Grade and Cross Slope Estimation from LIDAR-based Surface Models

APPLICATION OF ADVANCED REMOTE SENSING TECHNOLOGY TO ASSET MANAGEMENT

Final Report—October 2003

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16. Abstract

Many transportation agencies maintain grade as an attribute in roadway inventory databases; however, the information is often in an aggregated format. Cross slope is rarely included in large roadway inventories. Accurate methods available to collect grade and cross slope include global positioning systems, traditional surveying, and mobile mapping systems. However, most agencies do not have the resources to utilize these methods to collect grade and cross slope on a large scale.

This report discusses the use of LIDAR to extract roadway grade and cross slope for large-scale inventories. Current data collection methods and their advantages and disadvantages are discussed. A pilot study to extract grade and cross slope from a LIDAR data set, including methodology, results, and conclusions, is presented.

This report describes the regression methodology used to extract and evaluate the accuracy of grade and cross slope from three-dimensional surfaces created from LIDAR data. The use of LIDAR data to extract grade and cross slope on tangent highway segments was evaluated and compared against grade and cross slope collected using an automatic level for 10 test segments along Iowa Highway 1. Grade and cross slope were measured from a surface model created from LIDAR data points collected for the study area. While grade could be estimated to within 1%, study results indicate that cross slope cannot practically be estimated using a LIDAR derived surface model.

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TABLE OF CONTENTS

ACKNOWLEDGMENTS VII

EXECUTIVE SUMMARY IX

1. INTRODUCTION 1

- 1.1. Background 1
- 1.2. Other Data Collection Methods 1
- 1.3. LIDAR: The Technology 2
- 1.4. Accuracy of LIDAR 2
- 1.5. Scope of Work 3

2. PILOT STUDY AREA 5

3. METHODOLOGY 7

- 3.1. Defining Section Boundaries 9
- 3.2. Extraction of Grade and Cross Slope from LIDAR 11

4. COMPARISON AGAINST GROUND SURVEY 15

5. CALIBRATION 19

6. FEASIBILITY OF USING LIDAR 23

REFERENCES 27

APPENDIX: REGRESSION RESULTS BY TEST SEGMENT 31

LIST OF FIGURES

Figure 2.1. Iowa Highway 1 corridor 6
Figure 3.1. Location of the test segments along Iowa Highway 1 8
Figure 3.2. Regression planes fit to the LIDAR point cloud for each of the four analysis sections defined for each test segment 9
Figure 3.3. Roadway delineation from (a) 6-inch orthophoto and (b) 12-inch orthophoto and (c) triangular irregular network from LIDAR 10
Figure 3.4. Comparison of road segments derived by using the three base layers 11
Figure 3.5. Regression model variables 12
Figure 4.1. Data collection points for ground survey 15
Figure 5.1. Calibration of the regression results using survey results 21
Figure 5.2. Residuals after calibration using survey results 22

LIST OF TABLES

Table 1.1. Comparison of LIDAR from different studies 3
Table 3.1. Summary statistics for northbound pavement of test segment F using the surface model (scenario 2) to determine edge of features 13
Table 3.2. *R*-squared values 13
Table 4.1. Cross slope for segment F from ground survey 16
Table 4.2. Grade measurements for segment F from ground survey (presented north to south) 16
Table 4.3. Comparison of LIDAR and field data (absolute value) 17
Table 5.1. Comparison of calibrated LIDAR and field data (absolute value) 20

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EXECUTIVE SUMMARY

Many transportation agencies maintain grade as an attribute in roadway inventory databases; but the information is often in an aggregated format. Cross slope is rarely included in large roadway inventories. Accurate methods available to collect grade and cross slope include global positioning systems, traditional surveying, and mobile mapping systems. However, most agencies do not have the resources to utilize these methods to collect grade and cross slope on a large scale.

This report discusses the use of LIDAR to extract roadway grade and cross slope for large-scale inventories. Current data collection methods and their advantages and disadvantages are discussed. A pilot study to extract grade and cross slope from a LIDAR data set, including methodology, results, and conclusions, is presented.

This report describes the regression methodology used to extract and evaluate the accuracy of grade and cross slope from three-dimensional surfaces created from LIDAR data. The use of LIDAR data to extract grade and cross slope on tangent highway segments was evaluated and compared against grade and cross slope collected using an automatic level for 10 test segments along Iowa Highway 1. Grade and cross slope were measured from a surface model created from LIDAR data points collected for the study area. While grade could be estimated to within 1%, study results indicate that cross slope cannot practically be estimated using a LIDAR derived surface model.

1. INTRODUCTION

1.1. Background

Roadway grade and cross slope are used in a number of transportation applications. Grade is necessary to calculate adequacy of stopping and passing sight distances on vertical curves. Calculation of roadway capacity also requires grade as an input variable since vehicle operation, particularly for heavy-trucks, is affected by length and gradient of slope. Cross slope and grade may also be used to model drainage patterns for pavement performance assessment. Proper transverse slopes are necessary for pavement drainage. Detailed cross slope data may also be used to determine how quickly water drains from the roadway to evaluate locations where hydroplaning may occur.

Grade also affects vehicle emissions. Engine loading and subsequently emissions increase as vehicles accelerate against a positive grade. A study at the Fort McHenry tunnel under the Baltimore Harbor reported an increase in emissions by a factor of 2 for the +3.76 upgrade versus the –3.76 downgrade tunnel segment (Pierson et al. 1996). Cicero-Fernández et al. (1997) evaluated the impact of grade on emissions and reported an increase of 0.04 g/mi for hydrocarbons (HC) and 3.0 g/mi for carbon monoxide (CO) for each 1% increase in grade. Enns et al. (1994) also found increases in the CO emission rate on grades.

Many transportation agencies maintain grade as an attribute in roadway inventory databases; however, the information is often in an aggregated format. Cross slope is rarely included in large roadway inventories. Accurate methods are available to collect grade and cross slope; these include global positioning systems (GPS), traditional surveying, and mobile mapping systems. However, most agencies do not have the resources to utilize these methods to collect grade and cross slope on a large scale. This report discusses the use of LIDAR to extract roadway grade and cross slope for large-scale inventories. Current data collection methods and their advantages and disadvantages are discussed. A pilot study to extract grade and cross slope from a LIDAR data set, including methodology, results, and conclusions, is presented.

1.2. Other Data Collection Methods

Methods to collect high accuracy grade or cross slope data include use of as-built plans, photogrammetry using high-resolution ortho-rectified images, traditional surveying, GPS, and data-logging. Grade and cross slope information can be taken from as-built construction drawings if available. However, this process is time consuming and can also be error prone if analysts do not properly locate sections of drawings with electronic databases. Further, the drawings may not adequately represent field conditions if roadways have settled or if rehabilitation or maintenance has changed grade or cross slope. 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 for traffic. Photogrammetry is also accurate and less time consuming than traditional surveying. Additionally, once reference points are collected, most of the work is conducted in-office so it requires only minimal field data collection. However, collection and ortho-rectification of aerial imagery of sufficient resolution to yield accurate elevation measurements is expensive.

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 grade classified by maximum grade for each segment. 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. Other methods for the collection of cross slope and grade data include the use of GPS equipment and digital terrain models built from automated surveying and mapping data. Several state departments of transportation, including those of Maine, New York, and Missouri, use an Automatic Road Analyzer (ARAN) to collect the data. An ARAN is equipped with numerous state-of-the-art sensors, lasers, accelerometers, inertial navigation units, video cameras, and computers that operate in concert to collect all required data in one pass of a roadway lane with stated millimeter accuracy at speeds anywhere from 15 mph up to highway speeds. However, use of a slope meter, data-log vehicle, and ARAN requires that the data collection vehicle physically traverse each roadway, and for collection of cross slope, data must be collected in both directions. As a result data collection for large areas can be time consuming and expensive.

1.3. LIDAR: The Technology

The acronym LIDAR stands for "light detecting and ranging." LIDAR technology integrated with airborne GPS and inertial measuring systems are mounted on an aircraft and flown over a study area. Currently available laser units emit a stream of up to 25,000 light pulses per second and record both the time for each pulse to return and the angle at which it is reflected. GPS provides positional information and inertial measuring systems measure roll, pitch, and yaw of the aircraft. This information is used to adjust the distance measurement for each pulse, allowing calculation of corrected surface coordinates (x, y, z). Further data processing can extract measurements of the bare ground (removal of ground clutter such as vegetation, snow cover, etc.), allowing creation of digital elevation models or surface terrain models. Digital aerial photography can also be taken while LIDAR is flown, providing an additional layer of data, with the LIDAR surface model used to rectify the aerial image.

1.4. Accuracy of LIDAR

The horizontal accuracy of LIDAR data depends on flying height, with accuracies as good as 0.4 meters possible. LIDAR vendors report that the vertical accuracy of their data is generally on the order of 15-cm root mean squared error (RMSE) (Sapeta 2000). If flight layouts are optimized for GPS, vertical accuracies of 7 to 8 cm RMSE have been reported (O'Neill 2000). Actual accuracy depends on a number of factors, and several studies have examined the vertical accuracy of LIDAR data with varying results. Most of the studies reported used LIDAR data that were collected under leaf-off conditions (Pereira and Janssen 1999; Huising and Pereira 1998; Pereira and Wicherson 1999; Wolf, Eadie, and Kyzer 2000; Shrestha et al. 2001). Several studies also examined the accuracy of LIDAR data collected under leaf-on conditions (Berg and Ferguson 2001). Table 1.1 summarizes the results of different studies. The variations in the accuracies achieved by these studies can be attributed, in part, to the differences between laser systems employed, flight characteristics, the terrain surveyed, how well LIDAR is able to penetrate vegetation, and physical processing of the data itself such as vegetation removal algorithms used. As shown, accuracy ranged from 3 to 100 cm, with the majority of the studies reporting from 7 to 22 cm.

