EVALUATION OF THERMAL VARIATIONS ON CONCRETE PAVEMENT USING THREE DIMENSIONAL LINE LASER IMAGING TECHNOLOGY

A Thesis
Presented to
The Academic Faculty

By

Zachary Ludon Lewis

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in the
School of Civil Engineering

Georgia Institute of Technology
December 2013

Copyright © Zachary Ludon Lewis 2013
EVALUATION OF THERMAL VARIATIONS ON CONCRETE PAVEMENT USING THREE DIMENSIONAL LINE LASER IMAGING TECHNOLOGY

Approved by:

Dr. Yichang James Tsai, Advisor
School of Civil and Environmental Engineering
Georgia Institute of Technology

Wouter Gulden
Concrete Pavement Expert

Dr. Zhaohua Wang
GIS Center
Georgia Institute of Technology

Dr. James Lai
School of Civil and Environmental Engineering
Georgia Institute of Technology

Date Approved: November 7, 2013
ACKNOWLEDGEMENTS

First, I would like to express my sincere gratitude to my advisor Dr. James Tsai for his continued support, guidance and motivation through the duration of this work. I would like to thank the many members of our research team that have provided assistance that made it possible to complete this research. I would also like to thank Wouter Gulden, Dr. Zhaohua Wang, and Dr. James Lai for serving as members of my thesis committee and their extensive insight and guidance in this study.

In addition I would like to thank my parents, my girlfriend’s family, my church family and all of my other friends and family because without their never ending support, encouragement and prayers none of this would have been possible. I would like to thank all of the transportation agencies that provided funding which supplied the groundwork that made this research possible.

I would like to express my dearest and deepest gratitude to my girlfriend Casey Arnett for her continued love, support and for standing by my side through my academic career even with all of the difficult sacrifices that we had to make in order for me to complete this research. Most of all, I would like to thank GOD for my salvation and for giving me the strength, wisdom and knowledge that was vital to fulfill the requirements of this research. I would also like to thank Him for always letting me put Him first in my life and allowing me grow as a Christian no matter how demanding every other aspect of my life was.
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS .................................................................................................................................................. iii

LIST OF TABLES ............................................................................................................................................................ viii

LIST OF FIGURES .......................................................................................................................................................... ix

SUMMARY ........................................................................................................................................................................ xvii

CHAPTER 1 INTRODUCTION ......................................................................................................................................... 1

1.1 Study Objectives .......................................................................................................................................................... 2

1.2 Study Tasks ................................................................................................................................................................. 2

1.3 Report Organization ..................................................................................................................................................... 3

CHAPTER 2 LITERATURE REVIEW ............................................................................................................................ 5

2.1 Faulting Survey Practice ............................................................................................................................................... 5

2.1.1 AASHTO Standard Practice for Evaluating Faulting of Concrete Pavements ......................................................... 6

2.1.2 Faulting Practice in LTPP Distress Identification Manual ......................................................................................... 7

2.1.3 GDOT Faulting Practice .......................................................................................................................................... 8

2.2 Automated Faulting Survey Methods .................................................................................................................... 9

2.2.1 FDOT Semi-Automated Approach ....................................................................................................................... 9

2.3 Temperature Affect on Curling ................................................................................................................................. 14

2.3.1 Kansas Study .......................................................................................................................................................... 15

2.4 Slab Curvature Impact on Smoothness .................................................................................................................. 19

2.4.1 SCDOT Evaluation of Slab Curling on IRI ........................................................................................................... 20

2.4.2 USDOT and FHWA Study to Quantify Curvature on IRI ..................................................................................... 32

2.5 Thermal Effects on Faulting ..................................................................................................................................... 40

2.6 Literature Review Summary ..................................................................................................................................... 42
CHAPTER 3 SENSING EQUIPMENT .................................................................44
  3.1 Three Dimensional (3D) Line Laser Technology ....................................45
  3.2 Geo3D Sensing System .........................................................................50
  3.3 Thermal Data Logging System .................................................................54

CHAPTER 4 PRELIMINARY INVESTIGATION ..............................................56
  4.1 Site Selection ............................................................................................56
  4.2 Thermocouple Installation .......................................................................58
  4.3 Thermal Data .............................................................................................62
    4.3.1 Thermal Data Collection at Weigh Station ........................................62
    4.3.2 Thermal Data Analysis ....................................................................63
  4.4 Sensing Vehicle Data ...............................................................................70
    4.4.1 3D Line Laser Data Collection at Weigh Station .............................71
    4.4.2 3D Line Laser Data Analysis .............................................................72
  4.5 Summary ...................................................................................................98

CHAPTER 5 INITIAL I-16 INVESTIGATION ..............................................101
  5.1 Site Selection ............................................................................................101
  5.2 Initial I-16 Site Faulting Analysis .............................................................103
  5.3 Initial I-16 Site Roughness Analysis .........................................................113
  5.4 Summary ..................................................................................................116

CHAPTER 6 FINAL I-16 INVESTIGATION .................................................119
  6.1 Site Selection ............................................................................................119
  6.2 Final I-16 Site Faulting Analysis ...............................................................126
  6.3 Final I-16 Site Roughness Analysis ...........................................................144
  6.4 Summary ..................................................................................................154

CHAPTER 7 CONCLUSIONS .......................................................................157
7.1 Conclusions ........................................................................................................157
7.2 Recommendations for Future Research ..........................................................163

APPENDIX A THERMOCOUPLE INSTALLATION ...............................................168
A.1 Introduction ....................................................................................................171
A.2 Device Selection .........................................................................................171
A.3 Site Selection ...............................................................................................172
A.4 Slab Locations and Depths to Monitor .......................................................174
A.5 Installation Time Selection ..........................................................................176
A.6 Thermocouple Installation Procedure ........................................................177
  A.6.1 Shoulder Preparation for Housing and Protective Piping .................178
  A.6.2 Groove Cutting ...................................................................................181
  A.6.3 Hole Drilling ....................................................................................183
  A.6.4 Thermocouple Labeling ....................................................................186
  A.6.5 Housing Preparation and Thermocouple Placement in Protective Pipe ........................................................................................................188
  A.6.6 Thermocouple Placement in Slab ....................................................195
  A.6.7 Excess Thermocouple Placement and Electrical Box Sealing ..................201
  A.6.8 Soil Replacement ............................................................................202
  A.6.9 Data Logger Placement ......................................................................204

APPENDIX B DATA EXTRACTION PROCEDURE .............................................209
B.1 Introduction ..................................................................................................213
B.2 Procedure to Generate the IRI Results Using the 3D Line Laser Software ........................................................................................................214
B.3 Procedure to Generate the Faulting Results Using the 3D Line Laser Software ........................................................................................................221
  B.3.1 Faulting Parameters ............................................................................222
  B.3.2 Single Joint Faulting Processing .......................................................226
B.3.3. Multiple Joint Faulting Processing ..................................................230
B.3.4 Faulting Results .............................................................................233

B.4 Procedure to Produce Corrected Longitudinal Profiles from PROVAL ..............................................................................................................237

B.5 Procedure to Produce Longitudinal and Transverse Curvature From Raw 3D Line Laser Data .................................................................244
  B.5.1 File Conversion ..............................................................................246
  B.5.2 Locating Slab Extents Using LcmsRoadInspect Software.............248
  B.5.3 Using MATLAB to Extract Slab Profiles from Binary Files .........257
  B.5.4 Using Excel to Analyze the Slab Profiles ......................................262

B.6 Procedure to Extract Raw IMU Data ......................................................269

B.7 Procedure to Extract the Temperature Data from the Data Loggers .............271

B.8 Conclusions ..........................................................................................273

APPENDIX C WEIGH STATION DESIGN ..............................................................275

APPENDIX D FIRST PRELIMINARY INVESTIGATION ........................................281
  D.1 Introduction ........................................................................................282
  D.2 Site Selection ......................................................................................283
  D.3 Thermocouple Installation ................................................................284
  D.4 Thermal Data ......................................................................................288
    D.4.1 Thermal Data Collection at Weigh Station ....................................288
    D.4.2 Thermal Data Analysis .................................................................289
  D.5 Sensing Vehicle Data ..........................................................................292
    D.5.1 3D Line Laser Data Collection at Weigh Station ....................293
    D.5.2 3D Line Laser Data Analysis .......................................................294
  D.6 Summary ............................................................................................308

REFERENCES .................................................................................................311
LIST OF TABLES

Table 3.1 Geo3D Laser Specifications .................................................................52
Table 4.1 Variation Analysis Summary.................................................................69
Table 4.2 Weigh Station Average Faulting Statistics ............................................75
Table 4.3 Weigh Station Average Faulting Variation ............................................76
Table 4.4 Weigh Station Faulting Variation Detailed Analysis Results .................78
Table 4.5 Maximum and Minimum Average Faulting Occurrence Times .............79
Table 4.6 FDOT IRI Ground Truths .................................................................82
Table 4.7 3D Line Laser IRI Results from FDOT Test Sections .........................84
Table 4.8 FDOT Test Sections 3D Line Laser IRI Variation ...............................85
Table 4.9 Weigh Station IRI Statistics ...............................................................86
Table 5.1 Initial I-16 Average Faulting ...............................................................103
Table 5.2 Initial I-16 Average Faulting Variation Detailed Analysis Results .........105
Table 5.3 Maximum and Minimum Average Faulting Occurrence Times ............106
Table 5.4 Joint 24 Average Faulting Properties ..................................................111
Table 5.5 Initial I-16 Test Section IRI Statistics ...............................................114
Table 6.1 Concrete Pavement Design Summary ...................................................125
Table 6.2 Summary of Average Faulting for Final I-16 Test Site .........................128
Table 6.3 Variation in Average Faulting at Final I-16 Test Site ............................129
Table 6.4 Maximum and Minimum Average Faulting Occurrence Times ............130
Table 6.5 Final I-16 Test Site IRI Statistics ........................................................145
Table D.1 Weigh Station Average Faulting Statistics .........................................297
Table D.2 Weigh Station Average Faulting Variation .........................................298
Table D.3 Weigh Station IRI Statistics ..............................................................300
LIST OF FIGURES

Figure 2.1 Positions used to Measure Faulting using an Automated Procedure ..........7
Figure 2.2 Kansas Study Thermal Data .................................................................16
Figure 2.3 Kansas Study Extensometer Set Up ....................................................17
Figure 2.4 Curling and Thermal Gradients Recorded in Kansas Study ..............18
Figure 2.5 I-520 Digital Indicator and Thermal from SCDOT Study ...............25
Figure 2.6 I-385 Slab Movement and Thermal Data from SCDOT Study ..........26
Figure 2.7 I-385 Slab Profiles ..............................................................................27
Figure 2.8 HSIP and LIDAR Profile Comparison in SCDOT Study ...................29
Figure 2.9 Seasonal IRI Comparison for I-520 in SCDOT Study ......................30
Figure 2.10 Example of Raw Profile and Fitted Profile .....................................36
Figure 2.11 Curvature and Roughness Relationship ..........................................38
Figure 2.12 RoCK Diagram used to Evaluate Curvature Impact on Roughness ...39
Figure 2.13 Example of Faulted Joint ..................................................................41
Figure 2.14 Slab Expansion Example ..................................................................41
Figure 3.1 Georgia Tech Sensing Vehicle ............................................................45
Figure 3.2 3D Line Laser Data Collection ...........................................................46
Figure 3.3 3D Line Laser Profiles and Tilt Angle ...............................................47
Figure 3.4 Concrete Pavement Data Collected by Sensing Vehicle .................48
Figure 3.5 3D Line Laser Sensor .........................................................................50
Figure 3.6 Geo3D Sensing System ......................................................................53
Figure 3.7 Thermal Devices ................................................................................55
Figure 4.1 Aerial View of Weigh Station ............................................................57
Figure 4.2 Thermocouple Positions in Test Slab ................................................59
Figure 4.3 Thermocouple Depths in the Test Slab ............................................................61
Figure 4.4 Temperature Variations between Slab Positions........................................64
Figure 4.5 Daily Thermal Data Example from Position A ..........................................66
Figure 4.6 Thermal Data Logged During Sensing Vehicle Data Collection .............69
Figure 4.7 3D Line Laser Faulting Parameters ............................................................74
Figure 4.8 Joint 6, 20, and 24 Average Faulting Distributions ...................................81
Figure 4.9 Weigh Station IRI ....................................................................................87
Figure 4.10 Longitudinal Profiles for Curvature Analysis at Weigh Station ..........90
Figure 4.11 Weigh Station Slab 1 Profiles .................................................................93
Figure 4.12 Weigh Station Slab 13 Profiles ...............................................................94
Figure 4.13 Weigh Station Slab 25 Profiles ...............................................................95
Figure 4.14 Weigh Station Slab 1 Longitudinal Profile .............................................96
Figure 4.15 Weigh Station Quantitative Curvature Values .....................................97
Figure 4.16 Quantitative Transverse Curvatures .......................................................98
Figure 5.1 Initial I-16 Test Site ..................................................................................102
Figure 5.2 Average Faulting Distribution at Initial I-16 Site ..................................107
Figure 5.3 Sensing Vehicle Data for Joint/Slab 24 ....................................................108
Figure 5.4 Joint 24 Faulting Distribution .................................................................111
Figure 5.5 Joint 1 and Joint 24 Average Faulting Distributions at Initial I-16 Test Site .................................................................112
Figure 5.6 Faulting Measurements across Joint 24 .....................................................113
Figure 5.7 IRI Distribution at Initial I-16 Test Site .....................................................115
Figure 5.8 Longitudinal Profiles Collected at 2:30 P.M. used to indicate the Location of Broken Slab at Joint 24 .................................................................116
Figure 6.1 Final I-16 Test Site .................................................................................120
Figure 6.2 Section A Video Log Image ....................................................................122
Figure 6.3 Video Log Images of Sections B, C, D, and Milepost 38 .................123
Figure 6.4 Final I-16 Test Site Average Faulting Distributions .......................132
Figure 6.5 Joint 25 in Section A .......................................................................135
Figure 6.6 Joints with Abnormal Faulting in Section B .....................................136
Figure 6.7 Broken Repaired Slab in Section C ......................................................139
Figure 6.8 Individual Joint Average Faulting Distributions for Final I-16 Test Site ...............................................................................................................140
Figure 6.9 Joint 26 in Section B and Joint 20 in Section .....................................142
Figure 6.10 Section C Joint 20 Faulting Measurement Distributions ..................144
Figure 6.11 Section A IRI Distribution .................................................................147
Figure 6.12 Section B IRI Distribution .................................................................148
Figure 6.13 Section C IRI Distribution .................................................................149
Figure 6.14 Section D IRI Distribution .................................................................150
Figure 6.15 Example Longitudinal Profiles Collected on Section C to Show Repaired Slab .................................................................151
Figure 6.16 Joints Causing Irregularities in Section Cs Longitudinal Profiles ....152
Figure A.1 Shows the aerial view of the weigh station with the considered installation locations labeled and the slab that was selected for the installation........................................................................................................173
Figure A.2 shows the locations that were selected to monitor in the preliminary test section ........................................................................................................174
Figure A.3 shows the depths that the thermocouples were placed into the Concrete slab........................................................................................................176
Figure A.4 shows the shoulder after the grass was removed ................................178
Figure A.5 shows the hole that was dug so that the irrigation box could be below the ground surface ........................................................................................................179
Figure A.6 shows the trench that was dug to hold the protective pipe .............180
Figure A.7 shows the schematics of the slab to illustrate where the grooves were cut into the slab .................................................................182

Figure A.8 shows the groove that is closest to the joint being cut with the grinder ....................................................................................183

Figure A.9 shows the schematic of the slab to illustrate where the holes were drilled ..............................................................................184

Figure A.10 shows the dowel rod that was used to measure the depth of the holes that were drilled ................................................................185

Figure A.11 shows one of the holes being drilled with the hammer drill ..........186

Figure A.12 shows the letter locations and number depths used when labeling the thermocouples ...............................................................187

Figure A.13 shows one of the labeled thermocouples ..................................188

Figure A.14 shows the 1/8 inch holes being drilled into one of the electrical boxes .........................................................................................189

Figure A.15 shows one of the holes being drilled into the irrigation box ..........190

Figure A.16 shows the housings after some of the thermocouples were run through them .................................................................191

Figure A.17 shows the 10 foot protective pipe with the twine and the thermocouples ran through it .............................................................192

Figure A.18 shows the pipe at different stages as the thermocouples were ran through it .................................................................194

Figure A.19 shows the depths being measured and marked onto the thermocouples ..............................................................................195

Figure A.20 shows the thermocouples being bundled and inserted into the slab ....197

Figure A.21 shows one of the holes being filled with the concrete anchoring adhesive ..............................................................................198

Figure A.22 shows the different parts of the groove filling process ...............200

Figure A.23 shows the thermocouples after they were coiled in the electrical box and the holes after they were filled with the silicone ....202

Figure A.24 shows the shoulder during and after the soil replacement ..........204
Figure A.25 shows one of the data loggers being set up and shows one of the three labeled data loggers.................................................................205

Figure A.26 shows the data loggers as they are being placed into their protective housings ........................................................................208

Figure A.27 shows the site after the thermocouples were installed................208

Figure B.1 shows the LcmsRoadInspect software when opened using the two options that were described in this procedure.................................216

Figure B.2 the location of the start button that will begin the longitudinal profile processing by prompting the use to select the desired starting and ending files...............................................................................................217

Figure B.3 shows the window that allows the user to define the starting and ending files to be processed for the longitudinal profiles ......................218

Figure B.4 shows the location where the status of the processing is reported........219

Figure B.5 shows the IRI results that were generated from the longitudinal profiles that were created ........................................................................220

Figure B.6 shows a schematic of how the faulting is calculated in the LcmsRoadInspect software .....................................................................223

Figure B.7 shows the parameters that are used by the software to calculate the faulting ................................................................................224

Figure B.8 shows the configuration file as it is being edited, the faulting parameters are highlighted in blue.................................................................225

Figure B.9 shows the LcmsRoadInspect software window and the locations of the key components that are used to process the data. .........................227

Figure B.10 shows the qualitative results in the LcmsRoadInspect software, it also indicates some of the features that are used to view the results .................................................................228

Figure B.11 shows the Save Analysis Results window that allows the user to save the particular results that they want to use for further analysis.................................................................230

Figure B.12 shows where the file length and distance values are located in the LcmsRoadInspect software window ..................................................231
Figure B.13 shows the multiple road section analysis parameters window that allows the user to adjust the processing that the software will perform and the results that will be saved. .........................................................232

