vertical error for accuracy assessment purpose. Lidar data has some issue with horizontal accuracy also. In the future a horizontal accuracy assessment would be preferable.