Table 1.1. Comparison of LIDAR from different studies

Application	Vegetation	Vertical accuracy (RMSE cm)
Road planning (Pereira and Janssen 1998)	Leaf-off	8 to 15 (flat terrain), 25 to 38 (sloped terrain)
Highway mapping (Shrestha et al. 2001)	Leaf-off	6 to 10 (roadway)
Coastal, river management (Huising and Pereira 1998)	Leaf-off	18 to 22 (beaches), 40 to 61 (sand dunes), 7 (flat and sloped terrain, low grass)
Flood zone management (Pereira and Wicherson 1999)	Leaf-off	7 to 14 (flat areas)
Archeological mapping (Wolf, Eadie, and Kyzer)	Leaf-off	8 to 22 (prairie grassland)
Highway engineering (Berg and Ferguson 2000)	Leaf-on	3 to 100 (flat grass areas, ditches, rock cuts)

Al-Turk and Uddin (1999) examined the combination of a LIDAR-derived DTM and digital imagery for digital mapping of transportation infrastructure projects. The horizontal accuracy of the laser data was calculated to be 1 m (3 ft) and the vertical accuracy was better than 7 cm (2.75 in). Research conducted at the University of Florida examined the accuracy of elevation measurements derived from LIDAR data. A comparison was made between elevations derived from laser mapping and low altitude (helicopter based) photogrammetry data. LIDAR data were collected along a 50-km highway corridor. The elevations produced by laser data were found to be accurate to within ±5–10 cm. The mean differences between photogrammetric and laser data were 2.1 to 6.9 cm (.82 to 2.71 in) with a standard deviation of 6 to 8 cm (2.36 to 3.15 in) (Shrestha et al. 2001).

Berg and Ferguson (2001) evaluated LIDAR accuracy on different types of surfaces. The study reported that the LIDAR data had an accuracy of at least 15 cm on hard surfaces, such as pavement. The accuracies on other surfaces were less accurate. Error estimates of greater than 1 m were derived while comparing the accuracy on low vegetation, rocks, and ditches. Under forested canopy, the accuracy of LIDAR data ranged from 0.3 to 1 m.

1.5. Scope of Work

The purpose of this research was to investigate whether coordinate and elevation data from LIDAR could be used to determine cross slope and grade. LIDAR provides coordinate and elevation data, and LIDAR data can be fairly rapidly collected over large areas. Collection of LIDAR data with current technologies is still fairly expensive, so even collection of LIDAR only for calculation of grade and cross slope is likely not feasible. However, a number of states and agencies are collecting large-scale LIDAR data sets for other applications, consequently data available in-house could be used to extract grade and cross slope. The intent of the research was to evaluate whether grade and cross slope could be measured from LIDAR data assuming agencies already had access to that data and to determine how accurately they could be measured. A LIDAR data set for a pilot study area already available to the study team was used for assessment.

2. PILOT STUDY AREA

The pilot study area is an 18-mi corridor along Iowa Highway 1 as shown in Figure 2.1. The corridor originates at the Iowa 1/Interstate 80 interchange near Iowa City and terminates at the Iowa 1/U.S. Highway 30 junction outside Mount Vernon, Iowa. The town of Solon, Iowa, is located along Iowa 1 within the study area. Most of the non-urban land use along the corridor is farmland. Iowa Highway 1 is a two-lane undivided state highway. Unpaved shoulders were present along the length of the pilot study area. The southernmost region of the corridor is composed of rolling farmland. Just north of Solon, Iowa Highway 1 crosses the Cedar River. In addition to the high-resolution aerial imagery, a GIS street database was also provided by the Office of Transportation Data, Division of Planning and Programming, at the Iowa DOT. The GIMS data set contained roadway characteristics for all public roadways in the state of Iowa, including lane width, grade, traffic volume, surface, and shoulder type (Freund and Wilson 1997).

LIDAR data and 12-inch resolution orthophotos were collected for the Iowa Highway 1 corridor in October 2001 by a commercial vendor. The vendor also provided the gridded bare earth digital elevation model (DEM) of the area with 5-ft postings. Vendor specifications for accuracy of the LIDAR data set were for a horizontal accuracy of 0.98-ft RMSE and vertical accuracy of 0.49 ft.

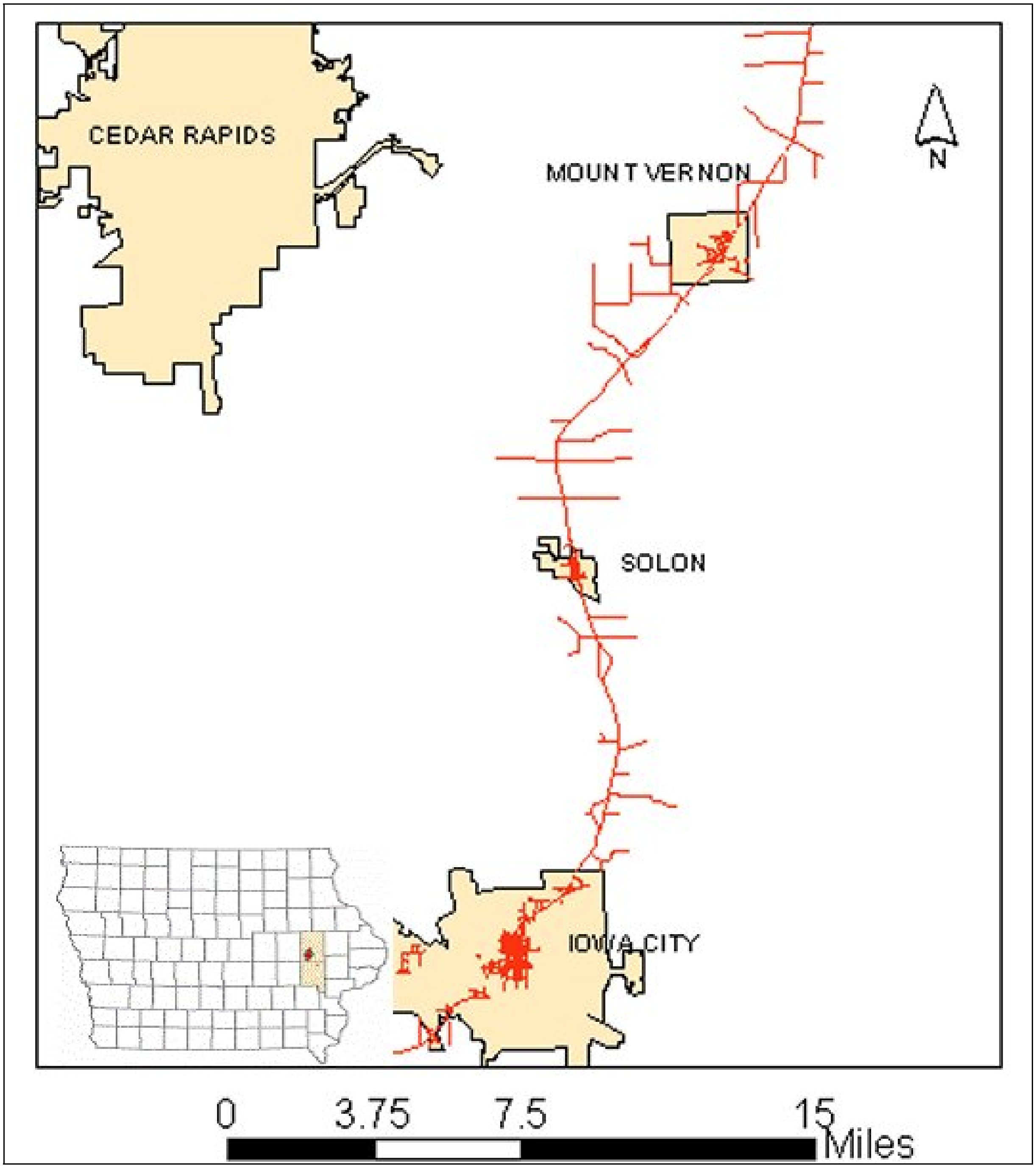

Figure 2.1. Iowa Highway 1 corridor

3. METHODOLOGY

Grade and cross slope were calculated for 10 test segments along the pilot study corridor and compared to grade and cross slope values measured on site using an automatic level. Test segments were selected on tangent roadway sections to avoid horizontal and vertical curves so that the gradient and cross slope were consistent throughout the segment. Each test segment was 100 ft in length. Figure 3.1 shows the location of the 10 test road segments along the Iowa Highway 1 corridor.

Each segment was evaluated separately. Grade and cross slope were measured for (1) the northbound (NB) travel lane, (2) the northbound shoulder, (3) the southbound (SB) travel lane, and (4) the southbound shoulder. This resulted in four analysis sections for each test segment. Grade and cross slope were calculated by fitting a plane to the LIDAR data corresponding to each analysis section using least squares regression analysis. As a result, each two-lane roadway segment was defined by two planes delineated by the center of the roadway crown and the edge of pavement. Shoulder sections were evaluated separately, since shoulder cross slopes are frequently steeper than the roadway cross slope. Figure 3.2 illustrates the concept of fitting a regression plane to each analysis section for a single test segment.