Figure B.14 shows the intensity and range images overlaid with the faulting results ......................................................................................................................234

Figure B.15 shows the faulting values being extracted from the XML files 236

Figure B.16 shows the faulting and temperature versus time plots generated in the faulting analysis. .................................................................237

Figure B.17 shows where the values used to calculate the starting point on the profile are located in the software window .............................................239

Figure B.18 shows the window that pops up and allows the user to input the parameters for generating the corrected longitudinal profiles .................240

Figure B.19 shows the ProVAL user interface and the location of the report button that is used to reproduce the profile data into other file formats. .................................................................242

Figure B.20 shows and example profile that was plotted using Excel .........................243

Figure B.21 Curvature Analysis Flow .........................................................................................245

Figure B.22 shows a screenshot of the files that must be present in the folder in order for the convertor to function.................................................................246

Figure B.23 shows the contents of the test.bat file as it is being edited .........................247

Figure B.24 shows the files that are created by the convertor when it is run ..................248

Figure B.25 shows where to position the mouse pointer and where the x values are displayed so that the center point of the slab can be located ...............249

Figure B.26 shows where the user has to click to determine the profile numbers and where they are displayed in the software .............................................252

Figure B.27 shows how the starting point of the longitudinal profile is found ...............254

Figure B.28 shows where to position the mouse and where the X values will be displayed when trying to locate the ends of the center transverse profiles .........................................................................................255

Figure B.29 shows where to find the filename in the LcmsRoadInspect software.......257
Figure B.30 shows the code where the file names are located and what it should look like when the slab is contained in two files ...............................259

Figure B.31 shows the center profiles being extracted from the main MATLAB window..................................................................................261

Figure B.32 shows an original profile and a shifted profile that had spikes on the beginning and end of the profile .........................................................264

Figure B.33 shows an example profile that contained an invalid point that needs to be removed..................................................................................266

Figure B.34 shows an example profile that had to be adjusted due to the elevation difference between the two sensors ..........................................................267

Figure B.35 shows one of the slab profiles that were generated from the raw 3D Line Laser data with the trend line, original corrected profile and the profile after the built in curvature was removed ..........................................................269

Figure B.36 shows the code where the IMU data is read and wrote into a matrix.........271

Figure B.37 shows the Temp Monitor_S2 after the temperature data was downloaded ..............................................................................................272

Figure C.1 Weigh Station Typical Section ......................................................................276
Figure C.2 Close up View of Each Lane Typical Station ................................................278
Figure C.3 Weigh Station Grade Profile Westbound Lanes ............................................279
Figure C.4 Weigh Station Grade Profile Eastbound Lanes .............................................280
Figure D.1 Aerial View of Weigh Station ..............................................................284
Figure D.2 Thermocouple Positions in Test Slab ..........................................................286
Figure D.3 Thermocouple Depths in the Test Slab..........................................................287
Figure D.4 Temperature Variations between Slab Positions ...........................................289
Figure D.5 Daily Thermal Data Example ........................................................................291
Figure D.6 3D Line Laser Faulting Parameters ...............................................................296
Figure D.7 Weigh Station IRI ..........................................................................................301
Figure D.8 Weigh Station Slab 1 Longitudinal Profile..................................................304
Figure D.9 Weigh Station Slab 1 Curvature .................................................................305

Figure D.10 Quantitative Transverse Curvatures .........................................................308
SUMMARY

Jointed Plain Concrete Pavements (JPCP) are some of the most popular forms of concrete pavement that are used in the state of Georgia. Each year the Georgia Department of Transportation (GDOT) inspects and surveys their highways to determine what condition the pavement is in and if any rehabilitation is required to maintain the integrity of the highway. These annual surveys include the JPCP and the key concrete pavement characteristics that are used to determine the condition of the JPCP are the faulting at the joints and the roughness of the section. Since it is well known that concrete will exhibit slight movement when subjected to thermal variations it is possible that these minor movements could have an impact on the measured slab properties used to rate the JPCP section. The focus of this research is to develop a methodology to use three dimensional technologies to capture JPCP surface data under a variety of thermal conditions, to develop a procedure to collect and analyze concrete temperature data, to develop a method to analyze the surface data and how to correlate all of the data that was collected. Three test sites were chosen that covered a total of 6 test sections that were composed of 25 slabs and 26 joints each. This provided a total of 150 slabs and 156 joints that were used for analysis.

A single slab was selected as a test specimen to install thermal logging devices into so that the temperature distributions through the slab could be investigated. Three positions were monitored to determine if the position that the temperature gradient was measured was critical. It was found that the temperature followed a similar trend for all of the positions with the profiles being slightly shifted from each other. It was also
concluded that the temperature in the bottom of the slab was approximately the same as the temperature in the base. It was discovered that the maximum positive temperature gradient occurred simultaneously with the maximum ambient air temperature and the maximum surface temperature. The results showed that the surface temperature followed a trend similar to the ambient air temperature. However the surface temperature was greater throughout the day.

The faulting analysis results indicated that out of the 156 joints inspected only 15 showed a variation in the average faulting that was greater than the 0.5 mm (0.02 in) accuracy of the sensors used to collect the JPCP surface data. Further investigation revealed that there was no clear trend between the temperature change and the average faulting variation. It was concluded that if there was a change in the average faulting due to temperature it is smaller than what can be depicted by the sensing vehicle and it is less than the 1 mm (0.04 in) measurement accuracy that is specified in the American Association of State Highway and Transportation Officials (AASHTO) R36-04 specification which governs the accuracy requirements for automated faulting measurement methods.

The International Roughness Index (IRI) was the method used to measure the roughness on each test site for each data collection run. This resulted in 336 IRI values that were inspected to determine whether there was an impact from the temperature variations. The IRI results showed that the roughness of the test sections did vary through the day. After it was found that the IRI did vary through the day the IRI distributions were compared to the temperature distribution and 7 out of the 12 distributions studied showed a weak correlation between the temperature and the IRI.
The amount of variation in the IRI was not quantified because the exact accuracy of the IRI values attained from the sensing vehicle was unknown. However it was attempted to validate the system and determine the accuracy but one of the validation test sections showed disappointing results while the other two showed promising results. Further research is required to fully evaluate the sensing vehicles ability and accuracy when measuring the IRI.

A procedure was also developed to extract the longitudinal and transverse curvature of the concrete pavement slabs. Three test slabs were selected at one of the test sites and curvature results were generated using the developed procedure. The curvature results were visually and quantitatively assessed. The visual analysis indicated that the curvature profiles measured by the 3D line lasers did change throughout the data collection, but the patterns did not follow what was expected and a correlation could not be created with the temperature. The quantitative results for the longitudinal curvature revealed that one of the slabs did show a pattern that followed the temperature changes during the data collection, but it did show as much as 4.65 mm (0.183 in) of change between consecutive data collection runs. The longitudinal curvature results for the other two slabs did not show a trend and exhibited unlikely changes in the curvature measured between consecutive data collection runs, which in some instances the deviation was as much as 12.09 mm (0.480 in). For the transverse curvature one of the slabs indicated that the curvature did not change during the data collection, while the other two showed sudden changes as high as 2.16 mm (0.085 in) between consecutive data collection runs. The developed procedure is only preliminary and needs to be further evaluated and refined for it to be able to adequately measure the curvature of as slab. The results also
need to be verified using actual measured ground truth curvatures to determine the validity of using the developed procedure and the 3D line laser data to measure the curvature of concrete slabs. Once the procedure is proven to produce reliable results it should be compared to other curvature computation methods, such as those that utilize road profilers or LIDARs, to determine which method is the best.
CHAPTER 1

INTRODUCTION

Currently the Georgia highway and state route systems consist of 500 miles of concrete pavement that is maintained by the Georgia Department of Transportation (GDOT), which is mostly composed of jointed plain concrete pavement (JPCP) (Tsai, Wu, and Wang, 2012). In order to maintain the concrete pavement and ensure that it remains functional, it is routinely inspected. Since 1971 GDOT has performed annual surveys to determine the condition of their pavements (GDOT, 1993). During these surveys there are many defects that are examined and they include faulting, longitudinal and transverse cracking, broken or replaced slabs, joint defects and shoulder distress. Of these defects faulting is one of the key distress types for JPCP that needs to be evaluated (Nazef, et al. 2009). Faulting is the differential vertical displacement of the slab edge across a transverse joint or crack (Jung et al. 2008). The possible causes of faulting include inadequate load transfer, differential deflection at the joint, inadequate base support, and sub base erosion (Tsai, et al., 2010). It is important to measure the faulting because it can lead to more severe distress such as corner breaks and blowups, it can accelerate vehicle damage, and it can decrease the ride quality (Tsai, et al., 2012).

Another concrete pavement characteristic that can decrease the ride quality or smoothness is the curvature of the slab caused by curling and warping (Nazef, et al. 2009). Curling and warping are the vertical deflections in slabs caused by moisture content differences and temperature differences (Suprenant, 2002). Studies have been performed to determine how to measure the curvature of the slabs and how it can impact
the ride quality. However these studies are limited and have not evaluated the impact that the curvature of the slab has on the faulting of the joints. Since the curvature and faulting both have a major impact on the smoothness it is important to assess how these characteristics affect each other. Therefore this study is to explore the feasibility of studying concrete pavement smoothness, curvature and faulting using three dimensional line laser imaging technology.

1.1 Study Objectives

The purpose of this study is to develop a methodology for studying concrete pavement behavior using three dimensional line laser imaging technology. This methodology would include procedures for collecting and interpreting thermal data, collecting three dimensional range data and how to process it to generate the required results. Once the procedure is completed then three dimensional range data and thermal data will be collected on three test sites. Then this data will be used along with the proposed methodology to conduct case studies to explore the feasibility of using the three dimensional line laser imaging technology to evaluate the concrete pavement smoothness, curvature and faulting.

1.2 Study Tasks

To accomplish the objectives of this study there are several task that need to be carried out. The first is to create a methodology for studying concrete pavement behavior using three dimensional line laser imaging technology and thermal logging devices. The second task is to perform an initial case study at the weigh station on I-16 near Savannah,
Georgia to test the procedure and get preliminary results to see how concrete pavement behaves in a controlled environment. The third task is to execute another case study on I-16 near Savannah, Georgia to extend the weigh station study and see how the procedure functions when implemented on an in service JPCP and how the in service concrete pavement behaves. The fourth and final task of the study is to select a test site on a newly constructed section of I-16 near Dublin, Georgia and on older sections, originally constructed in the 1970’s, surrounding the new section to study the concrete behavior of different pavement designs.

1.3 Report Organization

This report is organized into seven chapters. Chapter 1 identifies the research need and introduces the objectives and tasks of the study. Chapter 2 summarizes previous research that has studied concrete pavement behavior. Chapter 3 presents the sensing vehicle used to collect the three dimensional range data, the devices used to collect the concrete pavement temperature data and how the data was used to produce the desired results for the study. Chapter 4 describes the case study that was performed on the weigh station off of I-16 near Savannah to determine the feasibility of using the three dimensional laser imaging technology to study the behavior using the proposed methodology in a controlled environment. Chapter 5 presents the case study that was executed on an in service JPCP section on I-16 near Savannah just past the weigh station. Chapter 6 summarizes the case study that was completed on I-16 near Dublin, which compares the concrete behavior of newly constructed pavement to the original pavements that have been in service since the 1970’s. Finally, Chapter 7 concludes the findings.
from this study and discusses the suggestions for future research to further investigate concrete pavement behavior.
CHAPTER 2

LITERATURE REVIEW

Concrete pavement surveys are performed annually, or every other year depending on the specification that is used, on most concrete pavement sections by the agency responsible for maintaining the pavement. Many of the characteristics that are used to determine the condition of the pavement section require the evaluator to enter into the traffic lane and manually measure the defect. Therefore, the surveys are dangerous, labor intensive, time consuming and costly (Tsai, et al. 2010).

During these manual surveys the governing highway agencies are obligated to measure the faulting of the joints and cracks in order to meet the requirements of the new Highway Performance Monitoring System (HPMS) (FHWA, 2008). The need for an improved survey method and the need for a better understanding of concrete pavement have led to several research projects that evaluate the behavior of concrete pavements. This chapter reviews current survey practices used to measure faulting and some of the research that has been performed to enhance the survey process. This chapter will also explore the investigations that have evaluated the curvature of concrete pavement and how it impacts the smoothness of the pavement. In addition, this chapter will address the challenges and remaining research that is needed to overcome the shortcomings of the current research.

2.1 Faulting Survey Practice
This section will summarize the current manual methods used to evaluate faulting. The faulting measuring and reporting method defined in the Long Term Pavement
Performance (LTPP) Distress Identification Manual and the American Association of State Highway and Transportation Officials (AASHTO) Standard Practice for Evaluating Faulting of Concrete Pavements are the recommended procedures to follow, so they are summarized in this section (FHWA 2013). Since this study focuses on concrete pavement sections that are in Georgia, the GDOT practice will also be described.

2.1.1 AASHTO R 36-04 Standard Practice for Evaluating Faulting of Concrete Pavements

The AASHTO R 36-04 Standard Practice for Evaluating Faulting of Concrete Pavements is a protocol that standardizes the procedures for estimating and summarizing faulting on concrete pavement surfaces (ASSHTO, 2009). This protocol does not specify a particular type of equipment or instrument, although it does stipulate an accuracy requirement that must be met. It is stipulated that the faulting should be calculated to the nearest 1 mm (0.04 in) using the formula $F = D_1 - D_2$. Where $F$ is the absolute value of the faulting and $D_1$ and $D_2$ are the heights measured on each side of the joint. The faulting should be measured in the outside wheel path and summarized for every 0.1 km (0.062 miles). The protocol gives details to follow whether performing faulting measurement with an automated or manual method to measure the faulting.

2.1.1.1 AASHTO R 36-04 Requirements for Automated Faulting Measurement

When performing an automated survey the heights used to calculate the faulting should be taken between 75 mm (3 in) and 225 mm (8.8 in) from the joint and should be separated by 300 mm (11.8 in). These heights should then be substituted into the equation in section 2.1.1. Figure 2.1 shows a schematic of the points that should be used...
to measure the faulting when using an automated procedure. The faulting should be measured for every joint and used when reporting the aggregated survey results (AASHTO, 2009).

2.1.1.2 AASHTO R 36-04 Requirements for Manual Faulting Measurement

When performing a manual survey at least ten percent of the transverse joints or transverse cracks should be measured. The sampling rate should be uniformly spaced through the project. All of the faulting measurements that are taken should be recorded along with the location at which they were measured (AASHTO, 2009).

2.1.2 Faulting Practice in LTPP Distress Identification Manual

The LTPP Distress Identification Manual is a guide that was developed to provide a consistent and uniform basis for collecting pavement distress data for the LTPP program (FHWA, 2003). The method described is a manual survey process. The faulting should be reported to the nearest mm and should be measured at 0.3 m (0.984 ft)
and 0.75 m (2.46 ft) from the outside slab edge, which is approximately the outer wheel path. For each point three faulting measurements should be taken. These three values should then be averaged so that each transverse joint and crack has a single value to represent the faulting.

The device that is specified to measure the faulting is an FHWA-modified Georgia Faultmeter. The sign of the readings should also be reported to indicate the orientation of the faulting. A positive value indicates that the approach slab is higher than the departure slab. A negative value designates the opposite which is that the departure slab is higher than the approach slab (FHWA, 2003).

In some cases an abnormality such as patching, spalling, and corner breaks may prevent the surveyor from being able to measure the faulting at the specified location. If this is encountered then the measurements should be taken at an offset from the specified location. This offset should not exceed 0.3 m (0.984 ft) from the original location. If the faulting measurement is unattainable due to this offset requirement then a “Null” value should be used to report the faulting for this joint. The starting point for the survey should also be precisely identified and the location of the faulting measurements should be measured and recorded with an accuracy of less than 0.5 m (1.64 ft) (FHWA, 2003).

### 2.1.3 GDOT Faulting Practice

The GDOT faulting survey practice is similar to the method defined in the LTPP program. It is a manual survey where the faulting is measured on every eighth joint. The Georgia Faultmeter is used to measure the faulting. The main difference between the faultmeter used by GDOT and the faultmeter used in the LTPP program is the units of the
faulting values. The Georgia faultmeter measures the faulting to the nearest thirty second of an inch (0.794 mm). The location that the faulting measurement is taken is also different. The GDOT procedure requires that the faulting measurement be taken 6 inches (152.4 mm) inside the white line (GDOT, 1993).

2.2 Automated Faulting Survey Methods

Many agencies use faultmeters to manually collect faulting data. Attempts have been made to try and improve the process, especially since faulting is now a required performance indicator under the HPMS (FHWA, 2013), and current methods are not efficient nor or they safe. Few of these attempts have been successful and the agencies that do use them do not have confidence in the data they attain from them (Nazef, 2009). This section will explore some of the research efforts that have been taken to improve the faulting measurement process.

2.2.1 FDOT Semi-Automated Approach

In 2009 the Florida Department of Transportation (FDOT) performed a research project that suggested using a high speed inertial profiler (HSIP) to measure faulting. The study was entitled *A Semi-Automated Faulting Measurement Approach Using High Speed Inertial Profiler Data* and was summarized in the Transportation Research Record: Journal of the Transportation Research Board 2094.

This study starts by summarizing the current difficulties of current faulting measurement method that utilize profiler data. These methods are typically developed by the profiler manufacturer and estimate the faulting based on a predetermined distance
interval and by specifying a minimum faulting threshold value. The ability of these profilers to capture the faulting depends on the sampling interval used by the profiler. Even if a sampling interval less than an inch is used some joints may still be undetected when the profiles are analyzed. Since most agencies use distance measuring instruments to trigger the profiler there is a chance that they do not possess the ability to attain a sampling rate less than an inch. Since the sampling interval is larger then the amount of joints undetected would also be greater. One technique that has been used to address this is to collect multiple runs with the profiler and analyze them, but the process becomes more costly and time consuming. So there is a need to detect and measure faulting using a single run of profiler data.

2.2.2.1 FDOT Semi-Automated Approach Study Objectives

The objectives of this study are to address this need and include the development of an algorithm that can detect the presence and location of transverse joints. The second objective is to estimate the faulting of the joints that are detected by the algorithm using two approaches. The first of which is estimate the faulting using the guidelines stipulated in the AASHTO R36-04 standard for automated faulting measurement. The second approach is to use the profiler data to mimic the measurements that were taken using a faultmeter.

2.2.2.2 FDOT Semi-Automated Approach Study Test Equipment

In order to accomplish the objectives of this study several devices were used to collect data and to assist in the data collection. The three key devices that were used
include the Georgia Faultmeter, a joint marking template, and a multipurpose survey vehicle (Nazef, et al., 2009).

The Georgia Faultmeter used was capable of measuring the faulting to the nearest 0.1 mm (0.004 inches). The faultmeter data was collected at several locations on the joints and served as the faulting ground truths that the profiler faulting values was compared to. The joint marking template was a device that had a flat plate with 9 slots cut into it, to indicate where the faulting needed to be measured. This plate was attached to an arm that kept the slots a set distance from the pavement marking. This template was used to mark every joint so that the profiler faulting measurement locations could be matched to the faultmeter faulting measurement locations (Nazef, et al., 2009).

The FDOT survey vehicle is equipped with three HSIPs, a forward view camera, the INO Laser Road Imaging System (LRIS), the Laser Rut Measuring System (LRMS) and a differential Global Positioning System-enabled position and orientation system. For this study the HSIP on the front of the vehicle in the right wheel path is used to generate the longitudinal profiles. This profiler is a 32 KHz Selcom 5000 laser height sensor that is equipped with an accelerometer to compensate for the vertical motion of the vehicle (Nazef, et al., 2009). These longitudinal profiles are analyzed using to detect the joints and to calculate the faulting. The pavement images from the LRIS were used to align the profiler path with the faultmeter measurement locations. To align the images to the faultmeter measurement locations the offset between the profiler and the left edge of the right image was found and this offset was used as a constant.
2.2.2.3 FDOT Semi-Automated Approach Data Collection

To perform this study a test site was selected that was 2000 feet (609.6 m) long. The typical slab design at the site was 20 feet (6.1 m) long by 12 feet (3.7 m) wide. Multiple runs of data were collected at different sampling intervals while traveling at 45 mph (72 km/h). The sampling rates that were analyzed were Rate 1 (0.6812 in. or 1.73 cm), Rate 2 (1.3624 in. or 3.46 cm), Rate 3 (2.0436 in or 5.2 cm) and Rate 9 (6.1308 in or 15.6 cm). The test section was collected using Rates 1 and 2 five times and was collected using Rates 3 and 9 ten times (Nazef, et al., 2009).

2.2.2.4 FDOT Joint Detection Algorithm Development and Implementation

An algorithm was developed that analyzed the profiles to detect the joints. The joints were located by searching the profiles for peaks and valleys. Once the valleys were identified they were checked again to see if they were outside of a specified range. The specified range was called the sensitivity factor and is a variable that has a direct impact on the joints that are detected. Increasing this value decreases the amount of joints that are detected and decreasing the value increases the amount of joints that are detected. The valleys that were outside of this range were taken as the joints. The sensitivity value was adjusted for each profile until the best joint detection results were achieved. The profiles collected using Rate 1 produced a 93% to 97% joint detection rate, Rate 2 produced a 64% to 74% joint detection rate, Rate 3 produced a 58% to 66% joint detection rate, and Rate 9 produced a 34% to 38% joint detection rate (Nazef, et al., 2009).
2.2.2.5 FDOT Faulting Estimation using HSIP Data

The LRIS images were reviewed and the mark that the profiler path crossed was noted. Then the faulting value that was measured for that mark using the faultmeter was set as the ground truth for each joint in each run. The algorithm then estimated the faulting of the detected joints using the two methods. The method based on the AASHTO R36-04 standard and used the specified 3 in to 8 in (75 mm to 225 mm) spacing from the joint when estimating the faulting. All of the profile points in this range were used and the average difference in elevation was used as the faulting for that joint. The amount of points used did vary depending on the sampling rate that was used. The second method designed to mimic the faultmeter measurement uses two points, one on each side of the joint, to estimate the faulting. These two points are spaced 4.5 in. (11.4 cm) from the joint and the elevation difference between the two is the faulting value for the joint. The average error of the faulting values estimated using the profiler data when compared to the ground truths collected using the faultmeter ranged from 0.049 in (1.24 mm) to 0.058 in (1.47 mm) (Nazef, et al., 2009).

2.2.2.6 FDOT Semi-Automated Approach Study Conclusions

The conclusions that are drawn from this study are that the sampling interval Rate 1 can be used to detect and measure the faulting at a more detailed level than any other sampling interval. The sampling intervals Rate 2 and 3 do not provide very detailed information but may be sufficient when performing network level surveys. It was also concluded that Rate 9 was not an acceptable sampling interval because most of the joints were missed and the 6.1308 in (15.6 cm) spacing was greater than the maximum spacing
of 11.8 in (300 mm) specified in the AASHTO R36-04 standard. The study found that the faulting estimated by the profiler was greater than the required 0.04 in (1 mm) accuracy required in the AASHTO R36-04 standard (Nazef, et al., 2009).

2.2.2.7 FDOT Study Discussion

Although the semi-automated approach suggested in this research is an improvement over manual surveys there are several technical challenges that need to be addressed. The first challenge is that the joint detection is dependent upon a parameter and the sampling interval which cause joint to be undetected or falsely identified. Another challenge is the alignment of the image data with the profiler data. The method used in this study assumed that the vehicle would remain parallel to the driving direction from the instance that the profiler passed the joint until the instance that the image is taken. This is a challenge because there is a high probability that the vehicle would not remain parallel due to vehicle wandering. The final challenge is the limited amount of data that is collected by the profiler. Since the concrete condition surveys require more than faulting data to be collected, multiple site visits may be necessary in order to gather all of the required information for the survey. This thesis will focus on improving the concrete condition survey process and to provide more detailed information using three dimensional laser technologies.

2.3 Temperatures Affect on Curling

Before determining if there were an impact on the concrete pavement faulting and IRI it needed to be verified that there was movement in the slabs caused by temperature
variations. The verification of the slab movement would support the assumptions that the IRI and faulting could also change with temperature. To authenticate that the slabs do move due to thermal changes through the depth of the slab several studies were reviewed. This section summarizes one of the studies that evaluated slab movement due to temperature variations.

2.3.1 Kansas Study

One study that explored this affect was performed in Kansas and was entitled “Temperature and Curling Measurements on Concrete Pavement”. It started by researching previous studies that looked into the distribution of the temperature through the depth of the slab. This study started with the linear distribution assumed by Westergaard in the 1920’s, it included the studies that found that the temperature distribution through the depth were nonlinear, and ended with some of the methods that had been developed at the time of the study to estimate the nonlinear temperature distributions in the slab. The studies that had evaluated built in curvature were also reviewed. Then a test section was selected and temperature and curling data was collected and analyzed. A finite element model of the slab was created and subjected to thermal stresses to see how the slab should behave. The computerized behavior was compared to the actual observed behavior to see how well the computer could estimate the affects of the temperature variations. And finally the findings of the research were concluded (Siddique, et al. 2005).
2.3.1.1 Data Collection

The thermal information at the Kansas test section was logged using iButtons. The iButtons were placed at five different depths through the depth of the slab. The slab that the sensors were installed into was 12 in (304.8 mm) and the sensors were inserted on the slab surface, 3 in. (76.2 mm), 6 in. (152.4 mm), 9 in. (228.6 mm) from the top of the slab and the fifth sensor was placed at the bottom surface. The position that the sensors were located on the slab was 3 ft (0.914 m) from right edge of the slab, which is approximately in the right wheel path. The temperature data was logged at a 10 minute interval and used to determine that the temperature variation in the slab was not linear and the temperature fluctuated much more at the slabs surface than at the bottom (Siddique, et al. 2005). Figure 2.2 shows the thermal data that was collected during the study performed in Kansas.

Figure 2.2 Kansas Study Thermal Data (Siddique, et al. 2005)
The curvature of the slabs was measured using extensometers that were suspended over the middle of the slabs. Random slabs were selected throughout the test site during each data collection. The movement of the slabs was monitored on 5 different days between August and November, all of the movement was measured during the day and none were measured at night. The extensometers were always centered over the length of the slab and were positioned in the left wheel path, the right wheel path, and at the center of the width of the slab (Siddique, et al. 2005). Figure 2.3 shows how the extensometers were set up over the slab to record the movement of the slabs.

![Extensometer Diagram](image)

**Figure 2.3 Kansas Study Extensometer Set Up** (Siddique, et al. 2005)

### 2.3.1.2 Data Analysis

For all of the data collections the slab deflections were compared through the day and it was found that the slabs do move. The August data revealed that in the morning the slabs were curled up and as the temperature differential increased, moving from a negative gradient (bottom temperature greater than the top temperature) to a positive gradient (top temperature greater than the bottom temperature), the slabs shape gradually changed into a curled down shape. They also indicated that the maximum slab movement occurred at the same time as the maximum temperature occurred. It was also found that as the temperature differential magnitude decreases through the seasons so
does the slab movement (Siddique, et al. 2005). Figure 2.4 shows the curvature measurements that were taken during data collection and the corresponding temperature gradient that was derived from the thermal data that was collected.

(a) Curling Measured in Kansas Study

(b) Thermal Gradients in Kansas Study

Figure 2.4 Curling and Thermal Gradients Recorded in Kansas Study (Siddique, et al. 2005)
2.3.1.3 Finite Element Modeling

Finite element modeling was used to create computer models of the slabs that were analyzed in the field. These computerized models were then subjected to simulated thermal stresses to determine if the actual slab movements could be estimated using the model. The computerized results were compared to the actual measurements taken during the data collections and it was found that the computerized results showed the same trend as the actual results but the results were slightly lower in the simulated analysis. It also showed that the simulated models deviated from the actual results more as the temperature differential increased (Siddique, et al. 2005).

2.3.1.4 Kansas Study Discussion

The Kansas study was evaluated to verify that concrete pavement movement could be correlated to the temperature variation through the depth of the slab. The data that was collected and analyzed under this research showed sufficient evidence that the slabs move and there is a trend that can be correlated to the temperature changes. It was found that the maximum slab movement did occur with the maximum temperature differential. With sufficient evidence that the concrete pavement moves with the temperature it is necessary to investigate how these movements impact the other concrete pavement characteristics.

2.4 Slab Curvature Impact on Smoothness

The smoothness of a pavement section is typically measured using the International Roughness Index (IRI). Although faulting does have an impact on the IRI it
is not the only surface characteristic that does. The curvature of the slab caused by
curling and warping can also have a significant impact on the IRI. Several studies have
been conducted to study how the curvature affects the IRI and to determine how
substantial the influence is. This section presents some of the studies that have assessed
this phenomenon.

2.4.1 SCDOT Evaluation of Slab Curling on IRI

In 2010 the South Carolina Department of Transportation (SCDOT) and the
Federal Highway Administration (FHWA) performed an investigation to evaluate the
impact that the slab curling has on the concrete pavements in their state. The study was
entitled *Evaluating the Effect of Slab Curling on IRI for South Carolina Concrete
Pavements*.

In South Carolina and many other states the IRI value of a new concrete pavement
section is used to establish the pay factor or quality of the construction. Therefore the IRI
has an impact on the amount that contractors are paid and if they have to perform extra
work to bring the new pavement section to a condition that meets the IRI requirements.
This study is addressing this need to determine if the time or environmental conditions
during the data collection for the IRI evaluation can have a significant impact on the IRI
results and if it can be practically estimated so that surveys can be adjusted to take this
effect into consideration (Johnson, et al, 2010).
2.4.1.1 SCDOT Study Purpose

This study started by doing a literature review of the previous studies that have investigated the effect of slab curvature on the IRI. These studies found that the IRI could change significantly during the day especially in the first 12 months after construction and that the change in IRI was highly correlated to the pavement temperature. This review led to the main purpose of the study which was to measure the amount of curling on recently constructed concrete pavements and to evaluate the effect of both seasonal and daily changes in slab curling on the IRI measurements. A secondary purpose of the study was to do a comparison of different methods to measure the curling of the slab using digital indicators on the pavement surface, a terrestrial laser scanner, and a high speed inertial profiler (HSIP) (Johnson, et al, 2010).

2.4.1.2 SCDOT Study Equipment

The devices that were utilized to collect the data to achieve the goals of this study were digital indicators, a terrestrial laser scanner, an HSIP and temperature logging devices. The digital indicators were capable of detecting small changes in the slab elevation ranging from 0.0001 inches (0.00254 mm) to 1 inch (25.4 mm). These were suspended over the right wheel path using signpost cantilevered out from the shoulder so that the slab movement did not impact the supports holding the indicators. Three to five of these were placed on a single slab so the curvature could be estimated by stitching the readings together (Johnson, et al, 2010).

The terrestrial laser scanner that was used in the study was a Leica ScanStation II. This scanner is capable of collecting 50,000 points per second (Leica Geosystems,
2013). This point information is produced into a point cloud that is used to produce a three dimensional model of what is scanned by the scanner. These point clouds were used to obtain a three dimensional profile of the concrete pavement and were used to estimate the curvature of the slab (Johnson, et al, 2010).

The concrete slabs were also scanned using an HSIP. The model of the HSIP used in this study was a Dynatest 5051 Mark 3. This sensor was used to collect the longitudinal profiles of the slabs and this data was then used to calculate the IRI and to estimate the slab curvature. The slab temperature was also measured during the data collections using temperature probes connected to thermal data loggers to store the data and using infrared thermometers. The temperature probes were embedded into the bottom of the slabs by drilling holes in the slabs. The infrared thermometer was used to measure the temperature of pavement surface (Johnson, et al, 2010).

2.4.1.3 SCDOT Study Data Collection

Two test sites were selected for data collection for this study one was on I-520 westbound and the second was on I-385. Both of these projects were newly constructed pavements the I-520 section was 12 months old and the I-385 section was 2 months old. Neither test section had been opened to traffic at the time the initial 24 hour data collections were performed at the sites (Johnson, et al, 2010).

The I-520 initial data collection was performed on December 3-4, 2009. The digital indicator readings, the terrestrial laser scanner data, HSIP data, and slab temperature data was collected every two hours starting at 1 PM for a selected slab. Three digital indicator readings were taken for the selected slab and then they were
removed so that the HSIP data could be collected. The terrestrial laser scanner was set up in the median across from the test slab and it was set to collect a point density of 1 inch (25.4 mm) at 250 feet (76.2 m). After the digital indicators were removed the selected slab was collected using the HSIP. The HSIP was operated at 45 mph (72 km/h) and used a data collection rate of 1 inch (25.4 mm). Only one run of HSIP data was collected, but it did span a full mile (1.60934 km) of the test site. A steel plate was attached in the test section so that the test slab could be identified within the data. The pavement temperature was also measured using the temperature probes and data logger. Three probes were inserted in the slab one at 2 inches (50.8 mm) deep, another at 5 inches (127 mm), a third at 11 inches (279.4 mm), and a fourth was placed on the slab surface. All of the data was collected at approximately the same time so that it could all be synchronized and compared. Follow up data collections were performed on this test section in the spring and summer. During these data collections only the HSIP data was collected. Three runs were taken every hour on a 0.6 mile (0.9656 km) test section from the morning until the early afternoon (Johnson, et al, 2010).

The I-385 initial data collection was performed on June 17-18, 2010. The same sensors were used to collect the data at the I-385 test site as the I-520, although they were set up slightly different. Five digital indicators were used and set up in the right wheel path of the test slab. These were linked to a computer and readings were automatically recorded every minute. The laser scanner was set up on the outside shoulder and scanned the inside passing lane beside the slab being monitored by the digital indicators. The laser scanner recorded data using a 3 inch (76.2 mm) point density at 250 feet (76.2 m). The HSIP was run on the same lane as the laser scanner and collected a 0.2 mile (0.3219
km) section. Five runs of the profiler data were collected at 45 mph (76.2 km/h) using a measurement interval of 1 inch (25.4 mm). For this section the right wheel path had been diamond ground and the left had not so both wheel paths were collect using the HSIP for comparison. Both the laser scanner and the HSIP data were collected simultaneously. The pavement temperature data was also collected using the data logger and probes at 2 inches (50.8 mm) deep, 5 inches (127 mm) deep, and 9 inches (228.6 mm). The thermal data was recorded every 5 minutes. During this data collection a rain storm interrupted the laser scanner and HSIP data collections, but caused problems with the digital indicators and stopped them from recording data (Johnson, et al, 2010).

2.4.1.4 SCDOT Digital Indicator Results

The digital indicator from I-520 was plotted to determine if the slab is moving and to determine what time periods the movement was the greatest. The temperature that was logged was also plotted on the same plot so that the changes in the digital indicators could be correlated to the changes in temperature. It was found that the curling activity increased in the morning when the temperature begins to increase and there was little movement during the afternoon and at night. The results also showed that the slab movement of all of the locations followed the same trend (Johnson, et al, 2010). Figure 2.5 shows the digital indicator data that measured the slab movement through the data collection along with the thermal data that was logged.
The digital indicator data from the I-385 data collection also showed that the different locations on the slab followed a similar trend as they all moved up and down together. These results showed that the slabs movement settled down as the temperature data from various depths in the slab begins to converge. This indicates that the temperature variation is the cause of the slab curling. Figure 2.6 shows the measured slab movement and thermal data from the I-385 test section in the SCDOT study.
These readings were also plotted to generate slab profiles. The profiles show that the slab elevation increases at all locations in afternoon before 5 PM and decrease after that. These profiles also did not exhibit a clear convex or concave shape which is what was expected (Johnson, et al, 2010). Figure 2.7 shows the slab profiles that were generated from the digital indicator readings.
2.4.1.5 SCDOT Terrestrial Laser Scanner Results

The terrestrial laser scanner data was filtered and plotted to show the three-dimensional view of the slabs. The I-520 data contained a single slab, while the I-385 data contained six slabs—the slab before and after the test slab, the test slab, and the three adjacent slabs in the neighboring lane. The three-dimensional slab models from the I-520 data showed that the slab movement can range from 0.0006 feet (0.2 mm) in the center to 0.003 feet (0.9144 mm) on the edges. The plots also revealed that the edges of the slab were not always at the same height so this indicates that the curling is also affected by surrounding slabs and load transfer. For the I-385 plots showed that the center of the slabs would raise to form a peak and the edges if the slabs would have lower elevations. Most of the slabs had similar shapes but had variations in magnitude. These plots were
of multiple slabs and showed that the curvature did not occur in a single slab but a single curved section could span multiple slabs (Johnson, et al, 2010).