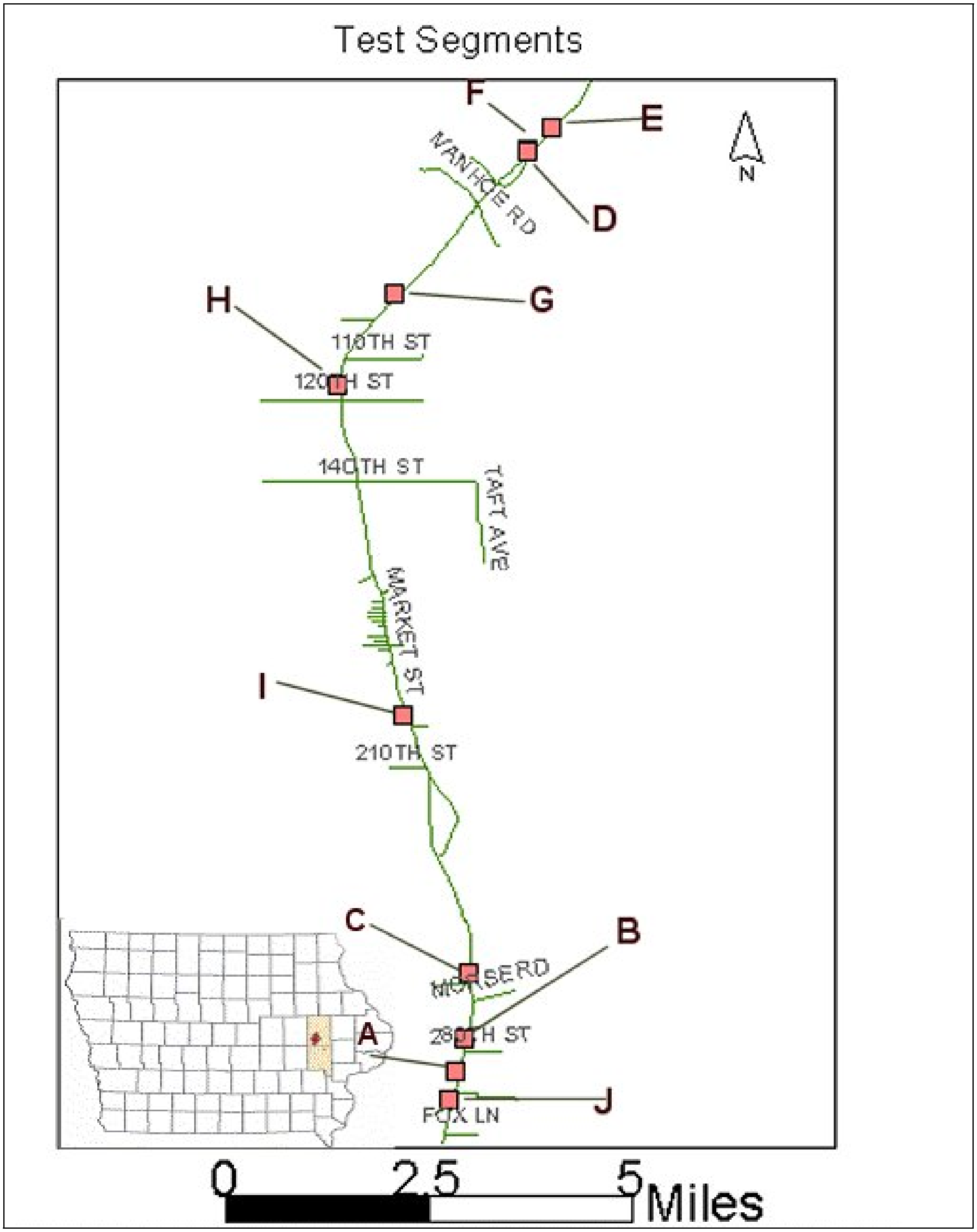

Figure 3.1. Location of the test segments along Iowa Highway 1

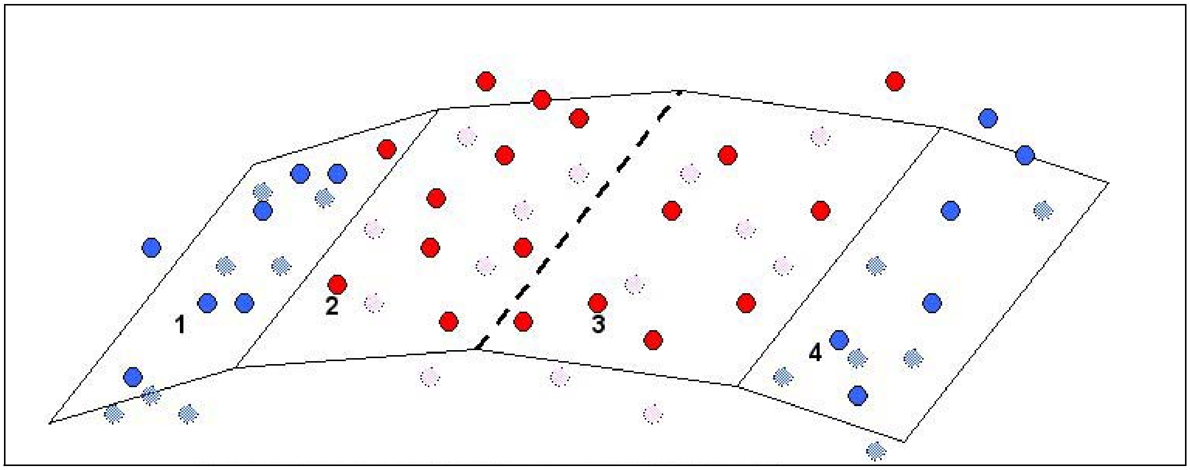

Figure 3.2. Regression planes fit to the LIDAR point cloud for each of the four analysis sections defined for each test segment

3.1. Defining Section Boundaries

The physical boundaries of each roadway analysis section were necessary to determine which of the LIDAR data points corresponded to a particular section. In order to define lane and shoulder regions, the location of the edge of pavement, centerline, and edge of shoulder was necessary.

Definition of roadway boundaries was attempted using three different methods. First, roadway boundaries for the four analysis sections were determined by visually inspecting roadway boundaries as shown in the 6-in resolution orthophotos that were available from the Iowa DOT. A polygon was drawn around each section in ArcView 3.2 as shown in Figure 3.3. This process was repeated using the 12-in resolution orthophotos that were taken concurrent with the LIDAR data collection. Definition of roadway boundaries using both sets of imagery was compared against a surface terrain model of the LIDAR data. Due to a combination of horizontal error in the images and the LIDAR data, the roadway segments determined using the imagery did not correspond well to the road surface defined by the LIDAR data as shown in Figure 3.4. It was determined that use of roadway boundaries from the imagery would result in selection of LIDAR points that did not actually correspond to the appropriate section so use of the images was determined to be infeasible.

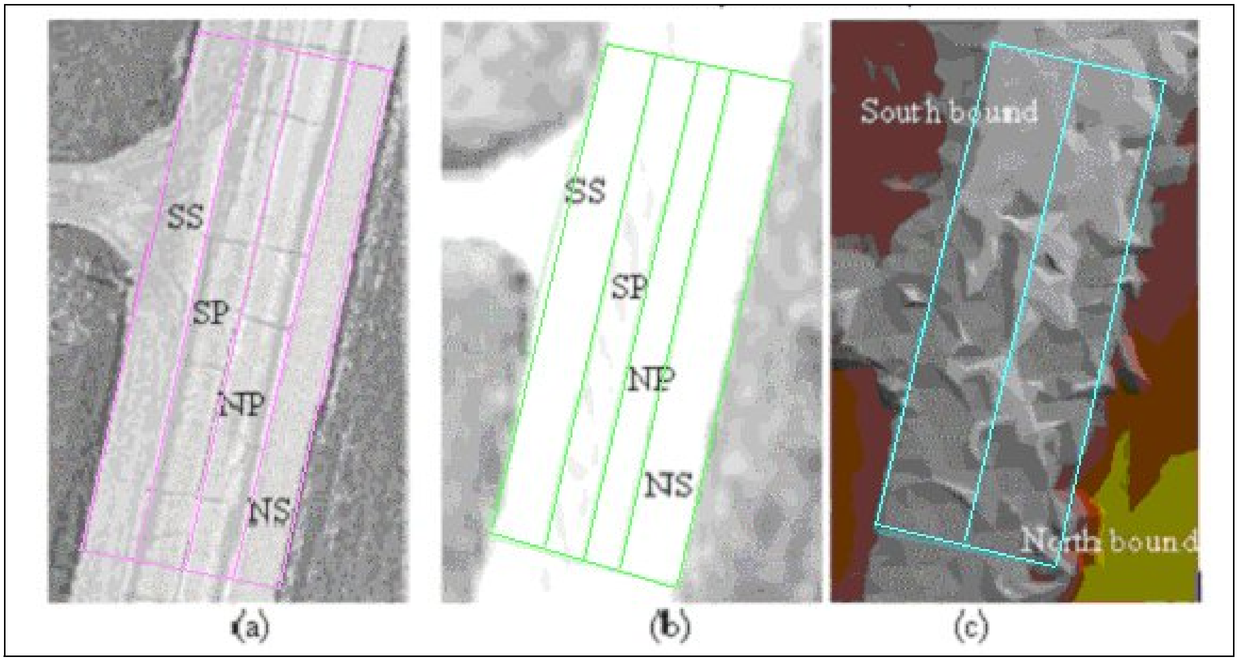

Figure 3.3. Roadway delineation from (a) 6-inch orthophoto and (b) 12-inch orthophoto and (c) triangular irregular network from LIDAR

In the third method, the actual surface terrain model was used to delineate analysis section boundaries. The surface terrain model was created from the LIDAR data by developing a triangular irregular network (TIN) using the spatial analyst module in ArcView. The edge of roadway was the only feature that could be clearly distinguished from the surface terrain model. A polygon was created for each of the ten test segments, which defined the edge of roadway for a 100-ft segment. The centerline was estimated by finding the midpoint from the delineated outer edge of the shoulders as shown in Figure 3.3(c). Edge of pavement was identified by extracting the lane width attribute from the Iowa DOT GIMS street database and drawing a line parallel to the centerline for both the north- and southbound lanes. The edge of pavement lines defined polygons representing the north- and southbound pavement analysis section. The shoulder was specified as the remaining area between the edge of pavement as determined in the previous step and the edge of roadway established from the surface model. This was compared against the shoulder width attribute for the section from the GIS database.