The scanner data was also compared to the HSIP data to see if the scanner was suitable to collect pavement surface data. For this comparison a 225 feet (68.58 m) section was selected from the passing lane in the I-385 test site. In order to match these profiles an indicator was placed on the pavement surface during the data collect then these points were aligned in the data. In most of the cases the IRI values from the scanner data were 15 to 20 inches/mile lower than the IRI values from the HSIP data. Both of these results show a much larger IRI in the right wheel path which is what is expected due to the diamond grinding. A cross correlation analysis was also performed to compare the actual profile collected by the two sensors. For the left wheel path there was an 80% correlation for the profiles from the left wheel path which was a good correlation. However, for the right wheel path there was a poor correlation of 40% (Johnson, et al, 2010). Figure 2.8 shows the profiles that were compared from the HSIP and LIDAR scanner.
2.4.1.6 SCDOT HSIP Results

The HSIP data was used to calculate the IRI values for each run of data and then these values were compared to see how it varied through the day. During the initial I-520 data collection there were 11 runs of data collected. The IRI from these runs were compare to each other and to the IRI values that were collected on July 22, 2009 for
quality control during construction. This comparison of these IRI values indicated that there was no significant change in the IRI. These runs were then used along with the runs from the follow up visits, collected in April and August 2010, to determine the effects of seasonal temperature variation. The mean roughness index (MRI), which is the average of the IRI from the left and right wheel path, was calculated for each of the profiles. The variation in the April MRI values was 7 inches/mile and was 3.5 inches/mile for the MRI derived from the August data. The corresponding values from the three collections were compared and the MRI values varied 1 to 3 inches/mile between the April and August collection. The MRI values from the December data was higher than both the April and August values. These results indicate that the change in the IRI due to seasonal temperature variation is small (Johnson, et al, 2010). Figure 2.9 shows the comparison of the seasonal IRI at the I-520 test site.

Figure 2.9 Seasonal IRI Comparison for I-520 in SCDOT Study (Johnson, et al, 2010)
The IRI values calculated from the I-385 data were analyzed separately for the left and right wheel paths since the right wheel path was diamond ground and the left wheel path was not. The IRI values to determine the pay factor for a concrete pavement are specified to the nearest 5 inches/mile. A histogram was created using the difference in IRI. The histogram showed that 65% of the variation was less than 5 inches/mile and 90% of the variation was less than 9 inches/mile. This variation was small especially when considering the variation that was caused by the diamond grinding in the right wheel path. These results indicate that the time that the HSIP profiler data is collected can have a small impact on the pay factor (Johnson, et al, 2010).

2.4.1.7 SCDOT Conclusions and Recommendations

The conclusions from the SCDOT study were that the curl of the concrete could span more than a single slab depending on the interaction at the joint, that the roughness of the pavement did increase as the temperature increased, the changes in the IRI due to daily temperature variation is expected to be less than 10 inches/mile, the change in the IRI due to seasonal temperature variations should be less than 5 inches/mile and that the terrestrial laser scanner can depict small changes in the pavement surface. The authors of the study also suggested that the following improvements be made to the current quality control methods. The changes include setting a time of the day to collect quality control data, specifying that the data should be collected between the hours of 11 AM to 5 PM after the pavement has begun to heat up which would approximately produce the worst case IRI, that the seasonal effects on the IRI should not be considered, that there should be a stipulation that allows the SCDOT or contractor to have the surface retested if they
believe the first test did not accurately depict the pavement surface, and that the network level surveys should not change to account for the effects of slab curling. The authors also proposed research to further investigate the effects of curling and warping which included collecting more data on the test sites and further investigating if the IRI values change. It was also recommended that since the terrestrial laser scanner showed potential for measuring pavement surface data it should be further tested to see what the capabilities are, to explore new technology to find better ways to measure the pavement surface and to do a more thorough investigation (Johnson, et al, 2010).

2.4.1.8 SCDOT Study Discussion

Through this literature review of the paper composed by the SCDOT it is determined that it only considered a miniscule amount of pavement surface to draw the conclusions that were. The exact pavement designs were not given in the report, but for one site only one slab was used and at the other site only six slabs were used. So not many pavement design were considered. This could be a flaw because it has been found in other studies that the slab length can have a significant impact on the IRI. It was found that as the slab length increases so does the IRI (Byrum, 2005). This thesis will incorporate several pavement designs into the analysis to ensure that the results are not bias to a particular design.

2.4.2 USDOT and FHWA Study to Quantify Curvature on IRI

Over a decade ago the United States Department of Transportation (USDOT) and the Federal Highway Administration (FHWA) launched a research project entitled,
“Inertial Profile Data for Pavement Performance Analysis”. From this project many papers have been produced and one in particular explored the effect of the curling and warping on concrete pavement smoothness. The title of this paper is “Quantifying the Impact of Jointed Concrete Pavement Curling and Warping on Pavement Unevenness”. The paper is addressing the need to determine if modern measurement technology and analytical tools can be used to measure and characterize curling and warping for the purpose of relating it to pavement performance (Chang, et al., 2008).

2.4.2.1 Curvature Quantification Study Objectives

To meet objectives of this study the profiler measurement quality assurance plans established in the study to collect concrete pavement profiles. The objectives of this study were to first develop an experimental plan that would provide a test section in all of the United States climate zones, all diurnal periods, and all seasons of the year in order to acquire sufficient data so that the slab curvatures could be fully characterized. The final objective of the study was to measure structural and functional pavement performance at a detailed level to correlate it to curling and warping (Chang, et al., 2008).

2.4.2.2 Curvature Quantification Data Collection

Data collection was a major component of the research and required much time, effort, and resources. So strategic planning and great care was taken when laying out the data collection plan. The data collection was performed over a 15 month period on 38 jointed plain concrete pavement test sites. Each site was visited seasonally which resulted in four test site visits per year one in the Spring (March-June), the Summer
(June-September), the Fall (September-December) and the Winter (January-March). During each site visit data was collected during four periods each day. The first time that data was collected was early morning (maximum negative temperature gradient), the second was midmorning (approximate zero temperature gradient), the third was around noon (maximum positive temperature gradient), and the fourth was in the evening (approximate zero temperature gradient). A research grade profiler was used so it was possible to collect the profile data with a sampling interval of 5mm to 6 mm (0.19685 in to 0.23622 in) (Chang, 2008). Each time that data was collected 10 runs were made (Chang, 2008) with the profiler resulting in 6000 longitudinal profiles covering approximately 400,000 JPCP slabs (Chang, et al., 2008).

2.4.2.3 Curvature Quantification Slab Isolation

The joints had to be identified within the longitudinal profiles so that slabs could be isolated and the curling and warping of each slab could be clearly identified. To do this great care was taken to synchronize the profiles collected for each site. After the profiles were synchronized then each profile was searched for narrow dips, which were found by applying a high pass filter, normalizing the profile using the root mean square, and then searching locations in the profile where the height of the dips were below the zero line by a set threshold. This approach was applied to all of the profiles collected for a single site, so in most cases 160 profiles were used (10 profiles per time, 4 times a day, 4 daily site visits over the study period). Then a histogram was created using the dip location as the bin size and the number of dips identified was counted. The location of the joint can be established by plotting the histogram and locating the spikes which
represent the joint (Chang, et al., 2008). Although many of the joints were detected there is still a possibility that some joints will be undetected (Chang, 2008).

2.4.2.4 Curvature Quantification Curvature Index Development

For this study a new curvature index was developed because existing curvature indices, such as the Byrum Curvature Index has been found to have shortcomings in accuracy, stability, and portability. The root mean square curvature index was also found to be an unsuitable index because short wavelengths dominate the curvature calculations while the longer slab wavelengths are negligible in the curvature calculations. The curvature index that was produced was termed the Second Generation Curvature Index (2GCI) and provided a way to quantify the magnitude of the curvature of a slab. The 2GCI is based on the Westergaard curling equations and real world joint restraints. A global approach was used to fit hypothesized slab profiles to the measured slab profile. The fitted models of the 2GCI have parameters that are connected to the physical parameters of a jointed concrete pavement system that is subjected to curling and warping (Chang, et al., 2008). The two parameters that were used in this research are the pseudo strain gradient and the pseudo radius of soil reaction. These original parameters established by Westergaard considered an ideal single slab, so the new pseudo parameters had to account for the joint friction, dowel bar, when present, and for the aggregate interlock at the joint (Chang, 2008). Figure 2.10 shows an example of the slab profiles collected by the profiler and the resulting fitted profile that was created using the develop curvature index parameters. The chattered line is the raw profile collected by the profiler and the smooth line is the fitted line (Chang, et al, 2008).
2.4.2.5 Curvature Quantification Curvature Analysis

The 2GCI algorithm was used to analyze the slab profiles on the data collected at the 38 test sites. The results from this analysis showed that the 2GCI was an appropriate tool to characterize slab curvature on profile data that was segmented using the profile synchronization and joint identification method mentioned in the previous section. These results showed that the diurnal variation and curvature clearly present how a slab curls. It was found that the curling pattern could be curled up or down at different levels or that the pattern could be alternating in either direction (Chang, et al., 2008). The results also indicate that the curvature for an entire site can vary in magnitude and even direction of curvature during the course of a day and that adjacent lanes may not display the same curvature characteristics. The seasonal curvature variation was found to be less than or equal to the diurnal variation in curvature (Chang, et al., 2008).
2.4.2.6 Curvature Quantification Curvature versus Smoothness

The quantitative curvature values found using the 2GCI were compared to the Half-car Roughness Index (HRI) values found using the same profiles. The HRI is similar to the IRI, but instead of using a profile from a single wheel path a new profile is created by averaging the points of the profiles collected on each wheel path. Then the roughness of that profile is determined and is known as the HRI. This analysis showed that the diurnal variation can be as much as 0.63 m/km, but on average it was 0.16 m/km. It also indicated that the timing of data collection can have an impact on the smoothness results so it may practical to incorporate timing requirements into specifications. It was observed that the curvature characteristics can vary considerably from site to site (Chang, et al., 2008).

The average of all of the curvature values for each site was plotted with their corresponding HRI values to see if there was a relationship between the two. From this plot it can be seen that there is an apparent linear relationship and if a trend line is used the slope provides a way to quantitatively access the influence of the curvature on the HRI. The relationship revealed that when the slabs are curled the most then the HRI values are the highest and that the HRI of the slabs when there is no curvature can be approximated using the trend line. Figure 2.11 shows the relationship between the measured curvature and roughness at one test site.
Using these findings a system called the Rasmussen-Chang-Karamihas (RoCK) diagram was developed to evaluate the impact of the curvature on the HRI. This system uses plot of the HRI and the curvature then applies a least square linear fit to the cluster to compute parameters that allow a test site to be categorized into one of five categories (Chang, et al., 2008). Figure 2.12 shows the RoCK diagram that was developed to evaluate the effect the curvature has on the roughness.
2.4.2.7 Curvature Quantification Findings Summary

There were four outcomes of this study which included a procedure to measure and characterize the curvature of concrete slabs, a method that can be used to synchronize profiles and to identify joint locations, a new curvature index to quantify slab curvature, and finally a system to quantify the relationship between the slab curvature and the HRI.

2.4.2.8 Curvature Quantification Discussion

The research performed in this study covered a vast amount of concrete pavement data including various pavement designs and several environments. This research used a profiler which only collects a limited amount of detail and with new technology it is possible to collect full lane three dimensional range data that can provide much more detail of the pavement surface. This study also concentrated mainly on the impact that
curling had on smoothness and did not investigate other distress types such as faulting. This thesis will utilize this new technology to determine how it can be used to perform concrete condition surveys and it will also study to see how the curvature impacts other pavement distresses with faulting being the main focus.

2.5 Thermal Effects on Faulting

Faulting is one of the key distress types in concrete pavement and as it increases so does the roughness (FHWA 2000). Since one of the possible causes of faulting has been identified as upward curling of pavement slabs (Baus and Stires, 2010), and because faulting has a direct effect on the roughness, which has been found to be impacted by the slab curvature, it is likely that the slab curvature could impact the faulting. So this affect needs to be evaluated to determine if it is significant enough to be of concern.

One of the possible ways that slab curvature can affect the faulting is when the joint is already faulted as the slabs curled downward the forces on the joints are increased. Since the joint is already faulted it is likely that the base under lower slab (Slab B in Figure 2.13) at the joint is slightly weaker than the base under the higher slab (Slab A in Figure 2.13). So when the force is increased, as the slab curls down, at the slab supported by the slightly weaker base (Slab B in Figure 2.13), the base will give slightly more than the stronger base supporting the upper slab (Slab A in Figure 2.13). As this occurs the faulting of the joint will increase because the lower slab moves down more than the upper slab. Figure 2.13 shows as example of a faulted joint used to explain how the change in slab curvature can impact faulting.
Another possible way that the faulting can change due to thermal changes in the slab is when several slabs begin to expand when they are heated. When these slabs are confined and not allowed to freely expand then it could cause the slabs to move up out of the plane of the pavement. As slabs A, B, and C, in Figure 2.14, heat up they begin to expand and eventually the slabs will expand beyond what can be confined and Slab B will move out of the plan of the pavement to account for the expansion. When Slab B moves up then faulting will be created at the joints or will be intensified. Figure 2.14 shows an example of how faulting will be affected as slabs expand due to temperature.

There is a lack of studies that directly explore the affects that daily thermal changes have on the faulting of a concrete pavement section. The aforementioned study entitled “Inertial Profile Data for Pavement Performance Analysis”, which was initiated...
by the USDOT and FHWA and has been one of the most extensive studies that has been performed to study the effect curling and warping has on concrete pavement (Chang, et al, 2008), noted in a tech brief that most of the test sites exhibited little to no faulting due to dowels and relatively young pavements (FHWA, 2010). The changes in faulting were likely not evaluated because there was no faulting to be accentuated and the dowels would more than likely prevent the affect that the thermal expansion would have on the joints. It is also likely that this study and others have not addressed this previously because current methods lack the ability to repeatedly measure the faulting at an exact location on the joint or they are too labor intensive to collect sufficient data to support a change due to the temperature variations. This thesis explores a way to measure the faulting at several locations on a joint with a frequency that would allow any significant changes to be identified and linked to temperature variations if they were responsible for the deviation.

2.6 Literature Review Summary

Currently concrete pavement condition evaluation surveys are performed manually. These manual surveys are dangerous to both the surveyor and the road user. They are also time consuming, labor intensive and costly. Attempts have been made to automate these surveys using high speed inertial profiler data, but the characteristics that can be measured and evaluated using this data are limited. These methods have not been widely accepted and the agencies that do utilize them do not have assurance in the results that are produced from them. Therefore there is a necessity to produce an automatic method that employs new technology to provide detailed pavement surface data that
delivers sufficient and reliable results to evaluate concrete pavement condition. This thesis utilizes emerging three dimensional technologies to enhance the concrete condition survey and to generate the required results. It will mainly concentrate on establishing a data collection technique to analyze faulting, smoothness, and curvature. However it is intended to pave the way to fully automate the surveys and produce all of the required results for the surveys.

Several studies have been performed to determine that the temperature variation in the concrete slabs do have an effect on the roughness of a concrete pavement section. However, some these studies require that specialized equipment be installed into the slabs at the time of placement or that the section be closed to traffic in order for the devices to be set up. Even though some of the studies do employee technology that allows the curvature information to be extracted without lane closure or specialized equipment being installed on or in the pavement, these methods like the others only provide a limited amount of information to be recorded. The proposed methodology in this thesis incorporates the use of some of the most advanced laser technology to collect concrete pavement characteristics and also how to correlate them to thermal changes in the slab. If the sensing vehicle from this research was utilized to rate concrete pavement sections and there was a discrepancy in the results the data could be further investigated to determine if it were due to temperature variations.
CHAPTER 3
SENSING EQUIPMENT

Technological advancements in the laser industry have led to manufactured products that have the capability to collect intricate highway data. This data provides sufficient detail to extract pavement characteristics. Therefore it can be used to evaluate the pavement for the purpose of condition assessment. In order to accomplish the objectives of this thesis this technology was utilized in the form of a sensing vehicle which was used to collect concrete pavement data. The particular vehicle used for this thesis was equipped with two systems the first being the Laser Crack Measurement System (LCMS), developed by INO, and the Geo3D system that is produced by Trimble. This study also used thermal data loggers to log the temperature of the pavement using embedded thermocouples. This chapter will present the sensing vehicle, the capabilities that it possesses, and the thermal monitoring devices used. The sensing vehicle used in this study is shown in figure 3.1. The LCMS was used for this research but it is noted that there are a variety of line laser systems in the market so for the remainder of this research it will be referred to as a three dimensional (3D) line laser to avoid a sense that there is a bias to that particular manufacturer.
3.1 Three Dimensional (3D) Line Laser Technology

The 3D line laser is installed on a full sized van and is composed of a set of sensors that are suspended off the rear of the vehicle, a computer, a control box, and a high resolution distance measuring instrument mounted on the right rear wheel. The computer is used to store the data collected by the sensors, to allow the user to modify survey parameters and to provide a display of the data as it is collected. The control box controls the data collection by acting a liaison between all of the components in the system. The control box reads the DMI data, uses it to determine when the sensors should collect data, and finally it tells the sensors when to collect data.

The sensors utilize three dimensional line laser imaging technology that combines high powered pulsed laser line projectors (Pavemetrics, 2013), high speed scanning cameras, and custom optics to acquire high resolution three dimensional range data and two dimensional intensity images (Tsai, et al. 2010). The sensors can procure more than 23 million data points per second (Tsai, et al., 2013) to produce a detailed three dimensional virtual model of the pavement. This model can then be analyzed to extract
pavement characteristics and features at a detailed level. An example of the detailed data collected by the 3D Line Laser is presented in figure 3.2.

The DMI is used to control the interval between the transversal profiles that are collected by the sensor (Tsai, et al., 2013). These profiles are not collected perfectly perpendicular to the driving direction, they are designed to have a tilt angle to the transverse direction so that the laser line projected from the sensors do not fall directly into joints or transverse cracks. This tilt angle ensures that the laser lines will intersect the joint or transverse crack allowing it to be detected by the sensor. The typical tilt angle used for data collection is 15° from the transverse direction. However this angle can be adjusted from -25° to 25°, which is the maximum angle that can be used and ensure that the full lane is covered. Figure 3.3 shows configuration of the profiles that are projected onto the pavement surface and how they are affected by the tilt angle.
The sensors produce a continuous fine laser line using the principle of structured light, and then the laser line is projected onto the pavement surface. The projected laser
line follows the contour of the pavement surface. The laser line is captured by a time-
delay integration camera and triangulation is used along with the camera and laser
positions to determine the range measurements. Each sensor has one of these high
resolution cameras that collect 2080 pixels in the transverse direction which results in a
total of 4160 pixels across the travel lane. Each of the laser lines that are projected onto
the pavement surface cover 2 m, so when they are combined a 4 m profile that covers the
typical pavement lane width is produced. This provides a 1 mm (0.04 in) resolution in
the transverse direction (x-axis) and the range measurements delivers a 0.5 mm (0.02 in)
resolution in the vertical direction (z-axis). 5600 of these profiles can be collected every
second which allows the system to collect the profiles with a resolution of as low as 1
mm (0.04 in) in the longitudinal direction (y-axis) (Tsai et al., 2010). However in order
for the vehicle to travel at a highway speeds of 62.1 MPH (100 km/hr) the longitudinal
resolution is 5 mm (0.197 in) (Pavemetrics, 2013). Figure 3.4 shows an example of the
cement pavement surface data that can be obtained using the sensing vehicle (Tsai, et
al., 2010).

(a) 2D Intensity Image
Figure 3.4 Concrete Pavement Data Collected by Sensing Vehicle (Tsai, et al.,
2010)
Each sensor is also equipped with an inertial measurement unit (IMU) that is used to account for the changes in vehicle position during the survey. The dynamic acceleration range of the IMUs is -5 g to 5 g and collects data at a sampling interval of 150 hertz. The data collected by the IMUs is used along with the three dimensional range data to generate longitudinal profiles in the wheel paths. From the longitudinal profiles
the IRI values can be attained. Figure 3.5 shows one of the 3D Line Laser sensors with the IMU attached.

![3D Line Laser Sensor](image)

**Figure 3.5 3D Line Laser Sensor**

The 3D Line Laser was chosen as the data collection method for this thesis because of the detailed information that it can provide about the pavement surface. The systems capability to measure the faulting of concrete data was previously assessed in a study performed by Tsai et al. (2010). This study found that the 3D Line Laser could measure the faulting with an error less than 1 mm (0.04 in) which meets the AASHTO R36-04 specification for automated surveys (Tsai, et al., 2010).

### 3.2 Geo3D Sensing System

The Geo3D system is installed on the same full size van as the 3D Line Laser and is comprised of several components including four high resolution cameras, two line
scanning lasers, a Global Positioning System (GPS), and an IMU. The cameras record video log images of the data collection from four different perspectives. These images can be processed using detection algorithms that can locate desired features from the highway (i.e. Traffic Signs, Pavement Markings, etc.). There are four views that are recorded three of which are forward facing and one is rear facing. The first forward facing camera records the left side view of the data collection, the second records the front view of the pavement the vehicle is traveling over, and the final front facing camera record the right side view of the data collection. The rear facing camera records another view of the pavement surface which can be correlated to the 3D Line Laser data that is collected to provide more information about the pavement characteristics. The cameras are designed to collect an image at a specified interval. The typical interval used is 5 m (16.4 ft), but it can be adjusted. This interval that the images are collected at is controlled by the same high resolution DMI that triggers the 3D Line Laser sensors.

The two line scanning lasers are positioned on the front of the vehicle and use Light Detection and Ranging (LIDAR) to scan the terrain that is traversed by the vehicle during the data collection and the surrounding environment. There are two views captured by the lasers one is horizontally positioned and the other is vertically positioned. The horizontal laser is a RIEGL LMS Q120i and can be aimed upward, to collect overhead sign and bridge data, or it can be aimed downward to collect pavement surface or pavement marking data. The vertical laser is a RIEGL LMS Q 120 and it is positioned so that it scans to the right of the vehicle during data collection, this is typically the shoulder in most cases. This laser is normally used to collect sign data. Both of these lasers collect 10,000 measurements per second (RIEGL, 2007 and 2010), which are
presented as a point cloud that can be overlaid on the image data collected by the cameras. This allows the objects collected by the lasers to be clearly viewed and for the locations of the laser points to be identified. This is critical because this data is being investigated for the use of retroreflectivity assessment so it allows the location of the laser measurements to be compared to the location of manually measured points on signs or pavement markings. The specifications for the lasers are shown in Table 3.1.

<table>
<thead>
<tr>
<th>Laser Model</th>
<th>LMS Q120</th>
<th>LMS Q120i</th>
<th>SICK LMS 211-S14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Measurement Range (m)</td>
<td>150</td>
<td>150</td>
<td>30</td>
</tr>
<tr>
<td>Minimum Measurement Range (m)</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Accuracy (mm)</td>
<td>25</td>
<td>20</td>
<td>35</td>
</tr>
<tr>
<td>Precision (mm)</td>
<td>15</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Measurement Rate</td>
<td>10000</td>
<td>10000</td>
<td>10000</td>
</tr>
</tbody>
</table>

The GPS used in the Geo3D system is capable of recording 100 measurements per second, but it is usually set to collect 5 measurements per second. After this data is post processed it can have an accuracy of 35 mm (1.38 in) in the x and y direction and an accuracy of 50 mm (1.97 in) in the z direction. The IMU in the Geo3D system can collect 100 measurements per second. The IMU data is used to account for the vehicle position between GPS readings. The IMU and GPS data are used to synchronize all of the data that is collected by the Geo3D system so that it can be linked for analysis. Figure 3.6 shows the Geo3D sensors on the sensing vehicle.
The Geo3D system was only briefly introduced here because it was not fully utilized for this thesis. The only data that was used was the back camera view and it was only used in some cases to identify locations in the 3D Line Laser data. It was also presented to show all of the capabilities of the sensing vehicle that could be used in the future to further improve concrete pavement condition evaluations.
3.3 Thermal Data Logging Devices

The devices used to measure the temperature in the concrete pavement were thermocouples. Thermocouples are thermoelectric devices that accurately measure temperature. The thermocouples used in this study were Omega hermitically sealed type K thermocouples that had a temperature range between -400°F to 450°F (-204.4°C to 232.2°C). Since the thermocouples require a power source to measure temperature and are unable to log the temperatures that are measured they had to be connected to a data logger. The data logger used to log the thermal data was a standard Omega four channel data logger. The logger has enough capacity to log 10,000 readings from each of the four thermocouples attached to it, resulting in 40,000 total readings. The interval between these temperature measurements can range from 1 second to 59 minutes. The data loggers are battery powered and can log data for approximately 550 hours. As part of this research a method was developed to install these sensors into an existing concrete slab. This procedure can be found in Appendix A of this thesis. Figure 3.7 shows the data logger and thermocouples used to measure the pavement temperature data for this study.
(a) Omega Data Logger

(b) Omega Thermocouple

Figure 3.7 Thermal Devices
CHAPTER 4
PRELIMINARY INVESTIGATION

To accomplish the objectives of this thesis a method had to be developed to ensure that all of the data was collected and processed in the same manner so that the comparison of the results was adequate. This method would include how to install thermal monitoring devices and how to use them to collect and analyze pavement temperature data. It would also entail developing a method to correlate this thermal data to the data collected by the sensing vehicle and how to best utilize the capabilities of the sensing vehicle. To develop this methodology a site was selected and the thermal devices were installed, thermal data was collected along with the sensing vehicle data and the developed analysis procedure was used to generate results for the preliminary investigation. This chapter summarizes the procedure that was produced and the logic and considerations that were deliberated when developing it. The resulting concrete pavement characteristics for the preliminary investigation site are also summarized in this chapter.

4.1 Site Selection

When selecting a site to perform a preliminary investigation on the main goal was to find a location that would provide a safe environment to install the thermocouples into the pavement and all the data to be collected safely. The site that was selected was the Weigh Station located approximately at mile 143 on I-16. Several site visits were made to coordinate with the personnel and determine a location that would be suitable and not
interfere with their daily operations. Originally it was decided to select a slab in the overflow parking area behind the weigh station, but the pavement design for this location was not recorded in the plans. The plans only consisted of the main truck lane, the scale lane, and the bypass lane, so another site visit was made to further discuss with the staff and finalize the location of the test section.

It was finally decided to use the main lane in front of the structure on site. This lane was chosen because it had a grass shoulder that was needed to install a housing for some of the thermal equipment that was used. Twenty five slabs in front of the guard station were selected as the actual test section that would be used for analysis. The twentieth slab was selected as the test slab to install the thermocouples into, because it was out of the way and would not obstruct any of the functions of the weigh station. Figure 4.1 shows the aerial view of the weigh station with the key features labeled.

![Figure 4.1 Aerial View of Weigh Station](image-url)
The pavement design at the weigh station consisted of a 20 feet (6.1 m) lane that was made up of two 10 feet (3.05 m) wide slabs. The slab length in the travel direction was 20 feet (6.1 m). These slabs were composed of a 12 inch (304.8 mm) deep Portland cement concrete cross section with doweled joints and rested on a 5 inch (127 mm) Portland cement concrete sub base or a 5 inch (127 mm) asphaltic concrete base. The plans for the weigh station can be found in Appendix C of this thesis. The exact coefficient of thermal expansion (CTE) for the weigh station was not known at this time and due to time constraints and the amount of effort required to estimate it a typical value is presented here. One studied that intensively studied the CTE for Georgia pavements was entitled “Determination of Coefficient of Thermal Expansion for Portland Cement Concrete Pavements for MEPDG Implementation”. In this study five cores were extracted from actual Georgia concrete pavements and it was found that they were mostly composed of high volumes of granite and natural sand. The average CTE for these five cores was found to be 4.911 µε/°F (8.840 µε/°C) (Kim, 2012).

4.2 Thermocouple Installation

After the test slab was identified the positions to monitor the temperature in the slab needed to be located. To determine these locations concrete experts were consulted and their inputs were used to find which positions and which depths to install the sensors. Three positions were decided upon. The first was the corner of the slab at the joint (location A in Figure 4.2), which would be the most critical, because it is where the most curling and warping movement should take place. The second location that was selected was the center of the slab (location B in Figure 4.2) so that it could be compared to the
corner to see if there is any heat loss due to edge effects. The third and final location that was selected was the center of the slab along the joint (location C in Figure 4.2). The thermal data collected at these three locations would show how the temperature varied through the slab and to determine if the location of the sensors in the slab would have a significant impact on variation of the pavement temperature. Figure 4.2 shows the locations in the slab that were selected to monitor and where the thermocouples were installed.

(a) Relative Monitoring Locations
Figure 4.2 Thermocouple Positions in Test Slab
The depth that each sensor would be inserted into the pavement also had to be established. This was necessary to see how the temperature varied through the depth of the slab at each of these locations. The data loggers that were used could log the temperature data from four thermocouples, so four depths were selected. Since the focus of this study is the curling and warping of the slab then the two most critical depths to measure are ½ an inch (12.7 mm) from the top of the slab (location T1 in Figure 4.3) and ½ an inch (12.7 mm) from the bottom of the slab (location T3 in Figure 4.3). These two
depths will give the variation between the top and bottom of the slab and these values can be used to determine the times that the maximum positive temperature variation, maximum negative temperature variation, and when there was no variation between the bottom of the slab and the top of the slab. This will determine the times that data needs to be collected on the test sections. There were two depths left to measure the center depth of the slab (location T2 in Figure 4.3) was selected so that the distribution of the temperature distribution throughout the depth of the slab could be estimated. The final depth that was selected was 1 inch (25.4 mm) into the base (location T4 in Figure 4.3), this would show if there was any deviation between the bottom of the slab and the base. Figure 4.3 shows the depths that were selected to place the thermocouples.

![Figure 4.3 Thermocouple Depths in the Test Slab](image)
Once all of the planning was complete the thermocouples were installed into the pavement. Due to the weigh station being an operating facility the installation had to be coordinated with the staff. At the time of the installation the weigh station was open seven days a week. The day with the least truck traffic was Saturday. The weigh station opened at 6:00 A.M. and closed at 12:00 A.M., so in order to reduce the amount of time that their operation was interrupted the installation started at 12:00 A.M. on a Saturday morning. The detailed procedure that was developed and implemented to install the thermocouples into the existing concrete pavement at the weigh station can be found in Appendix A of this thesis.

4.3 Thermal Data

After the thermocouples were installed in the pavement then the thermal data needed to be collected and analyzed. This analysis would provide a basis for determining when to collect data using the sensing vehicle. This section describes the how the thermal data was collected, interpreted and the conclusions that were made.

4.3.1 Thermal Data Collection at Weigh Station

The thermal data was collected at all 12 locations in the slab for four weeks prior to collecting the pavement surface data using the sensing vehicle. The interval between the readings was set to 15 minutes, which would provide sufficient detail to capture the gradual change in the pavement temperature. The day before the data collection was scheduled the thermal data was downloaded and analyzed to determine the data collection
windows when the slabs would be experiencing the most curvature. During the data
collection the thermal data was logged using an interval of 1 minute, this would provide
detailed data and would ensure that there would be a thermal reading to correspond to
each data collection run collected by the sensing vehicle.

4.3.2 Thermal Data Analysis

The thermal data was analyzed to determine two things. The first of which was to
determine if the position that the thermal data was logged from would impact the amount
of variation between the top and bottom of the slab. The second analysis was to
determine when different variations between the top and bottom of the slab were
observed prior to the data collection to determine when the sensing vehicle data should be
collected. The second analysis was also used on thermal data that was collected
simultaneously with the sensing vehicle data to determine how the temperature varied in
the slabs throughout the data collection.

4.3.2.1 Position Analysis

To see if there was a lot variation in the pavement temperature between the
positions that were measured the same depth from each location was plotted. Figure 4.4
shows the plot of the thermal data from the bottom of the slab for all of the positions.
(a) Recorded Temperature at Bottom of Slab (T2) for All Positions

(b) Recorded Temperature at Top of Slab (T4) for All Positions

Figure 4.4 Temperature Variations between Slab Positions
This plot shows that the temperature at all of the positions follow a similar trend. The plots are slightly shifted from each other. This was the case for all of the data that was collected so it was concluded that when determining the temperature difference between the top and bottom of the slab the position the data was taken from was not critical. Since the position was not critical it was decided to use the data that was collected in the edge of the slab because it is where the most slab movement would occur.

### 4.3.2.2 Variation Analysis Prior to Data Collection

The desired variation conditions were the maximum positive variation (center of the slab rises and edges go down), the maximum negative variation (center of the slab goes down and edges rise), and when there is zero variation (the slab is flat). The maximum positive variation occurs when the temperature in the top of the slab is greater
than the temperature in the bottom of the slab. Using the formula \( \Delta T = T_{Top} - T_{Bottom} \), this would occur at the same time as the maximum positive \( \Delta T \). The maximum negative variation occurs when the temperature in the top of the slab is less than the temperature in the bottom of the slab, this occurs at the same time as the maximum negative \( \Delta T \). The zero variation condition occurs when \( \Delta T \) is equal to zero. For the thermal analysis the temperature data was segmented into daily data sets and each of these conditions was identified in the data. Then the corresponding time was recorded. The occurrence time for these events did not happen at the same time each day. For each category all of the recorded times were evaluated and used to determine the time windows that the sensing vehicle data should be collected to cover all of the desired conditions. Figure 4.5 shows an example of the daily thermal plots used to determine the occurrence time of the desired variation conditions.

**Figure 4.5 Daily Thermal Data Example from Position A**
For this example the maximum positive variation occurred around 1:52 P.M. and the temperature difference ($\Delta T$) was 28.9 °F (16.06°C). The maximum negative variation occurred around 6:45 A.M. and the temperature difference ($\Delta T$) was -9.7°F (-5.39°C). In all cases the zero variation occurred twice each day, once in the morning as the slab surface heated and once in the evening as the surface began to cool. For this example the zero variation condition occurred at approximately 9:03 A.M. and 8:37 P.M.

This process was completed for all of the four weeks of thermal data that was collected to determine what the data collection time windows would be. These results showed that the optimal time to collect the maximum negative variation was early in the morning, the maximum positive variation was in the early afternoon, and the zero variation was between 8:30 A.M. and 10:30 A.M or between 3:00 P.M. to 8:00 P.M. To reduce the amount of time at the test site it was decided to only collect the zero variation during the morning window. For capturing the maximum negative variation and zero variation the data needed to be collected between 6:45 A.M. and 10:30 A.M. To capture the maximum positive variation the data needed to be collected from 12:30 P.M. to 5:30 P.M. It was also concluded that the temperature change was gradual so a 15 minute data collection interval could be used and each variation condition would be captured.

4.3.2.3 Variation Analysis during Data Collection

The thermal data was also collected on the same day when the sensing vehicle was used to collect the pavement surface data on the weigh station test section. In order to attain sufficient temperature information from the slabs during the sensing vehicle data...
collection the data logging interval was set to 1 minute. Since the sensing vehicle data would be collected using an interval of 15 minutes between runs the 1 minute thermal data interval would guarantee that there would be thermal data that could be linked to each data set collected by the sensing vehicle. To ensure that the thermal data could be matched to the data collected by the sensing vehicle the clocks on the data loggers were synchronized to the clocks on the computers in the van.