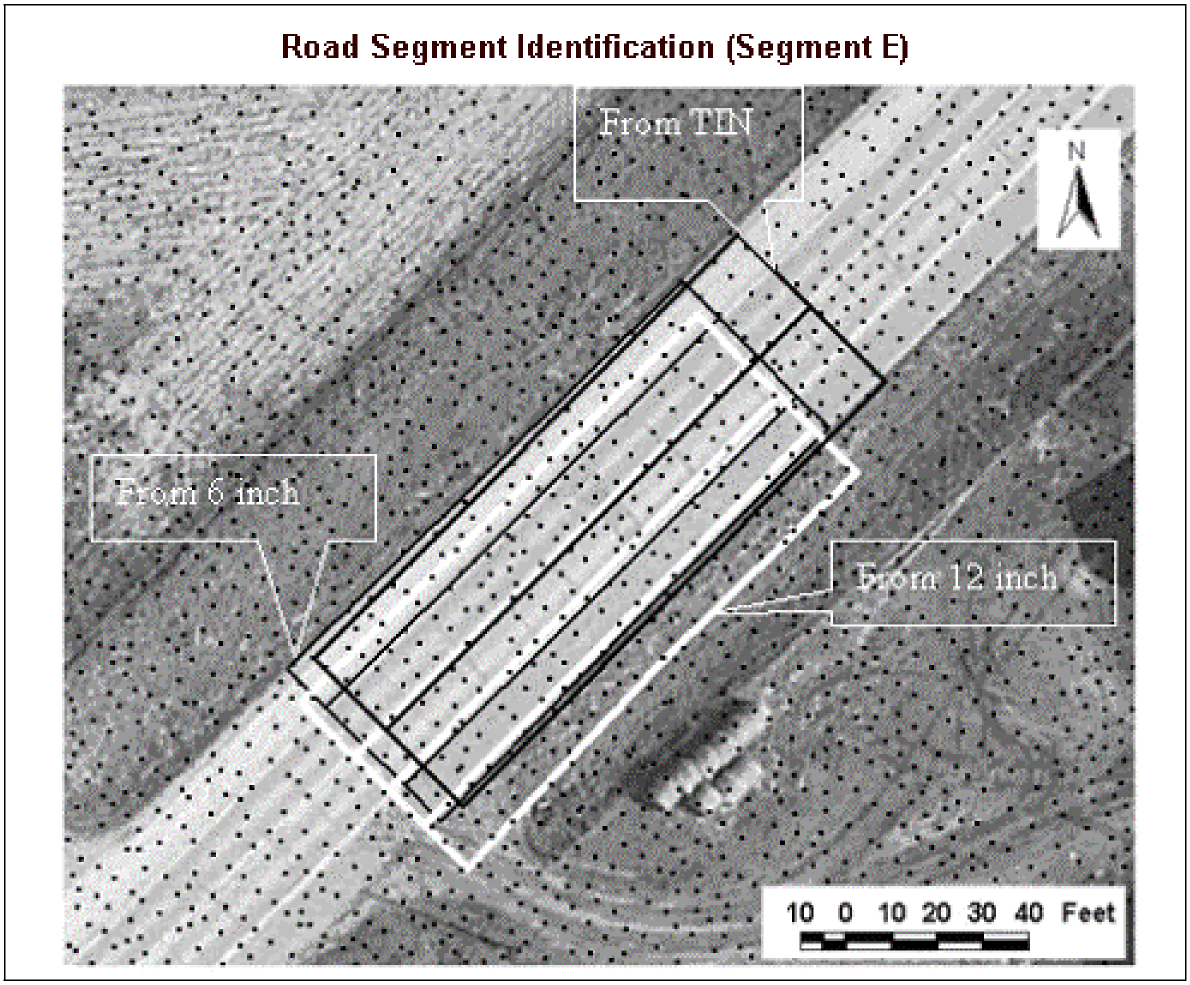

Figure 3.4. Comparison of road segments derived by using the three base layers

Due to spatial inaccuracies in the LIDAR data set and the method used to create the surface model, there was some uncertainty as to whether LIDAR points near the edges actually belonged to that section. To compensate, only data points that fell within the center 75% portion of the polygons were used to develop regression equations. The process resulted in polygons for northbound pavement, southbound pavement, northbound shoulder, and southbound shoulder for each of the 10 test segments. Once polygons were created for each analysis section, they were used to select the corresponding LIDAR points for each section using a polygon overlay in ArcView.

3.2. Extraction of Grade and Cross Slope from LIDAR

Multiple linear regression was used to fit a plane through the LIDAR points that corresponded to each analysis section. A regression equation was developed to estimate grade and cross slope for each section. Elevation was the dependent variable. Perpendicular distance from the roadway centerline and longitudinal distance along the section were the independent variables. The two independent variables were computed by defining a local origin in every section considered for regression analysis. Longitudinal and perpendicular distances are illustrated in Figure 3.5.

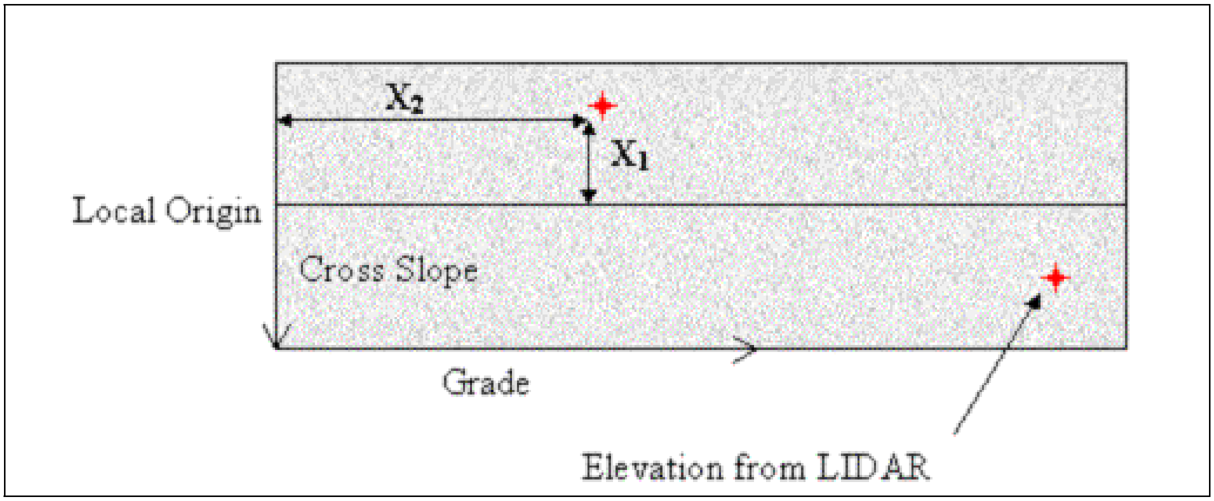

Figure 3.5. Regression model variables

The form of the regression equation was as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \varepsilon$$

where

Y = elevation
β_0 = constant
β_1 = coefficient for cross slope
X_1 = perpendicular distance from centerline
β_2 = coefficient for grade
X_2 = distance along the roadway
ε = error term

Table 3.1 provides summary statistics for the northbound pavement section of test segment F. As shown, a grade of –0.97% and a cross slope of –0.28% resulted for the section. Grade and cross slope for all remaining sections estimated from regression analysis are provided in the appendix. The goodness of fit of the estimated plane with the LIDAR points is shown in Table 3.2 for the rest of the sections. As shown, R^2 values vary from 0.127 for the southbound shoulder section of test segment J to 0.98 for the northbound pavement section for segment C. The variation may be due to due to the varying density of LIDAR points in different road segments but may also be due to errors in segment delineation. For only three of the sections (SB shoulder for segment I and SB pavement/shoulder for segment J) were the results poor (below 0.2)**.** This could be due to the errors induced while selecting LIDAR points defining the roadway regions or due to localized errors in the LIDAR data due to instrument operation. However, for the majority of the sections, the R^2 values were greater than 0.6 (50 sections) and 10 of those had an R^2 over 0.9.

Table 3.1. Summary statistics for northbound pavement of test segment F using the surface model (scenario 2) to determine edge of features

Regression statistics	
Multiple *R*	0.978684
R-square	0.957822
Adjusted *R*-square	0.955947
Standard error	0.024074
Observations	48

ANOVA				
	Df	**SS**	**MS**	**F**
Regression	2	0.592227	0.296113	510.9511
Residual	45	0.026079	0.00058	
Total	47	0.618306		

	Coefficients	**Standard Error**	***t*-statistic**	***P*-value**
Intercept	216.4207	0.010076	21479.86	2.1E-159
X_1 (grade)	–0.00974	0.001426	–6.8288	1.83E-08
X_2 (cross slope)	–0.00284	9.38E-05	–30.2381	1.53E-31

Table 3.2. *R*-squared values

	Section									
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**
NB shoulder	0.45	0.58	0.92	0.87	0.85	0.92	0.16	0.51	0.69	0.66
NB pavement	0.55	0.56	0.98	0.90	0.88	0.96	0.36	0.57	0.66	0.30
SB shoulder	0.67	0.54	0.95	0.66	0.76	0.59	0.63	0.85	0.19	0.13
SB pavement	0.54	0.64	0.42	0.56	0.84	0.75	0.36	0.45	0.56	0.03

4. COMPARISON AGAINST GROUND SURVEY

Grade and cross slope were also measured in the field for each section of the 10 test segments using an automatic level. Cross slope and grade were measured in the field to provide an independent data set for comparison against the LIDAR derived values. The automatic level was used to measure the elevation differences between the outer edge of the shoulder, pavement edge, and the crown of the roadway. The instrument was placed on the shoulder and then the elevation along sections L1, L2, C, R1, and R2 were measured as shown in Figure 4.1. Grade and cross slope were measured every 20 ft. The cross slope computed across each of the 20 ft in length sections were averaged as shown in Table 4.1 to calculate the final values, which were used for comparison with the results from regression analysis. The grade along the section was computed from the elevation difference between each section and then the average was computed. Grade and cross slope results for test segment F are shown in Table 4.2.

Grade and cross slope for each section as calculated from LIDAR using regression and as measured in the field is shown in Table 4.3. The comparison of surveyed measurements and results from regression show that the regression results consistently underestimate the survey measurements.

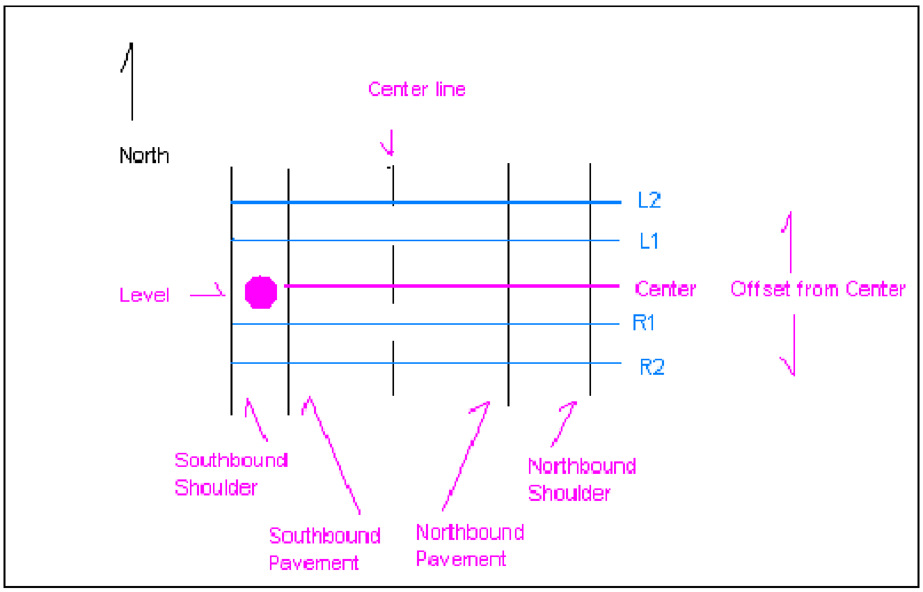

Figure 4.1. Data collection points for ground survey

Table 4.1. Cross slope for segment F from ground survey

Section	Offset from centerline (feet)	SB S (%)	SB P (%)	NB P (%)	NB S (%)
L2	40	7.1	2.2	2.2	7.9
L1	20	8.1	2.0	2.1	8.0
Center	—	4.7	1.8	1.8	8.1
R1	20	1.9	2.1	1.7	6.9
R2	40	8.7	2.0	1.7	3.6
Average		6.1	2.0	1.9	6.9

Table 4.2. Grade measurements for segment F from ground survey (presented north to south)

Section	Grade (%)
SB shoulder	1.3
SB pavement	1.2
NB pavement	1.2
NB shoulder	0.9

As shown, the best results from LIDAR were estimation of grade on the roadway itself. Grade estimates were within 0.87% grade of those calculated in the field, 14 of the 20 analysis sections were within 0.5% grade. All shoulder grade estimates were within 0.95%. Eleven of the 20 analysis sections were within 0.5% grade of the field estimates. Cross slope estimates performed worse than grade estimates. For roadway sections, cross slope estimated from LIDAR deviated from field measurements by 0.72% to 1.65%. Shoulder cross slope estimates compared poorly with LIDAR deviating from field measurements by over 2% for most analysis sections.