The thermal data from all 12 locations in the slab were collected during the data collection. The thermal data was collected at a 1 minute interval from approximately 6:30 A.M. to roughly 5:50 P.M. For location A the maximum negative variation occurred at 6:45 A.M. and was -7.9 °F (-4.39 °C), the time that there was no variation in the temperature between the top and bottom of the slab was 9:11 A.M. and the maximum positive variation occurred at 3:04 P.M. and was 27.8 °F (15.45 °C). For location B the maximum negative variation occurred at 6:50 A.M. and was -8.9 °F (-4.78 °C), the time that there was no variation in the temperature between the top and bottom of the slab was 9:13 A.M. and the maximum positive variation occurred at 3:04 P.M. and was 31.2 °F (17.34 °C). For location C the maximum negative variation occurred at 6:59 A.M. and was -9.2 °F (-5.12 °C), the time that there was no variation in the temperature between the top and bottom of the slab was 9:07 A.M. and the maximum positive variation occurred at 3:04 P.M. and was 34.6 °F (19.22 °C). Table 4.1 summarizes the results from the variation analysis. Figure 4.6 shows the plot of the thermal data that was recorded during the sensing vehicle data collection.
Table 4.1 Variation Analysis Summary

<table>
<thead>
<tr>
<th>Location</th>
<th>Variation Condition</th>
<th>Time</th>
<th>Temperature</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(°F)</td>
<td>(°C)</td>
</tr>
<tr>
<td>Location A</td>
<td>Maximum Negative</td>
<td>6:45 A.M.</td>
<td>-7.9</td>
<td>-4.39</td>
</tr>
<tr>
<td></td>
<td>Zero</td>
<td>9:11 A.M.</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Maximum Positive</td>
<td>3:04 P.M.</td>
<td>27.8</td>
<td>15.45</td>
</tr>
<tr>
<td>Location B</td>
<td>Maximum Negative</td>
<td>6:50 A.M.</td>
<td>-8.9</td>
<td>-4.78</td>
</tr>
<tr>
<td></td>
<td>Zero</td>
<td>9:13 A.M.</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Maximum Positive</td>
<td>3:04 P.M.</td>
<td>31.2</td>
<td>17.34</td>
</tr>
<tr>
<td>Location C</td>
<td>Maximum Negative</td>
<td>6:59 A.M.</td>
<td>-9.2</td>
<td>-5.12</td>
</tr>
<tr>
<td></td>
<td>Zero</td>
<td>9:07 A.M.</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Maximum Positive</td>
<td>3:04 P.M.</td>
<td>34.6</td>
<td>19.22</td>
</tr>
</tbody>
</table>

Figure 4.6 Thermal Data Logged During Sensing Vehicle Data Collection
From these results it was concluded that the properties of the slab that were found using the sensing vehicle data that was collected at approximately 9:15 A.M should be affected the least by the temperature variation in the slab. It was also concluded that the slab properties generated from the sensing vehicle data collected at 3:00 P.M should be affected the most by the positive temperature variation that would cause the slabs to curl up the most. Finally it was determined that the slab properties produced from the sensing vehicle data collected at 6:45 A.M. or 7:00 A.M. should be affected the most by the negative temperature variation that would cause the slabs to curl downward the most.

**4.4 Sensing Vehicle Data**

After the results from the thermal analysis were used to decide when the sensing vehicle should be used to collect data a strategy was devised to collect this data and analyze it. This section will describe the plan used to collect the data, how it was analyzed and the conclusions that were drawn.
4.4.1 3D Line Laser Data Collection at Weigh Station

Data was collected using the sensing vehicle at the weigh station during the specified time period. It was decided to use a fifteen minute interval between the data collection runs. Since the temperature change in the slab is gradual the fifteen minute interval should provide sufficient data to capture each of the temperature variation conditions. During the collection all of the sensors on the vehicle were used, so that as much detail as possible could be captured. Even though not all the data was utilized for this thesis the rest was collected so that if future research required the other data it would already be possessed and would not require more effort. The 3D Line Laser data was the main focus of the data collection since it would be used for this thesis.

The first data collection was performed on August 11, 2012. The first run of data was collected at 5:45 A.M. and continued every fifteen minutes after that until 10:30 A.M. The data collection then resumed at 12:45 P.M. and continued until 2:00 P.M. when an afternoon thunder storm interrupted the data collection for the day. During this collection there were 26 data collection runs collected that spanned 25 labeled slabs and 26 identifiable joints.

A second data collection was performed on October 27, 2012, but the temperature variation between the top and bottom of the slab was minimal (-6°F (-3.34°C) and 4.3°F (2.39°C)) so the effect of the curling on the pavement characteristics would be reduced. Though this data was used to analyze the built in curvature at the site, which occurs when there is no temperature variation between the top and bottom of the slab ($\Delta T=0$).

The first and second data collections were used to do an initial analysis on the weigh station data to obtain an idea of the conditions at the test site and to establish a
methodology to extract the required slab information using the collected data. The methods that were developed are only briefly mentioned in this section, but are described in full detail in Appendix B.

Due to the loss of the thermal data from the first data collection and the small temperature variation during the second data collection a third and final data collection was performed on August 3, 2013. The data collection began at 6:45 A.M. and continued until 5:30 P.M. One run of data was collected with the sensing vehicle every 15 minutes which resulted in a total of 44 runs of data. Each run of the data that was collected covered the same 25 slabs that were labeled in the first data collection, so the same 26 joints were also identifiable. The results that are expounded upon in the following subsections for the faulting and IRI analysis were all generated using the data that was collected during the third data collection on August 3, 2013. The results for the curvature analysis were derived using the data that was collected during the first data collection on August 11, 2012.

4.4.2 3D Line Laser Data Analysis

The 3D Line Laser data was processed and analyzed several ways to produce results that depict the characteristics of the concrete pavement. Some of the required results were direct outputs of the 3D Line Laser software while others required more in depth manual processing. The results that were generated included the faulting and the roughness.
4.4.2.1 Weigh Station Faulting Analysis

The faulting is computed by the 3D Line Laser software. To compute the faulting, the joint and lane marking have to be located within the data. After these are found then the algorithm goes a set distance before and after the joint to find elevation readings to use to calculate the faulting with. The distance between these two points is known as the footprint of the measuring method. For this thesis a 50 mm (1.97 in) footprint (Dimension A in Figure 4.7) was used, since the study was performed in Georgia and this is approximately the footprint of the Georgia Faultmeter. After the position that the elevation readings will be taken are found then the algorithm selects a set length of elevation readings parallel to the joint (Dimension B in Figure 4.7). The readings are also centered on the point established by the footprint. The average of these readings is then taken as the height for that side of the joint. For this thesis 100 mm (3.94 in) was used as the length of the elevation readings used to find the height for each side of the joint. After the height of each side of the joint was found then the difference between the two values was taken and the result is the faulting at that position.

With most automated methods a single faulting value is all that could be obtained, but with the detailed joint information that the 3D Line Laser provides multiple faulting measurements can be taken along the joints. To generate multiple faulting values for the joint the algorithm will move along the joint and repeat the faulting computation until the joint ends or intersects pavement markings. The locations that the faulting measurements are taken is variable and can be manipulated to produce as many faulting measurements for a joint as desired. The first fault measurement is taken this interval away from the beginning of the joint or where it intersects the pavement marking. Then the algorithm
moves along the joint and computes the faulting using this value as an interval between the measurements. For this thesis the interval between the faulting measurements that was used was 150 mm (5.91 in) (Dimension C in Figure 4.7). Figure 4.7 shows the parameters that the faulting computation algorithm uses when computing the faulting.

This process was performed on all the joints in the weigh station test section. There were a total of 44 data collection runs that covered 26 joints for a total of 1144 joints that were analyzed. The results from the processing that the 3D Line Laser software performs can produce a variety of results. For this faulting study the calculated faulting values and the intensity images that indicate where the faulting measurements that were taken were used.

The images were used to determine if any of the faulting measurements were invalid. An invalid faulting measurement was one that did not depict the actual faulting.
that the joint is exhibiting. The cases that were encountered in the weigh station analysis
were that vegetation was included in the elevation readings used to compute the faulting;
the longitudinal joints were included in the elevation readings used to compute the
faulting and some of the faulting values were calculated outside the travel lane. These
values had to be removed so that the final results were not affected by these irregularities.

Another problem that affected the faulting statistics was the joint detection
performed by the algorithm. In some cases the joints were falsely detected and in some
cases all or part of the joint was not detected. If there were false detections then they had
to be deleted from the final values and if there were joints that were not detected they had
to be considered to ensure that when interpreting the results the conclusions that were
drawn were not based on inaccurate results.

There were approximately a total of 21,000 faulting measurements taken and were
used to find the average faulting for each joint in each data collection run. This resulted
in 1144 average faulting values for which the statistics are presented in Table 4.2. These
results show that there is minimal faulting at the site with an average faulting of 0.48 mm
(0.019 in), a standard deviation of 0.28 mm (0.011 in), and a range from -0.07 mm (-3.0 x
10^{-4} in) to 1.44 mm (0.057 in).

<table>
<thead>
<tr>
<th>Table 4.2 Weigh Station Average Faulting Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weigh Station Average Faulting</td>
</tr>
<tr>
<td>(mm)</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Average</td>
</tr>
<tr>
<td>Median</td>
</tr>
<tr>
<td>Maximum</td>
</tr>
<tr>
<td>Minimum</td>
</tr>
<tr>
<td>Standard Deviation</td>
</tr>
<tr>
<td>25th Percentile</td>
</tr>
<tr>
<td>75th Percentile</td>
</tr>
</tbody>
</table>
After an overall idea of the faulting conditions at the weigh station test site were obtained then each joint was isolated and analyzed. This analysis used the average faulting values for a single joint from all data collection runs to see how the faulting of an individual joint changed throughout the day. This provided 26 average faulting values to represent each joint from which the maximum and minimum average faulting values were found. Then the variation of the average faulting was found by taking the minimum from the maximum (Faulting_Variation = Maximum Average Faulting – Minimum Average Faulting). This produced 26 variation values to show if there was a significant change in the faulting of each joint throughout the data collection. Table 4.3 shows the variation in the average faulting values for each joint.

<table>
<thead>
<tr>
<th>Weigh Station Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint</td>
</tr>
<tr>
<td>Joint 1</td>
</tr>
<tr>
<td>Joint 2</td>
</tr>
<tr>
<td>Joint 3</td>
</tr>
<tr>
<td>Joint 4</td>
</tr>
<tr>
<td>Joint 5</td>
</tr>
<tr>
<td>Joint 6</td>
</tr>
<tr>
<td>Joint 7</td>
</tr>
<tr>
<td>Joint 8</td>
</tr>
<tr>
<td>Joint 9</td>
</tr>
<tr>
<td>Joint 10</td>
</tr>
<tr>
<td>Joint 11</td>
</tr>
<tr>
<td>Joint 12</td>
</tr>
<tr>
<td>Joint 13</td>
</tr>
<tr>
<td>Joint 14</td>
</tr>
<tr>
<td>Joint 15</td>
</tr>
<tr>
<td>Joint 16</td>
</tr>
<tr>
<td>Joint 17</td>
</tr>
</tbody>
</table>
The maximum variation that was observed was 0.88 mm (0.035 in) and the minimum was 0.18 mm (0.007 in). The variation is less than 1 mm (0.04 in), so it is within the limits of the AASHTO R36-04 specification. Since this variation is less than the required accuracy then it will not have a significant impact when measuring the faulting using an automatic method. Out of the 26 joints only 4 had a variation greater than 0.5 mm (0.02 in) which is lower than the accuracy of the 3D Line Laser. The faulting measurement location is determined by the pavement marking detection which can be slightly shifted between the data collection runs. This slight shift causes the faulting measurements to be taken at somewhat different locations. Since the variation is so small the changes in the surface texture on the slabs between the measurement locations could slightly lower or raise the height readings used to calculate the faulting at a particular location causing the results to fluctuate.

To further investigate the effect of the thermal gradient on the faulting, the average faulting values from the data collection runs that were taken at the times that the maximum and zero temperature variations occurred. The data collection runs that were used were the run collected at 6:45 A.M, 7:00 A.M., 9:15 A.M, and 3:00 P.M. The variations from these four runs were compared back to the variations found using all of

<table>
<thead>
<tr>
<th>Joint</th>
<th>0.25</th>
<th>0.01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint 18</td>
<td>0.25</td>
<td>0.01</td>
</tr>
<tr>
<td>Joint 19</td>
<td>0.32</td>
<td>0.012</td>
</tr>
<tr>
<td>Joint 20</td>
<td>0.31</td>
<td>0.012</td>
</tr>
<tr>
<td>Joint 21</td>
<td>0.27</td>
<td>0.011</td>
</tr>
<tr>
<td>Joint 22</td>
<td>0.24</td>
<td>0.01</td>
</tr>
<tr>
<td>Joint 23</td>
<td>0.24</td>
<td>0.009</td>
</tr>
<tr>
<td>Joint 24</td>
<td>0.18</td>
<td>0.007</td>
</tr>
<tr>
<td>Joint 25</td>
<td>0.35</td>
<td>0.014</td>
</tr>
</tbody>
</table>

The maximum variation that was observed was 0.88 mm (0.035 in) and the minimum was 0.18 mm (0.007 in). The variation is less than 1 mm (0.04 in), so it is within the limits of the AASHTO R36-04 specification. Since this variation is less than the required accuracy then it will not have a significant impact when measuring the faulting using an automatic method. Out of the 26 joints only 4 had a variation greater than 0.5 mm (0.02 in) which is lower than the accuracy of the 3D Line Laser. The faulting measurement location is determined by the pavement marking detection which can be slightly shifted between the data collection runs. This slight shift causes the faulting measurements to be taken at somewhat different locations. Since the variation is so small the changes in the surface texture on the slabs between the measurement locations could slightly lower or raise the height readings used to calculate the faulting at a particular location causing the results to fluctuate.

To further investigate the effect of the thermal gradient on the faulting, the average faulting values from the data collection runs that were taken at the times that the maximum and zero temperature variations occurred. The data collection runs that were used were the run collected at 6:45 A.M, 7:00 A.M., 9:15 A.M, and 3:00 P.M. The variations from these four runs were compared back to the variations found using all of
the runs of the data. This comparison revealed that the greatest variation did not occur when the greatest temperature variation took place. The faulting variations that were compared during this analysis are shown in Table 4.4.

**Table 4.4 Weigh Station Faulting Variation Detailed Analysis Results**

<table>
<thead>
<tr>
<th>Joint</th>
<th>All Data Collection Runs</th>
<th>Runs Collected at 6:45 A.M, 7:00 A.M, 9:15 A.M, 3:00 P.M</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mm)</td>
<td>(in)</td>
</tr>
<tr>
<td>Joint 1</td>
<td>0.26</td>
<td>0.01</td>
</tr>
<tr>
<td>Joint 2</td>
<td>0.25</td>
<td>0.01</td>
</tr>
<tr>
<td>Joint 3</td>
<td>0.22</td>
<td>0.008</td>
</tr>
<tr>
<td>Joint 4</td>
<td>0.43</td>
<td>0.017</td>
</tr>
<tr>
<td>Joint 5</td>
<td>0.24</td>
<td>0.009</td>
</tr>
<tr>
<td>Joint 6</td>
<td>0.45</td>
<td>0.018</td>
</tr>
<tr>
<td>Joint 7</td>
<td>0.29</td>
<td>0.011</td>
</tr>
<tr>
<td>Joint 8</td>
<td>0.48</td>
<td>0.019</td>
</tr>
<tr>
<td>Joint 9</td>
<td>0.36</td>
<td>0.014</td>
</tr>
<tr>
<td>Joint 10</td>
<td>0.53</td>
<td>0.021</td>
</tr>
<tr>
<td>Joint 11</td>
<td>0.65</td>
<td>0.026</td>
</tr>
<tr>
<td>Joint 12</td>
<td>0.88</td>
<td>0.035</td>
</tr>
<tr>
<td>Joint 13</td>
<td>0.53</td>
<td>0.021</td>
</tr>
<tr>
<td>Joint 14</td>
<td>0.26</td>
<td>0.01</td>
</tr>
<tr>
<td>Joint 15</td>
<td>0.34</td>
<td>0.014</td>
</tr>
<tr>
<td>Joint 16</td>
<td>0.26</td>
<td>0.01</td>
</tr>
<tr>
<td>Joint 17</td>
<td>0.33</td>
<td>0.013</td>
</tr>
<tr>
<td>Joint 18</td>
<td>0.25</td>
<td>0.01</td>
</tr>
<tr>
<td>Joint 19</td>
<td>0.25</td>
<td>0.01</td>
</tr>
<tr>
<td>Joint 20</td>
<td>0.32</td>
<td>0.012</td>
</tr>
<tr>
<td>Joint 21</td>
<td>0.31</td>
<td>0.012</td>
</tr>
<tr>
<td>Joint 22</td>
<td>0.27</td>
<td>0.011</td>
</tr>
<tr>
<td>Joint 23</td>
<td>0.24</td>
<td>0.01</td>
</tr>
<tr>
<td>Joint 24</td>
<td>0.24</td>
<td>0.009</td>
</tr>
<tr>
<td>Joint 25</td>
<td>0.18</td>
<td>0.007</td>
</tr>
<tr>
<td>Joint 26</td>
<td>0.35</td>
<td>0.014</td>
</tr>
</tbody>
</table>
The time that the maximum and minimum average faulting occurred was also examined to determine if there was some trend between the temperature variation and the average faulting variation. These results indicated that there was not a clear definable relationship that could be identified between the time that the different temperature variation conditions occurred and the time that the maximum and minimum average faulting was exhibited by the joints. The times that the maximum and minimum average faulting values occurred are summarized in Table 4.5. The temperature variation conditions that were considered were the maximum positive temperature variation which occurred at 3:15 P.M., the maximum negative temperature variation which occurred between 6:45 and 7:00 A.M., and the zero variation condition which occurred around 9:15 A.M. It was expected that the maximum or minimum average faulting would happen around the same time that the temperature variation was in one of the described conditions, since the slabs should undergo the most movement during these times. However this was not the trend that was observed so the temperature gradient that arises in the slab due to temperature fluctuations does not seem to have a significant impact on the faulting at a transverse joint in a concrete pavement section.