Table 4.3. Comparison of LIDAR and field data (absolute value)

		Grade (%)				Cross Slope (%)			
		SB		NB		SB		NB	
		Shoulder	Pavement	Pavement	Shoulder	Shoulder	Pavement	Pavement	Shoulder
Section A	LIDAR	0.32	0.39	0.45	0.41	1.53	0.57	0.11	0.86
	Survey	0.93	0.76	0.80	1.11	4.18	1.62	1.42	6.84
	Difference	0.61	0.37	0.35	0.70	2.65	1.05	1.31	5.98
Section B	LIDAR	0.19	0.16	0.18	0.12	0.31	0.25	0.97	1.54
	Survey	0.40	0.41	0.41	0.35	5.80	1.90	2.15	5.10
	Difference	0.21	0.25	0.23	0.23	5.49	1.65	1.18	3.56
Section C	LIDAR	0.37	0.37	0.37	0.39	0.86	0.21	0.26	2.27
	Survey	1.19	0.83	0.73	0.59	3.52	1.57	1.80	5.17
	Difference	0.82	0.46	0.36	0.20	2.66	1.36	1.54	2.90
Section D	LIDAR	0.10	0.12	0.21	0.21	2.52	0.60	0.75	1.36
	Survey	0.66	0.63	0.55	0.36	8.88	1.33	2.18	4.56
	Difference	0.56	0.51	0.34	0.15	6.36	0.73	1.43	3.20
Section E	LIDAR	0.35	0.33	0.35	0.29	2.04	0.69	1.18	1.85
	Survey	1.29	1.20	1.17	0.88	6.10	2.02	1.90	6.89
	Difference	0.94	0.87	0.82	0.59	4.06	1.33	0.72	5.04
Section F	LIDAR	0.29	0.22	0.28	0.26	2.87	0.89	0.97	3.04
	Survey	0.95	0.98	0.97	0.86	8.31	1.70	2.23	10.18
	Difference	0.66	0.76	0.69	0.60	5.44	0.81	1.26	7.14
Section G	LIDAR	0.32	0.25	0.39	0.36	3.70	0.19	0.64	1.16
	Survey	0.83	0.77	0.77	0.79	6.34	1.79	2.23	8.99
	Difference	0.51	0.52	0.38	0.43	2.64	1.60	1.59	7.83
Section H	LIDAR	0.34	0.32	0.35	0.44	0.07	0.36	0.73	8.57
	Survey	0.91	1.00	1.01	0.96	1.72	1.72	2.02	7.50
	Difference	0.57	0.68	0.66	0.52	1.65	1.36	1.29	1.07
Section I	LIDAR	0.05	0.04	0.04	0.04	1.21	0.61	0.61	1.21
	Survey	0.09	0.05	0.04	0.06	3.88	1.57	1.92	3.33
	Difference	0.04	0.01	0	0.02	2.67	0.96	1.31	2.12
Section J	LIDAR	0.09	0.02	0.12	0.17	1.47	0.59	0.01	1.58
	Survey	0.25	0.24	0.24	0.31	1.87	1.65	1.20	7.80
	Difference	0.16	0.22	0.12	0.14	0.40	1.06	1.19	6.22

5. CALIBRATION

Initial regression results were disappointing. However, it was assumed that some amount of error would be systematic. Systematic errors in the local model may derive from the initial removal of artifacts from the LIDAR data set (e.g., smoothing or thresholding). Estimation of grade and cross slope from the final product is consequently affected by these global spatial operations. An indication of systematic error is the consistently underestimated measurements observed when the LIDAR data set was compared to ground survey.

In an attempt to improve regression results, a subset of the surveyed values was used to calibrate the model, holding out the remaining measurements for validation. In addition to removing systematic errors, calibration can improve results by taking advantage of correlated errors in individual LIDAR point measurements. For example, while the standard error of LIDAR on hard surfaces may be 15 cm, absolute, relative errors—those most important to measurements of grade and cross slope— may be much lower. Measurements from ground survey (verified against as-built plans of the corridor) were used as a benchmark value for calibration. The subset included the survey measurements along the northbound pavement and shoulder sections. Figure 5.1 depicts the calibration results.

The calibration equation for the slope is as follows:

calibrated value = 2.2684 * grade + 0.0485

The calibration equation for cross slope is as follows:

Calibrated Value = 0.7166 * cross slope + 1.4583

The residuals after calibration are shown in Figure 5.2. The calibration equations are only suitable for the data set used in this study, as the parameters of the global operations while preprocessing other data sets would be different due to the instrument, scene, and flying height. Table 5.1 compares LIDAR results after calibration. As shown, results for calibrated slope and cross slope were much closer to field measurements. The results after calibrating the output from regression analysis are shown in Table 5.1. The results of grade estimation are within 0.3% of the actual grade values. Cross slope values were estimated within 0.5% for the pavements sections, but the estimated values for the roadway shoulders were not encouraging, with residuals of up to 6% as shown in Figure 5.2. The high residual values for shoulders were likely caused by poor definition of shoulder edge or by inaccurate measurement during ground survey due to local undulations.

As shown, roadway grade after calibration was estimated to within 0.3% of its absolute value, and cross slope was estimated to within 0.5% for the pavement sections. Cross slope measurements of the shoulders were unsuccessful.

Table 5.1. Comparison of calibrated LIDAR and field data (absolute value)

		Grade (%)				Cross slope (%)			
		SB		NB		SB		NB	
		Shoulder	Pavement	Pavement	Shoulder	Shoulder	Pavement	Pavement	Shoulder
Section A	Calibrated	0.79	0.94	1.05	0.98	3.11	1.99	1.45	3.44
	Survey	0.93	0.76	0.80	1.11	4.18	1.62	1.42	6.84
	Difference	0.14	0.18	0.25	0.13	1.07	0.37	0.03	3.40
Section B	Calibrated	0.54	0.48	0.52	0.40	1.68	1.61	2.45	3.12
	Survey	0.40	0.41	0.41	0.35	5.80	1.90	2.15	5.10
	Difference	0.14	0.07	0.11	0.05	4.12	0.29	0.30	1.98
Section C	Calibrated	0.90	0.90	0.89	0.93	2.33	1.57	1.63	3.97
	Survey	1.19	0.83	0.73	0.59	3.52	1.57	1.80	5.17
	Difference	0.29	0.07	0.16	0.34	1.19	0	0.17	1.20
Section D	Calibrated	0.36	0.40	0.58	0.58	4.27	2.02	2.20	2.91
	Survey	0.66	0.63	0.55	0.36	8.88	1.33	2.18	4.56
	Difference	0.30	0.23	0.03	0.22	4.61	0.69	0.02	1.65
Section E	Calibrated	0.86	0.82	0.86	0.74	3.71	1.64	2.7	3.48
	Survey	1.29	1.20	1.17	0.88	6.10	2.02	1.90	6.89
	Difference	0.43	0.38	0.31	0.14	2.39	0.38	0.80	3.41
Section F	Calibrated	0.74	0.60	0.72	0.68	4.68	2.36	2.45	4.88
	Survey	0.95	0.98	0.97	0.86	8.31	1.70	2.23	10.18
	Difference	0.21	0.38	0.25	0.18	3.63	0.66	0.22	5.30
Section G	Calibrated	0.80	0.66	0.94	0.88	5.65	1.54	2.07	2.68
	Survey	0.83	0.77	0.77	0.79	6.34	1.79	2.23	8.99
	Difference	0.03	0.11	0.17	0.09	0.69	0.25	0.16	6.31
Section H	Calibrated	0.84	0.80	0.86	1.04	1.40	1.74	2.17	11.35
	Survey	0.91	1.00	1.01	0.96	1.72	1.72	2.02	7.50
	Difference	0.07	0.20	0.15	0.08	0.32	0.02	0.15	3.85
Section I	Calibrated	0.25	0.24	0.24	0.24	2.74	2.04	2.04	2.74
	Survey	0.09	0.05	0.04	0.06	3.88	1.57	1.92	3.33
	Difference	0.16	0.19	0.20	0.18	1.14	0.47	0.12	0.59
Section J	Calibrated	0.34	0.20	0.40	0.50	3.04	2.01	1.33	3.17
	Survey	0.25	0.24	0.24	0.31	1.87	1.65	1.20	7.80
	Difference	0.09	0.04	0.16	0.19	1.17	0.36	0.13	4.63

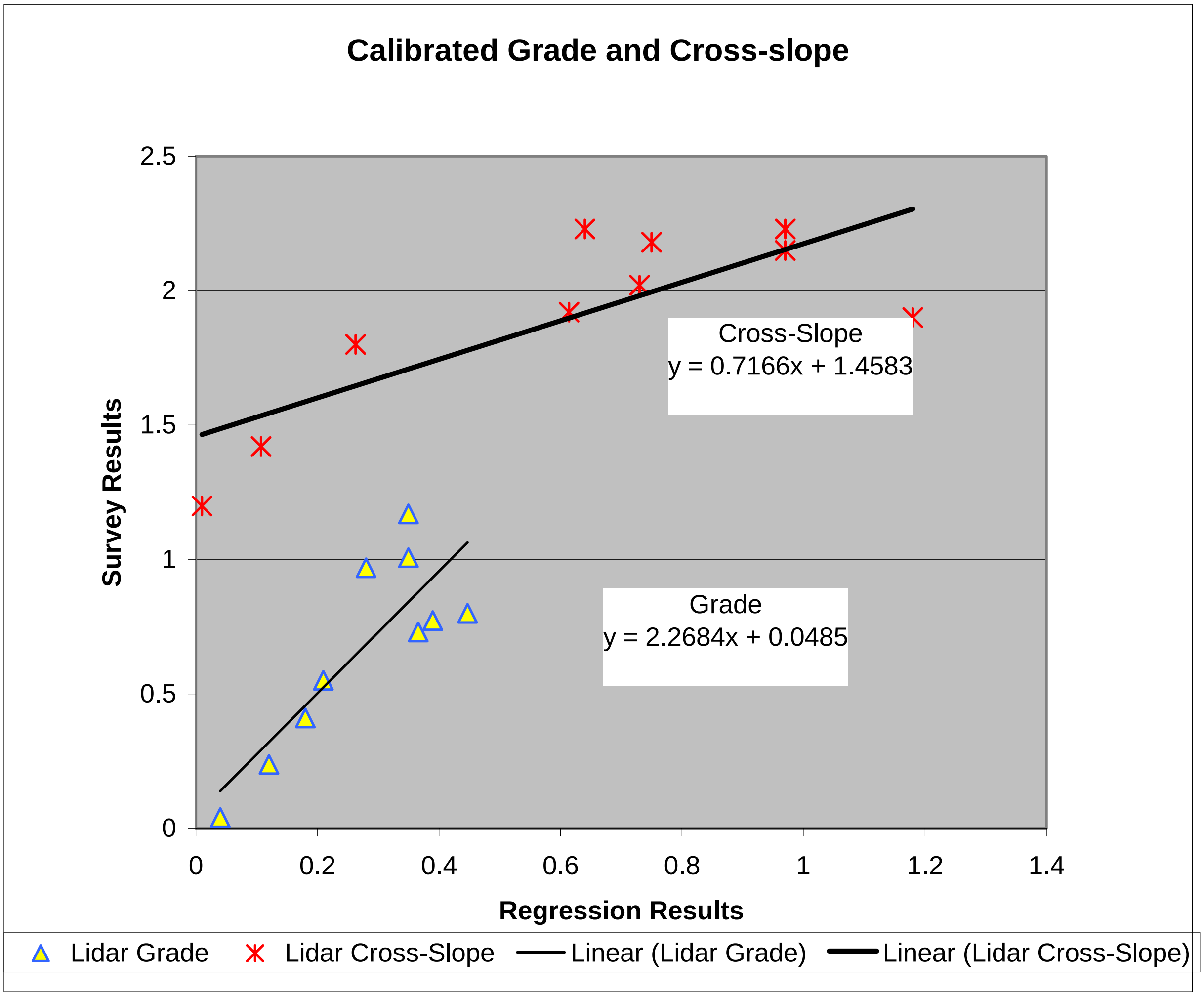

Figure 5.1. Calibration of the regression results using survey results

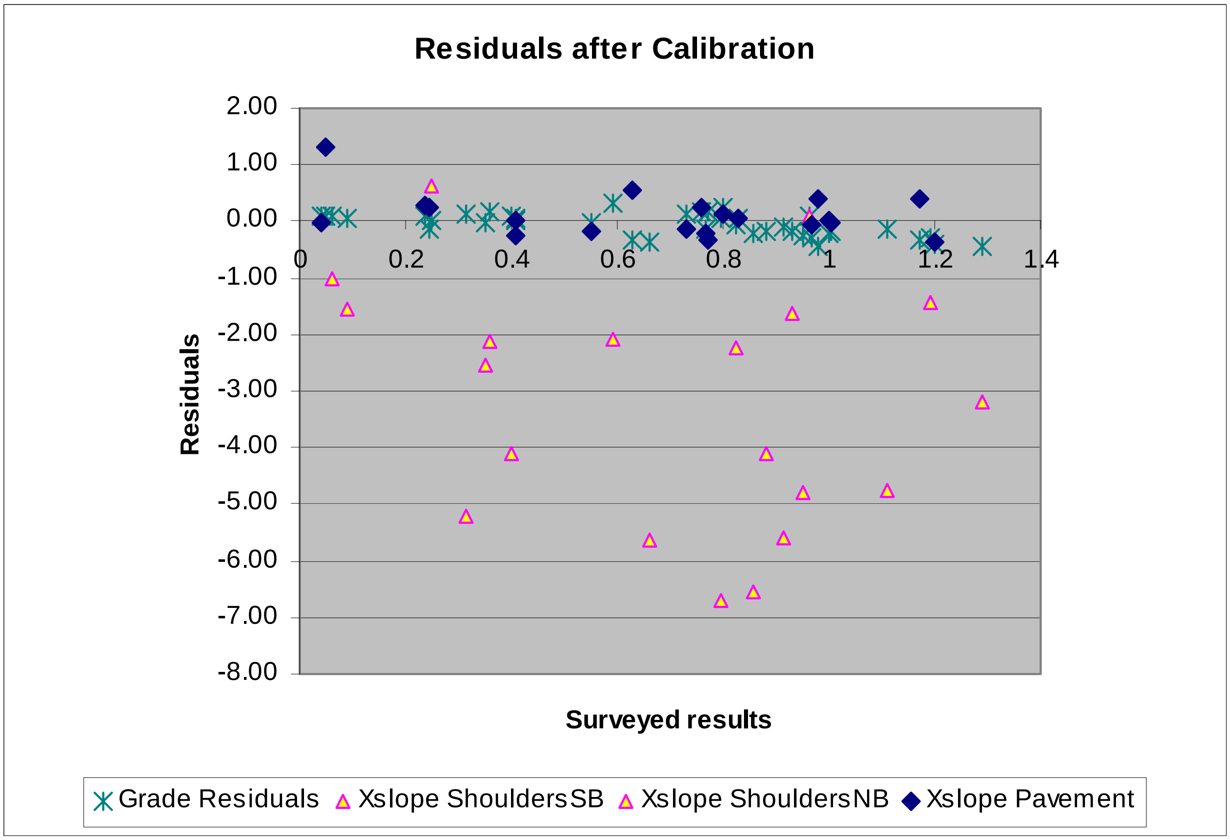

Figure 5.2. Residuals after calibration using survey results

6. FEASIBILITY OF USING LIDAR

The time required to derive the grade and cross slope of a segment using an auto level was about 40 minutes once the crew was set up in the field. As the survey involved three crewmembers, the total time for each section was about two person-hours, and the total time taken for each section was 160 minutes. The above estimate does not include the commute to the study area.

The time to extract LIDAR points and perform regression analysis for each segment was about 30 minutes. This estimate does not include the time for calibration, which is a one-time process. Considering a hypothetical scenario involving 50 segments, the total time required for collecting grade and cross slope would be close to 25 hours. The time required for calibration would involve ground survey to measure grade and cross slope for at least five segments. This would add about a day's work, which translates, to 24 person-hours with a three-member crew. Consequently 49 hours would be required to derive the grade and cross slope for 50 segments, which gives about 1.25 for each section. The total time for deriving grade and cross slope from ground survey would be at least 200 hours in the field. Therefore, a quick comparison of the time required to derive results shows that regression analysis offers 50% savings. However, the skill level of the analyst performing regression analysis would be higher than those of the survey technicians.

Collection of LIDAR data for the sole purpose of estimating grade and cross slope would likely not be justifiable. The process of collecting and processing LIDAR data is fairly expensive. However, a number of states and agencies are already investing in large-scale collection of LIDAR for other purposes such as flood mapping, resulting in existing data sets that can be used.

7. CONCLUSIONS

The use of LIDAR data to extract grade and cross slope on tangent highway segments was evaluated and compared against grade and cross slope collected using an automatic level for 10 test segments along Iowa Highway 1. Grade and cross slope were measured from a surface model created from LIDAR data points collected for the study area. Grade on pavement surfaces was calculated to within 0.5% for most sections and within 0.87% for all sections. On shoulder sections, grade was calculated within 1% of the surveyed value. Cross slope estimates were much less accurate than grade estimates. For roadway pavement sections, cross slope estimated from LIDAR deviated from field measurements by 0.72% to 1.65%. Cross slope on shoulder sections could not be estimated with any confidence. This may be due to the narrowness of the shoulder sections used coupled with randomness of the LIDAR points. It is concluded that grade could be estimated to within 1%. Whether this is adequate depends on the specific application. Study results indicate that cross slope cannot practically be estimated using a LIDAR surface model.

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APPENDIX: REGRESSION RESULTS BY TEST SEGMENT

SEGMENT A

NorthBound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.673667
R Square	0.453828
Adjusted R Square	0.410134
Standard Error	0.173357
Observations	28

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.624291	0.312145	10.38656	0.000521
Residual	25	0.75132	0.030053		
Total	27	1.375611			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	243.1829	0.319365	761.4582	4.28E-56	242.5251	243.8406	242.5251	243.8406
X Variable 1	-0.00858	0.019644	-0.437	0.665865	-0.04904	0.031873	-0.04904	0.031873
X Variable 2	0.004124	0.000919	4.486208	0.000141	0.002231	0.006018	0.002231	0.006018

NorthBound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.745859
R Square	0.556306
Adjusted R Square	0.535178
Standard Error	0.134274
Observations	45

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.949436	0.474718	26.32991	3.88E-08
Residual	42	0.757244	0.01803		
Total	44	1.70668			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	243.1246	0.064816	3750.968	1.2E-117	242.9938	243.2554	242.9938	243.2554
X Variable 1	-0.00107	0.007633	-0.14061	0.888848	-0.01648	0.014331	-0.01648	0.014331
X Variable 2	0.004474	0.000617	7.256708	6.26E-09	0.00323	0.005719	0.00323	0.005719

Southbound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.769303
R Square	0.591827
Adjusted R Square	0.57239
Standard Error	0.121227
Observations	45

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.894955	0.447477	30.44872	6.73E-09
Residual	42	0.617236	0.014696		
Total	44	1.512191			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	243.1398	0.05656	4298.824	3.8E-120	243.0257	243.254	243.0257	243.254
X Variable 1	0.005692	0.007076	0.804401	0.425695	-0.00859	0.019972	-0.00859	0.019972
X Variable 2	-0.00389	0.000498	-7.80045	1.06E-09	-0.00489	-0.00288	-0.00489	-0.00288

SouthBound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.817673
R Square	0.66859
Adjusted R Square	0.647208
Standard Error	0.077881
Observations	34

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.379326	0.189663	31.2698	3.68E-08
Residual	31	0.188027	0.006065		
Total	33	0.567353			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	243.3252	0.129507	1878.852	6E-80	243.0611	243.5893	243.0611	243.5893
X Variable 1	0.015385	0.008437	1.823487	0.077885	-0.00182	0.032592	-0.00182	0.032592
X Variable 2	-0.00316	0.0004	-7.90202	6.41E-09	-0.00398	-0.00235	-0.00398	-0.00235

SEGMENT B

Northbound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.821769
R Square	0.675304
Adjusted R Square	0.654356
Standard Error	0.036954
Observations	34

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.088043	0.044022	32.23694	2.68E-08
Residual	31	0.042332	0.001366		
Total	33	0.130376			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	249.5705	0.058443	4270.294	5.3E-91	249.4513	249.6897	249.4513	249.6897
X Variable 1	-0.01537	0.003475	-4.4233	0.000111	-0.02246	-0.00828	-0.02246	-0.00828
X Variable 2	0.001171	0.00019	6.168861	7.6E-07	0.000784	0.001558	0.000784	0.001558