Table 4.5 Maximum and Minimum Average Faulting Occurrence Times

<table>
<thead>
<tr>
<th>Weigh Station</th>
<th>Maximum and Minimum Average Faulting Occurrence Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint 1</td>
<td>Maximum Time: 3:15 P.M.</td>
</tr>
<tr>
<td>Joint 2</td>
<td>Maximum Time: 5:00 P.M.</td>
</tr>
<tr>
<td>Joint 3</td>
<td>Maximum Time: 4:00 P.M.</td>
</tr>
<tr>
<td>Joint 4</td>
<td>Maximum Time: 12:15 P.M.</td>
</tr>
<tr>
<td>Joint 5</td>
<td>Maximum Time: 10:30 A.M.</td>
</tr>
<tr>
<td>Joint 6</td>
<td>Maximum Time: 10:30 A.M.</td>
</tr>
<tr>
<td>Joint 7</td>
<td>Maximum Time: 3:00 P.M.</td>
</tr>
</tbody>
</table>
### Table 4.5 (Continued)

<table>
<thead>
<tr>
<th>Joint</th>
<th>Time 1</th>
<th>Time 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint 8</td>
<td>3:00 P.M.</td>
<td>1:30 P.M.</td>
</tr>
<tr>
<td>Joint 9</td>
<td>12:00 P.M.</td>
<td>9:30 A.M.</td>
</tr>
<tr>
<td>Joint 10</td>
<td>7:45 A.M.</td>
<td>4:30 P.M.</td>
</tr>
<tr>
<td>Joint 11</td>
<td>9:45 A.M.</td>
<td>7:15 A.M.</td>
</tr>
<tr>
<td>Joint 12</td>
<td>11:00 A.M.</td>
<td>4:15 P.M.</td>
</tr>
<tr>
<td>Joint 13</td>
<td>12:00 P.M.</td>
<td>4:30 P.M.</td>
</tr>
<tr>
<td>Joint 14</td>
<td>12:00 P.M.</td>
<td>1:00 P.M.</td>
</tr>
<tr>
<td>Joint 15</td>
<td>1:45 P.M.</td>
<td>9:30 A.M.</td>
</tr>
<tr>
<td>Joint 16</td>
<td>9:45 A.M.</td>
<td>3:15 P.M.</td>
</tr>
<tr>
<td>Joint 17</td>
<td>7:00 A.M.</td>
<td>4:45 P.M.</td>
</tr>
<tr>
<td>Joint 18</td>
<td>3:15 P.M.</td>
<td>4:15 P.M.</td>
</tr>
<tr>
<td>Joint 19</td>
<td>9:00 A.M.</td>
<td>9:45 A.M.</td>
</tr>
<tr>
<td>Joint 20</td>
<td>10:30 A.M.</td>
<td>1:30 P.M.</td>
</tr>
<tr>
<td>Joint 21</td>
<td>3:30 P.M.</td>
<td>1:30 P.M.</td>
</tr>
<tr>
<td>Joint 22</td>
<td>11:15 A.M.</td>
<td>1:30 P.M.</td>
</tr>
<tr>
<td>Joint 23</td>
<td>9:00 A.M.</td>
<td>1:00 P.M.</td>
</tr>
<tr>
<td>Joint 24</td>
<td>10:15 A.M.</td>
<td>4:30 P.M.</td>
</tr>
<tr>
<td>Joint 25</td>
<td>12:30 P.M.</td>
<td>8:15 A.M.</td>
</tr>
<tr>
<td>Joint 26</td>
<td>2:15 P.M.</td>
<td>8:15 A.M.</td>
</tr>
</tbody>
</table>

After there was not a clear trend defined from the maximum and minimum occurrence time the joints that had the maximum and minimum faulting were isolated and analyzed separately to see if a trend between the faulting and temperature variations could be identified. If there was not a significant change in the faulting it will also allow the repeatability, ability to produce similar results consistently, of the system to be verified. The joint that had the maximum average faulting was joint 24 and the joint with the lowest average faulting was joint 6. Joint 20 was also examined in this analysis because it was the closest joint to the thermal logging devices that were installed into the slabs. The results showed that there was no clear trend between the faulting and the temperature that was recorded in the slabs. The average faulting variation on all three of these joints was less than 0.5 mm (0.02 in), so this indicates that the repeatability of the
system is sufficient and it can produce reliable faulting results. Figure 4.8 shows the average faulting distribution from joint 6, 20, 24, and the temperature variation that was measured between the top and bottom of the test slab.

![Figure 4.8 Joint 6, 20 and 24 Average Faulting Distributions](image)

**Figure 4.8 Joint 6, 20 and 24 Average Faulting Distributions**

4.4.2.2 Weigh Station Roughness Analysis

Like the faulting the roughness is a direct output from the 3D Line Laser software. The roughness is quantified using the International Roughness Index (IRI). The IRI is found by first defining the starting and end points of the test section then a longitudinal profile is created for each wheel path. These profiles are created from the 3D Line Laser range data and then are corrected using the IMU data so that the up and down motion of the vehicle is accounted for. The corrected profiles are then used to generate the IRI values for each wheel path. An algorithm simulates how a reference vehicle would respond if it traveled the profile. As this profile is traversed the algorithm accrues the suspension movement which is the IRI. For the 3D Line Laser this value is
reported in meters of suspension travel per kilometer that the sensing vehicle traveled (m/km).

Due to the lack of documented validation of the 3D Line Laser’s ability to measure the IRI of a pavement section it was necessary to perform a validation analysis to see how accurately the 3D Line Laser could measure the IRI. The method used to validate the 3D Line Laser IRI calculations and the results from the weigh station analysis is described in this subsection.

4.4.2.2.1 3D Line Laser IRI Validation

To validate how accurately that the 3D Line Laser can calculate the IRI of a pavement section it was essential to find a test site that the IRI was known for. While searching for a validation site it became known that the Florida Department of Transportation (FDOT) has three IRI test sections that they use to validate the equipment that they use to measure the IRI for quality control and rating of their roadways. The sensing vehicle was taken to each of these three test sites for data collection and IRI results were generated from the data that was collected.

Of the three sites one was a newly paved smooth section with a low IRI, one was an older rough section, and the third was somewhere in between rough and smooth. Each of the test sites was a 0.1 mile (0.161 km) test section that was labeled to ensure that the same pavement section was compared. The first test section was located in Hawthorne, Florida and was on S.E. 221 Street in the northbound travel lane. This was the rough section and had an IRI of 1.82 m/km (115.3 in/mile) in the left wheel path and 2.10 m/km (133.0 in/mile) in the right wheel path (This section was known as Section 10 to the
The second section was located on state route (S.R.) 20 approximately 7 miles (11.27 km) west of Hawthorne, Florida in lane 2 of the westbound direction. This section was the newer smooth pavement section having an IRI of 0.46 m/km (29.1 in/mile) in the left wheel path and 0.57 m/km (36.1 in/mile) in the right wheel path (This section is known as Section 11). The third and final IRI test section was located on county road (C.R.) 1471 in the westbound travel lane approximately 1 mile (1.609 km) west of its intersection with US Highway 301. This section has an IRI of 1.18 m/km (74.7 in/mile) in the left wheel path and 1.04 m/km (65.9 in/mile) in the right wheel path (This section was known as Section 12). Table 4.6 summarizes the ground truth values for each of the FDOT validation sections.

<table>
<thead>
<tr>
<th>Weigh Station</th>
<th>Wheel Path</th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>m/km</td>
<td>m/km</td>
</tr>
<tr>
<td></td>
<td></td>
<td>in/mile</td>
<td>in/mile</td>
</tr>
<tr>
<td>Section 10</td>
<td></td>
<td>1.82</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>115.3</td>
<td>133</td>
</tr>
<tr>
<td>Section 11</td>
<td></td>
<td>0.46</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29.1</td>
<td>36.1</td>
</tr>
<tr>
<td>Section 12</td>
<td></td>
<td>1.18</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>74.7</td>
<td>65.9</td>
</tr>
</tbody>
</table>

Each of the validation test sections were collected three times simultaneously with the sensing vehicle. This was done so that the amount of variation in the sensing vehicle results could also be assessed with the accuracy. Since the goal of the IRI analysis performed in this thesis was to determine how the temperature affected the IRI of a pavement section and how it changed throughout the day as the temperature fluctuated it was critical to know how much the IRI results could differ due to other effects rather than what was caused by temperature. The average variation of the IRI values calculated from
the 3D Line Laser data from the ground truth values was 0.086 m/km (5.45 in/mile) and the maximum variation was 0.3 m/km (19 in/mile). The IRI values that were derived from the sensing vehicle data are presented in Table 4.7.

<table>
<thead>
<tr>
<th>Section</th>
<th>Time</th>
<th>Left IRI (m/km)</th>
<th>Left IRI (in/mile)</th>
<th>Right IRI (m/km)</th>
<th>Right IRI (in/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Run 1</td>
<td>1.62</td>
<td>100.7</td>
<td>1.8</td>
<td>112.1</td>
</tr>
<tr>
<td></td>
<td>Run 2</td>
<td>1.64</td>
<td>102</td>
<td>2.07</td>
<td>128.6</td>
</tr>
<tr>
<td></td>
<td>Run 3</td>
<td>1.79</td>
<td>110.9</td>
<td>2.27</td>
<td>140.6</td>
</tr>
<tr>
<td>11</td>
<td>Run 1</td>
<td>0.58</td>
<td>36.1</td>
<td>0.59</td>
<td>36.7</td>
</tr>
<tr>
<td></td>
<td>Run 2</td>
<td>0.48</td>
<td>30.4</td>
<td>0.58</td>
<td>36.7</td>
</tr>
<tr>
<td></td>
<td>Run 3</td>
<td>0.5</td>
<td>31</td>
<td>0.67</td>
<td>41.8</td>
</tr>
<tr>
<td>12</td>
<td>Run 1</td>
<td>1.31</td>
<td>82.4</td>
<td>0.99</td>
<td>62.1</td>
</tr>
<tr>
<td></td>
<td>Run 2</td>
<td>1.27</td>
<td>79.8</td>
<td>1.04</td>
<td>65.9</td>
</tr>
<tr>
<td></td>
<td>Run 3</td>
<td>1.23</td>
<td>77.3</td>
<td>1.03</td>
<td>64.6</td>
</tr>
</tbody>
</table>

The next comparison that was made was to compare only the IRI values for each of the test sites that were generated from the sensing vehicle data. These results showed that the IRI values could vary an average of 0.16 m/km (10.14 in/mile). They also indicated that there could be as much as 0.47 m/km (29.77 in/mile) of variation in the IRI results. This high variation only occurred once and the next highest variation was 0.17 m/km (10.77 in/mile) and both of these higher variations occurred in the rougher test section. For the smooth test section and the test section in between smooth and rough all of the variation in the results were less than 0.1 m.km (6.33 in/mile). The variation of the IRI values that were generated from the 3D Line Laser data is given in Table 4.8.
Table 4.8 FDOT Test Sections 3D Line Laser IRI Variation

<table>
<thead>
<tr>
<th>Section</th>
<th>3D Line Laser IRI Variation</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left</td>
<td>(m/km)</td>
<td>(in/mile)</td>
<td>Right</td>
<td>(m/km)</td>
</tr>
<tr>
<td>Section 10</td>
<td>0.17</td>
<td>10.77</td>
<td>0.47</td>
<td>29.77</td>
<td></td>
</tr>
<tr>
<td>Section 11</td>
<td>0.1</td>
<td>6.33</td>
<td>0.09</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>Section 12</td>
<td>0.08</td>
<td>5.07</td>
<td>0.05</td>
<td>3.17</td>
<td></td>
</tr>
</tbody>
</table>

From these results it seems that further investigation is required to fully assess the accuracy of the IRI values that are generated using the sensing vehicle data. Due to the jump in the variation more runs of data should be collected to determine if this large variation is due to the accuracy of the system or if it is some random anomaly. The larger variations also occurred on the rougher test section so it may also be beneficial to test other test sections with varying smoothness conditions to see if the results always follow this trend. For this thesis it will be assumed that the 0.47 m/km (29.77 in/mile) is the accuracy of the IRI values generated from the sensing vehicle data and that if the results vary more than this then they could be due to the thermal effects on the test section. Otherwise it will be determined that the effects of the temperature on the test section are smaller than what can be depicted by the data collected by the sensing vehicle.

4.4.2.2.2 Weigh Station IRI Variation Analysis

The exact starting point of the IRI test path was defined as the intersection of the wheel paths and the first joint on the first labeled slab in the weigh station test section. The ending point of the IRI test path was taken as the intersection of the wheel paths and the second joint on the 25\(^{th}\) labeled slab in the test section. For the weigh station test section there was one IRI value for each wheel path in each data collection run. This
resulted in 88 IRI values or 44 IRI values for the left wheel path and 44 IRI values for the right wheel path to use to study how the IRI changed through the data collection. The average IRI for the left wheel path was 2.03 m/km (128.38 in/mile) and the average IRI for the right wheel path was 2.45 m/km (155.30 in/mile). Table 4.9 shows the statistics for the IRI results.

Table 4.9 Weigh Station IRI Statistics

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Weigh Station IRI</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(\text{m/km})</td>
<td>(\text{in/mile})</td>
<td>(\text{m/km})</td>
</tr>
<tr>
<td>Average</td>
<td>2.03</td>
<td>128.38</td>
<td>2.45</td>
</tr>
<tr>
<td>Median</td>
<td>2.04</td>
<td>129.23</td>
<td>2.44</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.1</td>
<td>6.27</td>
<td>0.16</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.33</td>
<td>147.6</td>
<td>3.02</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.84</td>
<td>116.56</td>
<td>2.18</td>
</tr>
<tr>
<td>Variation</td>
<td>0.49</td>
<td>31.04</td>
<td>0.84</td>
</tr>
</tbody>
</table>

The variation was found by subtracting the minimum IRI from each wheel path from the maximum IRI from each wheel path. The variation for the left wheel path was 0.49 m/km (31.04 in/mile) and for the right wheel path it was 0.84 m/km (53.21 in/mile). This indicates that the temperature gradient through the slab does have an impact on the IRI and should be considered when evaluating the smoothness of a concrete pavement section. The IRI values were then plotted to see how they varied during the course of the day. Figure 4.9 shows the plot of the IRI values versus time for each wheel path and the plot of the temperature difference between the top and bottom of the slab throughout the data collection versus time. This was included to see how the IRI correlated to the temperature variation.
The results from the right wheel path exhibit what is expected because the IRI shows a slight upward trend until around 7:45 A.M. Then the IRI slightly decreases until approximately 8:30 A.M. where it levels out until roughly 10:00 A.M where it begins to gradually rise until about 3:15 P.M. After 3:15 P.M. the IRI progressively begins to decrease. This trend is expected because in the morning the slabs are curled up somewhat due to the negative temperature gradient which causes the IRI to increase. Then as the temperature variation approaches zero and the slabs flatten out the IRI decreases until the positive temperature gradient causes the slabs to start to curl down. The downward curl of the slabs then begins to cause the IRI to rise until the temperature gradient reaches a maximum positive state. After this point is reached the temperature gradient decreases causing the slabs to curl less and the IRI to decrease. On the other
hand the IRI from the left wheel path does not follow this trend it seems to stay somewhat constant through the data collection with small peaks. These small peaks could possibly be caused by the accuracy of the IRI values that are produced by the 3D Line Laser.

4.4.2.3 Weigh Station Curvature Analysis

After it was determined that the curvature did have an impact on the IRI, it was analyzed to see if the 3D Line Laser could be used to measure the curvature. There is not a function in the 3D Line Laser software that allows the curvature of a slab to be assessed so a procedure had to be developed that would use the 3D Line Laser data to measure the curvature. This procedure would extract both the longitudinal and transverse curvature. This section briefly describes the steps that were taken to quantify the curvature and the conclusions that were made from it. The detailed method to extract the curvature from the 3D Line Laser data is in Appendix B of this thesis.

4.4.2.3.1 Longitudinal Curvature

There are two options to get longitudinal profiles from the data that was collected; the first is to use the raw 3D Line Laser range data. The second is to use the corrected profiles that were created from the raw 3D Line Laser range data and the IMU data. These are the same profiles that were used to calculate the IRI. For this analysis only the 3D line laser data was used to perform a curvature analysis. An explanation of why the raw data was used as opposed to the corrected data is provided in Appendix D.
An algorithm was created to read the raw 3D Line Laser range data and to combine the data from multiple files to create a complete profile. After the profile was attained then it had to be manually filtered to remove irregularities. Some of the irregularities that were encountered in the profiles include spikes caused by the joints, spikes caused by anomalies in the data (i.e. random error from the sensors), and large steps in the profiles that were caused by data from multiple sensors being combined together. Once the profiles were filtered then they were plotted in Excel and the trend line function was used to get a smooth profile for the slab. Then the trend line equation was used to get a numerical value for the curvature of the slab. To get a numerical value for the curvature the x position values were substituted into the trend line equation to get a y value for the beginning, middle and end of the profile. The beginning and end points were averaged to level out the profile and then the difference between this average value and the middle y value was taken as the quantitative curvature value.

For the weigh station three slabs were selected as test slabs to be examined for the curvature analysis. The slabs that were selected were the first slab, the thirteenth slab, and the twenty fifth slab. Since the center of the slab would undergo the most curvature the center longitudinal profile was selected for comparison because it would move the most it should be the easiest to measure. Each slab was collected in each run of data so a total of 26 profiles were extracted for each slab.

The first step of the curvature analysis was to compare all of the profiles collected for each slab to determine if the change through the day had a distinct definable pattern. All of the profiles were plotted and visually assessed. The results indicated that the shape of the slab did change through the day and that all three of the slabs exhibited a curled
down shape through the entirety of the data collection. Figure 4.10 shows all of the slab profiles that were extracted from the 3D line laser data for all three of the test slabs used in the curvature analysis at the weigh station.

![Figure 4.10 Longitudinal Profiles for Curvature Analysis at Weigh Station](image)

(a) Slab 1 Longitudinal Profiles

(b) Slab 13 Longitudinal Profiles
The profiles did not exhibit a continuous uniform curved shape, but had peaks and valleys. The exact cause of these peaks and valleys is not determinable from this analysis, but it is expected that they are due to the up and down vertical movement of the vehicle during the data collection. This vertical movement is introduced when the tires of the vehicle cross the joints. The affect does not occur directly at the joints in the profiles because the 3D sensors are positioned off the rear of the vehicle so there is an offset between them and the tires. It is expected that the magnitude of the peaks and valleys will be intensified when the speed of the vehicle is increased and as the amount of faulting increases. Further research is needed to investigate the changes in the profiles and what could be the possible causes.

After it was found that the profiles did show that there was a change in curvature particular profiles were isolated and compared to see if there was a clear trend that could
be correlated to the temperature variation that occurred during the data collection. The changes in air temperature during the data collection were evaluated to determine the times when the maximum and minimum temperature occurred. It was found that the maximum temperature occurred at 1:53 P.M and that the minimum temperature occurred at 5:53 A.M. The profiles collected in each of the runs closest to these times were extracted because it is expected that the temperature gradient should change the most between these two occurrences. The data collection runs that were used to obtain these profiles were the runs collected at 5:45 A.M and at 2:00 P.M.

All of the profiles were examined and the profiles that appeared to exhibit the most curvature were also pulled out for comparison. The profiles that were on the opposite end of the spectrum, the ones that appeared to be the flattest, were also taken out for comparison. It is expected that these conditions would occur at similar times for all three of the slabs if the temperature affected all of the slabs in a similar manner.

For slab 1 the profile that was collected at 1:15 P.M (1315 in figure 4.11) had the flattest shape out of all of the profiles and the profile collected at 8:15 A.M (815 in figure 4.11) showed the most curvature out of all of the profiles. These profiles indicated that slab 1 curled down more from 5:45 A.M to 8:45 A.M. This is feasible if the slab has a built in curvature that is curled down because as the temperature gradient is negative and approaches zero (form 5:45 A.M. to 8:45 A.M.) the magnitude of the curled up shape created by the negative temperature gradient is reduced causing the curvature to increase. The profiles collected toward the end of the data collection at 1:15 P.M and 2:00 P.M should show an increase in the curvature from what was measured because as the temperature gradient increases positively the slab should curl down more and heightened
the built in curvature causing a higher overall curvature. These profiles do not follow this expected trend. Figure 4.11 shows the four profiles that were further analyzed for slab 1 at the weigh station.