Northbound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.795314
R Square	0.632524
Adjusted R Square	0.616547
Standard Error	0.053303
Observations	49

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.224958	0.112479	39.5892	1E-10
Residual	46	0.130693	0.002841		
Total	48	0.355652			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	249.5096	0.024377	10235.55	7E-148	249.4606	249.5587	249.4606	249.5587
X Variable 1	-0.00969	0.003082	-3.14529	0.002906	-0.0159	-0.00349	-0.0159	-0.00349
X Variable 2	0.001791	0.000217	8.246225	1.29E-10	0.001354	0.002228	0.001354	0.002228

Southbound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.852124
R Square	0.726116
Adjusted R Square	0.714704
Standard Error	0.03409
Observations	51

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.14789	0.073945	63.62829	3.17E-14
Residual	48	0.055783	0.001162		
Total	50	0.203672			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	249.5047	0.016025	15569.85	1.5E-162	249.4724	249.5369	249.4724	249.5369
X Variable 1	0.002503	0.001973	1.268954	0.210577	-0.00146	0.006469	-0.00146	0.006469
X Variable 2	-0.00162	0.000146	-11.0757	8.04E-15	-0.00192	-0.00133	-0.00192	-0.00133

Southbound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.87007
R Square	0.757022
Adjusted R Square	0.739024
Standard Error	0.03726
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.116786	0.058393	42.06058	5.07E-09
Residual	27	0.037484	0.001388		
Total	29	0.15427			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	249.4888	0.065674	3798.894	7.16E-79	249.354	249.6235	249.354	249.6235
X Variable 1	0.003141	0.004111	0.764008	0.451488	-0.00529	0.011576	-0.00529	0.011576
X Variable 2	-0.00188	0.000205	-9.14805	9.25E-10	-0.0023	-0.00146	-0.0023	-0.00146

SEGMENT C

NorthBound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.963186
R Square	0.927727
Adjusted R Square	0.919696
Standard Error	0.045752
Observations	21

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.483646	0.241823	115.5275	5.38E-11
Residual	18	0.037678	0.002093		
Total	20	0.521324			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	256.2563	0.086601	2959.037	1.22E-52	256.0744	256.4383	256.0744	256.4383
X Variable 1	-0.02267	0.005247	-4.3202	0.000412	-0.03369	-0.01164	-0.03369	-0.01164
X Variable 2	0.003857	0.000267	14.44415	2.42E-11	0.003296	0.004418	0.003296	0.004418

Northbound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.984875
R Square	0.969978
Adjusted R Square	0.967833
Standard Error	0.02391
Observations	31

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.51718	0.25859	452.3225	4.83E-22
Residual	28	0.016007	0.000572		
Total	30	0.533187			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	255.9862	0.014086	18172.87	1.5E-100	255.9573	256.015	255.9573	256.015
X Variable 1	-0.00263	0.00167	-1.57149	0.127303	-0.00605	0.000797	-0.00605	0.000797
X Variable 2	0.003668	0.000123	29.81906	9.26E-23	0.003416	0.00392	0.003416	0.00392

Southbound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.650209
R Square	0.422772
Adjusted R Square	0.37837
Standard Error	0.173909
Observations	29

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.57594	0.28797	9.52142	0.00079
Residual	26	0.786356	0.030244		
Total	28	1.362297			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	256.0445	0.103067	2484.254	2.04E-71	255.8326	256.2564	255.8326	256.2564
X Variable 1	0.002111	0.012943	0.163093	0.871706	-0.02449	0.028715	-0.02449	0.028715
X Variable 2	-0.00371	0.000864	-4.29716	0.000215	-0.00549	-0.00194	-0.00549	-0.00194

Southbound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.973811
R Square	0.948309
Adjusted R Square	0.940924
Standard Error	0.034486
Observations	17

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.305456	0.152728	128.4191	9.86E-10
Residual	14	0.01665	0.001189		
Total	16	0.322106			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	256.0943	0.08311	3081.378	3.17E-42	255.9161	256.2726	255.9161	256.2726
X Variable 1	0.008603	0.005129	1.677525	0.115615	-0.0024	0.019603	-0.0024	0.019603
X Variable 2	-0.00371	0.000233	-15.9361	2.28E-10	-0.00421	-0.00321	-0.00421	-0.00321

SEGMENT D

Northbound shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.931574
R Square	0.867831
Adjusted R Square	0.861957
Standard Error	0.034727
Observations	48

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.356324	0.178162	147.7365	1.68E-20
Residual	45	0.054268	0.001206		
Total	47	0.410592			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	215.5998	0.046272	4659.422	1.6E-129	215.5066	215.693	215.5066	215.693
X Variable 1	-0.01364	0.002579	-5.28649	3.52E-06	-0.01883	-0.00844	-0.01883	-0.00844
X Variable 2	0.002064	0.000136	15.18258	2.54E-19	0.00179	0.002338	0.00179	0.002338

Northbound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.947505
R Square	0.897767
Adjusted R Square	0.894179
Standard Error	0.026267
Observations	60

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.345357	0.172679	250.2738	5.93E-29
Residual	57	0.039328	0.00069		
Total	59	0.384685			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	215.5077	0.011388	18923.81	1.9E-195	215.4849	215.5305	215.4849	215.5305
X Variable 1	-0.0075	0.001426	-5.25953	2.26E-06	-0.01036	-0.00464	-0.01036	-0.00464
X Variable 2	0.002098	9.77E-05	21.48244	5.23E-29	0.001903	0.002294	0.001903	0.002294

Southbound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.773403
R Square	0.598152
Adjusted R Square	0.582696
Standard Error	0.044728
Observations	55

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.154849	0.077425	38.70102	5.08E-11
Residual	52	0.104031	0.002001		
Total	54	0.25888			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	215.5415	0.018483	11661.81	1.5E-168	215.5044	215.5786	215.5044	215.5786
X Variable 1	-0.00601	0.002319	-2.59004	0.012421	-0.01066	-0.00135	-0.01066	-0.00135
X Variable 2	0.001205	0.000145	8.327164	3.88E-11	0.000914	0.001495	0.000914	0.001495

Southbound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.814609
R Square	0.663588
Adjusted R Square	0.650395
Standard Error	0.048771
Observations	54

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.239285	0.119642	50.29994	8.61E-13
Residual	51	0.121308	0.002379		
Total	53	0.360593			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	215.7857	0.052103	4141.548	1.3E-142	215.6811	215.8903	215.6811	215.8903
X Variable 1	-0.02519	0.002984	-8.44091	2.99E-11	-0.03118	-0.0192	-0.03118	-0.0192
X Variable 2	0.00097	0.000172	5.634932	7.61E-07	0.000624	0.001316	0.000624	0.001316

SEGMENT E

NorthBound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.909326
R Square	0.826873
Adjusted R Square	0.817255
Standard Error	0.051677
Observations	39

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.459161	0.22958	85.97013	1.95E-14
Residual	36	0.096137	0.00267		
Total	38	0.555297			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	229.4783	0.063112	3636.074	8.9E-102	229.3503	229.6063	229.3503	229.6063
X Variable 1	-0.01856	0.003791	-4.89578	2.07E-05	-0.02625	-0.01087	-0.02625	-0.01087
X Variable 2	-0.00286	0.000222	-12.8845	4.76E-15	-0.00331	-0.00241	-0.00331	-0.00241

NorthBound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.944261
R Square	0.891629
Adjusted R Square	0.886588
Standard Error	0.049677
Observations	46

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.873068	0.436534	176.8924	1.78E-21
Residual	43	0.106115	0.002468		
Total	45	0.979183			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	229.3611	0.02224	10312.85	4.2E-139	229.3163	229.406	229.3163	229.406
X Variable 1	-0.01181	0.002734	-4.31807	9.1E-05	-0.01732	-0.00629	-0.01732	-0.00629
X Variable 2	-0.00354	0.000199	-17.8044	1.85E-21	-0.00394	-0.00314	-0.00394	-0.00314

Southbound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.920343
R Square	0.847031
Adjusted R Square	0.839382
Standard Error	0.049685
Observations	43

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.546772	0.273386	110.7451	4.92E-17
Residual	40	0.098744	0.002469		
Total	42	0.645516			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	229.3743	0.023955	9575.352	7.8E-129	229.3259	229.4227	229.3259	229.4227
X Variable 1	0.006961	0.00309	2.252683	0.029834	0.000716	0.013205	0.000716	0.013205
X Variable 2	-0.00334	0.000226	-14.792	8.21E-18	-0.00379	-0.00288	-0.00379	-0.00288

SouthBound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.891807
R Square	0.79532
Adjusted R Square	0.784256
Standard Error	0.072457
Observations	40

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.754788	0.377394	71.88498	1.8E-13
Residual	37	0.194249	0.00525		
Total	39	0.949038			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	229.5424	0.099873	2298.334	5.68E-97	229.34	229.7447	229.34	229.7447
X Variable 1	0.020458	0.005738	3.565466	0.001024	0.008832	0.032084	0.008832	0.032084
X Variable 2	-0.00353	0.000305	-11.5488	7.87E-14	-0.00415	-0.00291	-0.00415	-0.00291

SEGMENT F

Northbound Shoulder

Regression Statistics	
Multiple R	0.95928
R Square	0.920219
Adjusted R Square	0.91642
Standard Error	0.034018
Observations	45

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.560599	0.2803	242.2194	8.71E-24
Residual	42	0.048603	0.001157		
Total	44	0.609202			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	216.6601	0.044175	4904.596	1.50E-122
X Variable 1	-0.03039	0.00247	-12.3029	1.63E-15
X Variable 2	-0.00262	0.000148	-17.7158	4.22E-21

Northbound Pavement

Regression Statistics	
Multiple R	0.978684
R Square	0.957822
Adjusted R Square	0.955947
Standard Error	0.024074
Observations	48

ANOVA

	df	SS	MS	F
Regression	2	0.592227	0.296113	510.9511
Residual	45	0.026079	0.00058	
Total	47	0.618306		

	Coefficients	Standard Error	t Stat	P-value
Intercept	216.4207	0.010076	21479.86	2.10E-159
X1 (grade)	-0.00974	0.001426	-6.8288	1.83E-08
X2 (cross slope)	-0.00284	9.38E-05	-30.2381	1.53E-31

South bound Pavement

Regression Statistics	
Multiple R	0.865334
R Square	0.748803
Adjusted R Square	0.738336
Standard Error	0.050375
Observations	51

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.363095	0.181548	71.54238	3.98E-15
Residual	48	0.121806	0.002538		
Total	50	0.484901			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	216.3949	0.020786	10410.8	3.70E-154
X Variable 1	-0.00894	0.0026	-3.43726	0.001223
X Variable 2	-0.00219	0.000194	-11.286	4.17E-15

South Bound Shoulder

Regression Statistics	
Multiple R	0.768514
R Square	0.590614
Adjusted R Square	0.565802
Standard Error	0.097975
Observations	36

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.456998	0.228499	23.80423	3.98E-07
Residual	33	0.31677	0.009599		
Total	35	0.773767			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	216.685	0.134922	1606.007	2.54E-82
X Variable 1	-0.02869	0.007369	-3.89256	0.000456
X Variable 2	-0.00286	0.000464	-6.1728	5.81E-07

SEGMENT G

Northbound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.395246
R Square	0.156219
Adjusted R Square	0.026407
Standard Error	0.217998
Observations	16

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.114381	0.057191	1.203423	0.331507
Residual	13	0.617802	0.047523		
Total	15	0.732183			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	264.3459	0.788657	335.185	5.6E-27	262.6421	266.0497	262.6421	266.0497
X Variable 1	-0.01159	0.053366	-0.21723	0.831399	-0.12688	0.103698	-0.12688	0.103698
X Variable 2	0.003559	0.002301	1.547078	0.145836	-0.00141	0.00853	-0.00141	0.00853

Northbound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.602009
R Square	0.362414
Adjusted R Square	0.331313
Standard Error	0.185836
Observations	44

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.804845	0.402422	11.65255	9.84E-05
Residual	41	1.41594	0.034535		
Total	43	2.220785			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	264.3063	0.08746	3022.029	2.9E-111	264.1296	264.4829	264.1296	264.4829
X Variable 1	-0.00642	0.010613	-0.60492	0.548563	-0.02785	0.015013	-0.02785	0.015013
X Variable 2	0.003853	0.000822	4.685585	3.06E-05	0.002192	0.005513	0.002192	0.005513

Southbound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.597943
R Square	0.357535
Adjusted R Square	0.324589
Standard Error	0.117718
Observations	42

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.30076	0.15038	10.85187	0.000179
Residual	39	0.540443	0.013858		
Total	41	0.841203			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	264.2849	0.059462	4444.572	7.3E-113	264.1646	264.4051	264.1646	264.4051
X Variable 1	0.001855	0.007113	0.260799	0.79562	-0.01253	0.016242	-0.01253	0.016242
X Variable 2	0.002521	0.000541	4.655765	3.69E-05	0.001426	0.003616	0.001426	0.003616

Southbound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.791483
R Square	0.626445
Adjusted R Square	0.579751
Standard Error	0.105606
Observations	19

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.299247	0.149623	13.41588	0.000379
Residual	16	0.178443	0.011153		
Total	18	0.47769			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	264.6885	0.315113	839.9794	1.37E-38	264.0205	265.3566	264.0205	265.3566
X Variable 1	-0.03703	0.020388	-1.81646	0.088081	-0.08026	0.006187	-0.08026	0.006187
X Variable 2	0.00324	0.000741	4.370844	0.000475	0.001668	0.004811	0.001668	0.004811

SEGMENT H

Northbound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.710303
R Square	0.50453
Adjusted R Square	0.438467
Standard Error	0.138247
Observations	18

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.291924	0.145962	7.637133	0.00516
Residual	15	0.286682	0.019112		
Total	17	0.578606			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	258.1533	0.589058	438.2478	3.17E-32	256.8978	259.4089	256.8978	259.4089
X Variable 1	-0.08566	0.039409	-2.17359	0.04616	-0.16966	-0.00166	-0.16966	-0.00166
X Variable 2	-0.0044	0.001134	-3.88053	0.001479	-0.00682	-0.00198	-0.00682	-0.00198

Northbound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.756977
R Square	0.573015
Adjusted R Square	0.555936
Standard Error	0.104512
Observations	53

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.732917	0.366458	33.55006	5.76E-10
Residual	50	0.546137	0.010923		
Total	52	1.279053			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	257.0296	0.043873	5858.504	1.4E-147	256.9415	257.1177	256.9415	257.1177
X Variable 1	-0.0073	0.00534	-1.36644	0.177914	-0.01802	0.003429	-0.01802	0.003429
X Variable 2	-0.00348	0.000437	-7.96687	1.87E-10	-0.00436	-0.00261	-0.00436	-0.00261

SouthBound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.666756
R Square	0.444564
Adjusted R Square	0.421421
Standard Error	0.114603
Observations	51

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.50458	0.25229	19.20931	7.43E-07
Residual	48	0.63042	0.013134		
Total	50	1.135			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	257.0031	0.049707	5170.338	1.4E-139	256.9032	257.1031	256.9032	257.1031
X Variable 1	-0.0036	0.006122	-0.58808	0.559236	-0.01591	0.008709	-0.01591	0.008709
X Variable 2	-0.00322	0.000523	-6.16567	1.4E-07	-0.00427	-0.00217	-0.00427	-0.00217

Southbound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.924104
R Square	0.853968
Adjusted R Square	0.836788
Standard Error	0.055105
Observations	20

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.301878	0.150939	49.70643	7.9E-08
Residual	17	0.051622	0.003037		
Total	19	0.3535			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	256.9195	0.200671	1280.305	8.22E-44	256.4961	257.3429	256.4961	257.3429
X Variable 1	-0.0007	0.014583	-0.04797	0.962297	-0.03147	0.030068	-0.03147	0.030068
X Variable 2	-0.0034	0.000345	-9.87732	1.85E-08	-0.00413	-0.00268	-0.00413	-0.00268

SEGMENT I

Northbound Shoulder

Regression Statistics	
Multiple R	0.692051
R Square	0.478934
Adjusted R Square	0.442998
Standard Error	0.029213
Observations	32

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.022748	0.011374	13.32757	7.85E-05
Residual	29	0.024749	0.000853		
Total	31	0.047497			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	247.1492	0.048249	5122.327	6.27E-88	247.0505	247.2479	247.0505	247.2479
X Variable 1	-0.01212	0.002929	-4.13799	0.000275	-0.01811	-0.00613	-0.01811	-0.00613
X Variable 2	0.000447	0.000143	3.115235	0.004117	0.000154	0.00074	0.000154	0.00074

Northbound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.663186
R Square	0.439816
Adjusted R Square	0.41249
Standard Error	0.026819
Observations	44

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.023153	0.011577	16.09509	6.93E-06
Residual	41	0.02949	0.000719		
Total	43	0.052643			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	247.0627	0.013228	18677.15	1.1E-143	247.036	247.0894	247.036	247.0894
X Variable 1	-0.00614	0.001565	-3.92426	0.000325	-0.0093	-0.00298	-0.0093	-0.00298
X Variable 2	0.000411	0.00011	3.742023	0.00056	0.000189	0.000632	0.000189	0.000632

Southbound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.566062
R Square	0.320426
Adjusted R Square	0.283693
Standard Error	0.024536
Observations	40

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.010503	0.005251	8.722951	0.000788
Residual	37	0.022275	0.000602		
Total	39	0.032777			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	247.1153	0.011946	20686.88	2.8E-132	247.0911	247.1395	247.0911	247.1395
X Variable 1	0.004197	0.001442	2.910642	0.006075	0.001275	0.007118	0.001275	0.007118
X Variable 2	0.000346	0.00012	2.889967	0.006409	0.000103	0.000588	0.000103	0.000588

Southbound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.192442
R Square	0.037034
Adjusted R Square	-0.03175
Standard Error	0.039489
Observations	31

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.001679	0.00084	0.538417	0.589594
Residual	28	0.043663	0.001559		
Total	30	0.045342			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	247.1227	0.065048	3799.064	1.6E-81	246.9895	247.256	246.9895	247.256
X Variable 1	0.003418	0.004122	0.829243	0.41398	-0.00503	0.011862	-0.00503	0.011862
X Variable 2	8.28E-05	0.000194	0.427871	0.672018	-0.00031	0.000479	-0.00031	0.000479

Section J

Northbound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.811377
R Square	0.658333
Adjusted R Square	0.636289
Standard Error	0.048318
Observations	34

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.13945	0.069725	29.86575	5.9E-08
Residual	31	0.072373	0.002335		
Total	33	0.211824			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	248.7803	0.087757	2834.876	1.74E-85	248.6013	248.9593	248.6013	248.9593
X Variable 1	-0.01575	0.005284	-2.98128	0.005545	-0.02653	-0.00498	-0.02653	-0.00498
X Variable 2	0.00168	0.00025	6.733843	1.55E-07	0.001171	0.002189	0.001171	0.002189

Northbound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.54912
R Square	0.301533
Adjusted R Square	0.274142
Standard Error	0.064888
Observations	54

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.092701	0.046351	11.00854	0.000106
Residual	51	0.214731	0.00421		
Total	53	0.307432			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	248.6602	0.027482	9048.259	6.4E-160	248.605	248.7154	248.605	248.7154
X Variable 1	-0.00011	0.003412	-0.03238	0.974295	-0.00696	0.006739	-0.00696	0.006739
X Variable 2	0.00116	0.000248	4.684012	2.12E-05	0.000663	0.001657	0.000663	0.001657

Southbound Pavement

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.167525
R Square	0.028064
Adjusted R Square	-0.01419
Standard Error	0.097752
Observations	49

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.012692	0.006346	0.664121	0.519591
Residual	46	0.439549	0.009555		
Total	48	0.45224			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	248.7367	0.041039	6061.042	2.1E-137	248.6541	248.8193	248.6541	248.8193
X Variable 1	-0.0059	0.005594	-1.0555	0.29671	-0.01716	0.005356	-0.01716	0.005356
X Variable 2	-0.00015	0.000396	-0.38515	0.701904	-0.00095	0.000644	-0.00095	0.000644

Southbound Shoulder

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.356477
R Square	0.127076
Adjusted R Square	0.059928
Standard Error	0.108018
Observations	29

ANOVA

	df	SS	MS	F	Significance F
Regression	2	0.044162	0.022081	1.892469	0.170882
Residual	26	0.303366	0.011668		
Total	28	0.347528			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	248.9008	0.208562	1193.416	3.87E-63	248.4721	249.3295	248.4721	249.3295
X Variable 1	-0.01468	0.0126	-1.1652	0.254516	-0.04058	0.011218	-0.04058	0.011218
X Variable 2	-0.00092	0.00059	-1.56169	0.130453	-0.00214	0.000292	-0.00214	0.000292