For slab 13 the profile with the maximum curvature was collected at 9:30 A.M (930 in figure 4.12) and the profile with the least curvature was collected at 1:15 P.M (1315 in figure 4.12). The profiles for slab 13 followed a trend that was similar to the trend of the profiles for slab 1, except the profile with the maximum curvature occurred at 9:30 A.M rather than at 8:15 A.M which is when the maximum curvature occurred for slab 1. Figure 4.12 shows the profiles that were further analyzed for slab 13 at the weigh station.
For slab 25 the profile with the least amount of curvature was collected at 1:00 P.M (1300 in figure 4.13). There was not a single profile that could be isolated and clearly identified as the maximum curvature for slab 25. However there were 6 profiles that showed a similar trend and magnitude for the maximum curvature profile. The 6 profiles that were examined for the maximum curvature were the profiles collected at 6:45 A.M. (645 in figure 4.13), 7:30 A.M. (730 in figure 4.13), 9:45 A.M. (945 in figure 4.13), 10:00 A.M. (1000 in figure 4.13), 10:30 A.M. (1030 in figure 4.13), and 2:00 P.M (1400 in figure 4.13). The profiles indicate that the curvature increased to a maximum at 6:45 A.M. The curvature profiles collected after 6:45 A.M. would either be similar to the one collected at 6:45 A.M. or they would be slightly less curved until 1:00 P.M. (1300 in figure 4.13) which is when the flattest profile occurred. After 1:00 P.M. (1300 in figure 4.13) the profile began to show an increase in the curvature where it reached the maximum again in the profile collected at 2:00 P.M. (1400 in figure 4.13). Figure 4.13
shows the profiles that were compared for the more in depth curvature profile analysis for slab 25 at the weigh station.

![Figure 4.13 Weigh Station Slab 25 Profiles](image)

After the slab profiles were visually examined a quantitative curvature value was obtained for each slab from each data collection run using the proposed methodology in Appendix B. This resulted in a data set of 26 quantitative curvature values for each of the slabs. Figure 4.14 shows one of the longitudinal profiles for slab 1 along with the trend line that was used to quantify the curvature. The profile in the figure indicates that the slab is curled 2.79 mm (0.11 in).
The curvature values were compared throughout the data collection to see if there was a trend that could be correlated to the temperature variation that occurred. The results from slab 1 showed a parabolic trend that seemed to show a correlation to the temperature. However there were several dips in the curvature plot that suggested the curvature changed by an unlikely magnitude in a short time period. The curvature changes for slab 13 and 25 show a large amount of variation between the curvatures measured from consecutive runs, in some cases it was as high as 12.09 mm (0.48 in). It is unlikely that the curvature undergoes a change of this magnitude in such a short time period. Figure 4.15 shows the quantitative curvature results that were measured on slab 1, 13, and 25 at the weigh station.
4.4.2.3.2 Transverse Curvature

The transverse curvature was also evaluated. The profiles were extracted, processed and analyzed in the same manner as the longitudinal profiles were from the raw 3D Line Laser data. The quantitative curvature values were found using the trend line function and subbing into the equation the same way as the longitudinal quantitative curvature values were found. The first, thirteenth, and twenty fifth slabs were used for this analysis also. The profile that passed through the center of the slab was used. This profile was not perfectly perpendicular to the travel direction but was at a 15° angle from the transverse direction.

For each slab there were 26 profiles, one from each data collection run. The results for slab one show that the curvature did not change during the data collection it...
remained constant at 8.64 mm (0.34 in). The results for slab 13 indicate that the curvature remained constant at 10.80 mm (0.425 in) until 10:15 A.M. where it jumped to 12.97 mm (0.51 in). The curvature then returned to 10.80 mm (0.425 in) in the 10:30 A.M. run and jumped back to 12.97 mm (0.51 in) in the 12:45 P.M. to 1:45 P.M. runs. In the final data collection run, collected at 2:00 P.M., the curvature returned to 10.80 mm (0.425 in). The results for slab twenty five showed that the curvature jumped back and forth from 10.80 mm (0.425 in) to 12.97 mm (0.51 in) in the data collected between 5:45 A.M. to 10:30 A.M. In all of the runs collected from 12:45 P.M. to 2:00 P.M. the curvature remained constant at 12.97 mm (0.51 in). Figure 4.16 shows the curvature values for the three slabs throughout the day.

4.5 Summary

This chapter described the procedures that were developed to collect thermal and 3D Line Laser data at a test site. After the weigh station was selected as a suitable test site a procedure was developed to install the thermocouples and to collect data with them in a way that the thermal information in the slab could be correlated to the 3D Line Laser
data. The thermal data was used to determine when to collect the 3D Line Laser data. Once the 3D Line Laser data was collected it was processed and analyzed to see if the system were capable of detecting the changes in the concrete pavement characteristics caused by thermal variations in the slab. The characteristics that were evaluated included the faulting of the transverse joints and the smoothness.

The faulting results indicated that the thermal effects on the faulting were smaller than what could be detected by the sensors in most of the cases observed. Out of the 26 joints that were examined 4 exhibited a variation in the faulting that was greater than the accuracy of the system, so these four cases were looked at in greater detail and it was determined that the variation was less than 1 mm (0.04 in). This is the accuracy that equipment used to automatically measure is required to have according to the governing specifications, so the variation caused by the thermal effects on the slab would not have a significant impact on the faulting results that are found using an automated method.

The accuracy of the IRI values obtained from the 3D Line Laser data was assessed to determine how much variation could be introduced into the IRI results from factors other than temperature variations. It was found that the results could vary up to 0.47 m/km (29.77 in/mile), but typically varied an average of 0.16 m/km (10.14 in/mile). It was suggested that the accuracy of the system be investigated further and to assume that variations less than the 0.47 m/km (29.77 in/mile) be considered as variations caused by effects other than temperature variations. The IRI results from the weigh station showed that the temperature change during the day can cause some variation in the IRI values. The IRI values from the right wheel path exhibited variation greater than the
assessed accuracy so it was affected by the temperature changes that occurred during the
data collection. However the IRI values from the left wheel path varied less than the
assessed accuracy so it did not appear to be affected by the temperature changes. The
difference in the behavior of the left and right wheel paths may be due to the large shift in
the variation of the IRI values used to assess the accuracy of the IRI values produced by
the 3D Line Laser.

The results from the curvature analysis show that the proposed methodology and
the 3D line lasers ability to measure the curvature of a concrete slab needs to be further
investigated. For the three slabs only the longitudinal curvature values from slab 1
showed a weak correlation with the temperature while the other two showed as much as
12.09 mm (0.48 in) of variation between the curvatures measured between consecutive
data collection runs. The results from the transverse curvature analysis showed that the
transverse curvature measured on slab 1 did not change throughout the data collection.
The transverse curvature results from slab 13 and 25 showed a change of 2.16 mm (0.085
in) in the curvatures measured between consecutive data collection runs. This method
should be compared to ground truth values to determine if the results that were generated
actually depict the curvature that occurs in the slabs. If the results do not sufficiently
represent the curvature of the slab then the proposed method needs to be refined and
modified so that adequate curvature results can be attained. Once this method is proved
to be a suitable method to measure the curvature then it should be compared to current
curvature measuring techniques, such as road profilers and LIDARs, to determine which
the best method is.
CHAPTER 5
INITIAL I-16 INVESTIGATION

With the successful implementation of a data collection and analysis procedure to evaluate the effects that the thermal gradient in a concrete slab has on its characteristics on an isolated site there was a need to test the same procedure on an in service pavement section. This is a necessity since concrete condition evaluation surveys are performed on in service pavements. This chapter summarizes the site that was selected to perform the initial study on an in service concrete pavement section and the results from the analyses that were performed using the data collected at the site.

5.1 Site Selection

A short test section was chosen on Interstate 16 near the weigh station test section. This site was chosen because of its close proximity to the weigh station it would allow the data to be collected on this site simultaneously with the weigh station site. A site that spanned 25 slabs and covered 26 joints was labeled just past the weigh station on ramp, which allows the traffic from the weigh station to merge back onto I-16. The end of the test section was just before the exit 143 off ramp this would allow the weigh station site and the initial I-16 site to be collected in one continuous data collection run and would help minimize the effort required to collect the data. The data collection path that was taken was to start in the main lane of the weigh station just before the beginning of the weigh station test section. The data would then be collected through the weigh station test section, and then the sensing vehicle would merge onto I-16, would traverse through the initial I-16 test section and then merge off of I-16 onto the Exit 143 off ramp.
where the data collection would be stopped at the stop sign. After the data collection run was finish the vehicle would merge back onto I-16 east bound past the weigh station and would turn back onto I-16 west bound using the emergency vehicle turn around past the weigh station. The sensing vehicle would then return to the main lane of the weigh station where it would remain stationary on the shoulder until time for the next data collection run. Figure 5.1 shows the location of the initial I-16 test section.

![Figure 5.1 Initial I-16 Test Site](image)

The initial I-16 test section was completed in 1968 and was composed of 10 inch (254 mm) thick concrete slabs. The joint orientation at the site was square and a 30 feet (9.144 m) joint spacing was used. The slabs were 12 feet (3.66 m) wide and were supported by an 8 inch (203.2 mm) soil base with a 3 inch (76.2 mm) bituminous stabilized asphalt interlayer. The slabs were bordered by a hot mix asphalt (HMA) shoulder and there were no dowels used to reinforce the joints from faulting. As with the
Weigh Station the CTE was unknown for this section so it is also assumed to have an approximate value of 4.911 µε/°F (8.840 µε/°C) (Kim, 2012).

5.2 Initial I-16 Site Faulting Analysis

Since the initial I-16 test section also spanned 25 slabs and covered 26 joints like the weigh station test section there was also a data set of 1144 average faulting values to use to study the faulting. These average faulting were aggregated from about 26,000 faulting measurements that were taken on the joints of the I-16 test section. The average faulting of the initial I-16 test section was 1.51 mm (0.059 in) and the average faulting ranged from 0.21 mm (0.008 in) to 4.59 mm (0.181 in). The results from the statistical analysis performed on the average faulting from the initial I-16 test section are presented in Table 5.1.

<table>
<thead>
<tr>
<th>Initial I-16 Average Faulting</th>
<th>(mm)</th>
<th>(in)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average</strong></td>
<td>1.51</td>
<td>0.059</td>
</tr>
<tr>
<td><strong>Median</strong></td>
<td>1.42</td>
<td>0.056</td>
</tr>
<tr>
<td><strong>Maximum</strong></td>
<td>4.59</td>
<td>0.181</td>
</tr>
<tr>
<td><strong>Minimum</strong></td>
<td>0.21</td>
<td>0.008</td>
</tr>
<tr>
<td><strong>Standard Deviation</strong></td>
<td>0.69</td>
<td>0.027</td>
</tr>
<tr>
<td><strong>25th Percentile</strong></td>
<td>1.21</td>
<td>0.048</td>
</tr>
<tr>
<td><strong>75th Percentile</strong></td>
<td>1.66</td>
<td>0.065</td>
</tr>
</tbody>
</table>

The variation of the average faulting on the initial I-16 test section was also evaluated to see if the pavement different pavement design had more or less faulting variation than the weigh station test section due to thermal effects. The variation of the initial I-16 test section average faulting values was found using the same method that was
used to find the average faulting variation on the weigh station test section, which was to locate the maximum average faulting and subtract the minimum average faulting from it. The average faulting variation ranged from 0.31 mm (0.012 in) to 0.71 mm (0.028 in). Of the 26 values five of them were greater than 0.5 mm (0.02 in) which is the accuracy of the 3D Line Laser sensors. The maximum of these values was 0.71 mm (0.028 in) which is less than the 1 mm (0.04 in) accuracy requirement set in the AASHTO R36-04 specification for automated faulting measurement methods.

It was assumed that the temperature gradient in the initial I-16 test section would behave similar to the temperature gradient at the weigh station test section. Based on this assumption it is presumed that the maximum positive, maximum negative and zero variation curvature conditions would occur at approximately the same time. Considering this it was supposed that the faulting measurements would be affected the most by the temperature during the data collection runs collected when these variation conditions occurred. These variation conditions occurred at 6:45 A.M., 7:00 A.M, 9:15 A.M, and 3:00 P.M, so the average faulting values from the runs collected at these times were isolated and the variation between them was found. This variation was compared to the variation found using all of the data collection runs. It was observed that none of the greatest changes in the average faulting occurred at time same time as the specified temperature variation conditions. Table 5.2 shows the variation in the average faulting at the initial I-16 test section from all of the data collection runs and from the runs that correspond to the specified temperature variation conditions.
Table 5.2 Initial I-16 Average Faulting Variation Detailed Analysis Results

<table>
<thead>
<tr>
<th>Joint</th>
<th>All Data Collection Runs</th>
<th>Runs Collected at 6:45 A.M, 7:00 A.M, 9:15 A.M, 3:00 P.M</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mm)</td>
<td>(in)</td>
</tr>
<tr>
<td>Joint 1</td>
<td>0.37</td>
<td>0.015</td>
</tr>
<tr>
<td>Joint 2</td>
<td>0.41</td>
<td>0.016</td>
</tr>
<tr>
<td>Joint 3</td>
<td>0.48</td>
<td>0.019</td>
</tr>
<tr>
<td>Joint 4</td>
<td>0.4</td>
<td>0.016</td>
</tr>
<tr>
<td>Joint 5</td>
<td>0.49</td>
<td>0.019</td>
</tr>
<tr>
<td>Joint 6</td>
<td>0.52</td>
<td>0.02</td>
</tr>
<tr>
<td>Joint 7</td>
<td>0.52</td>
<td>0.02</td>
</tr>
<tr>
<td>Joint 8</td>
<td>0.41</td>
<td>0.016</td>
</tr>
<tr>
<td>Joint 9</td>
<td>0.5</td>
<td>0.02</td>
</tr>
<tr>
<td>Joint 10</td>
<td>0.54</td>
<td>0.021</td>
</tr>
<tr>
<td>Joint 11</td>
<td>0.43</td>
<td>0.017</td>
</tr>
<tr>
<td>Joint 12</td>
<td>0.42</td>
<td>0.017</td>
</tr>
<tr>
<td>Joint 13</td>
<td>0.32</td>
<td>0.012</td>
</tr>
<tr>
<td>Joint 14</td>
<td>0.45</td>
<td>0.018</td>
</tr>
<tr>
<td>Joint 15</td>
<td>0.59</td>
<td>0.023</td>
</tr>
<tr>
<td>Joint 16</td>
<td>0.34</td>
<td>0.013</td>
</tr>
<tr>
<td>Joint 17</td>
<td>0.41</td>
<td>0.016</td>
</tr>
<tr>
<td>Joint 18</td>
<td>0.37</td>
<td>0.014</td>
</tr>
<tr>
<td>Joint 19</td>
<td>0.38</td>
<td>0.015</td>
</tr>
<tr>
<td>Joint 20</td>
<td>0.35</td>
<td>0.014</td>
</tr>
<tr>
<td>Joint 21</td>
<td>0.71</td>
<td>0.028</td>
</tr>
<tr>
<td>Joint 22</td>
<td>0.37</td>
<td>0.015</td>
</tr>
<tr>
<td>Joint 23</td>
<td>0.48</td>
<td>0.019</td>
</tr>
<tr>
<td>Joint 24</td>
<td>0.57</td>
<td>0.022</td>
</tr>
<tr>
<td>Joint 25</td>
<td>0.43</td>
<td>0.017</td>
</tr>
<tr>
<td>Joint 26</td>
<td>0.31</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Since the actual temperature gradient in the initial I-16 test section was not measured the occurrence time of the maximum and minimum average faulting was evaluated to see if there was a clear trend in the faulting variation. The results indicated that there was no clear trend for the maximum and minimum average faulting occurrence.
time. These results were also compared to the weigh station occurrence times for the maximum and minimum average faulting to see if there was any correlation between the two. This comparison yielded that there was no relationship between the two data sets. Table 5.3 shows the maximum and minimum average faulting occurrence times for the initial I-16 and weigh station test sections.

### Table 5.3 Maximum and Minimum Average Faulting Occurrence Times

<table>
<thead>
<tr>
<th>Joint</th>
<th>Initial I-16 Site</th>
<th>Weigh Station</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum Time</td>
<td>Minimum Time</td>
</tr>
<tr>
<td>Joint 1</td>
<td>2:30 P.M.</td>
<td>7:15 A.M.</td>
</tr>
<tr>
<td>Joint 2</td>
<td>10:45 A.M.</td>
<td>7:45 A.M.</td>
</tr>
<tr>
<td>Joint 3</td>
<td>7:45 A.M.</td>
<td>8:30 A.M.</td>
</tr>
<tr>
<td>Joint 4</td>
<td>2:45 P.M.</td>
<td>1:00 P.M.</td>
</tr>
<tr>
<td>Joint 5</td>
<td>8:30 A.M.</td>
<td>1:00 P.M.</td>
</tr>
<tr>
<td>Joint 6</td>
<td>10:15 A.M.</td>
<td>11:30 A.M.</td>
</tr>
<tr>
<td>Joint 7</td>
<td>12:30 P.M.</td>
<td>7:30 A.M.</td>
</tr>
<tr>
<td>Joint 8</td>
<td>3:45 P.M.</td>
<td>10:15 A.M.</td>
</tr>
<tr>
<td>Joint 9</td>
<td>10:00 A.M.</td>
<td>9:45 A.M.</td>
</tr>
<tr>
<td>Joint 10</td>
<td>7:30 A.M.</td>
<td>11:15 A.M.</td>
</tr>
<tr>
<td>Joint 11</td>
<td>12:30 P.M.</td>
<td>8:00 A.M.</td>
</tr>
<tr>
<td>Joint 12</td>
<td>9:30 A.M.</td>
<td>2:30 P.M.</td>
</tr>
<tr>
<td>Joint 13</td>
<td>5:30 A.M.</td>
<td>3:00 P.M.</td>
</tr>
<tr>
<td>Joint 14</td>
<td>2:30 P.M.</td>
<td>10:15 A.M.</td>
</tr>
<tr>
<td>Joint 15</td>
<td>8:45 A.M.</td>
<td>4:15 P.M.</td>
</tr>
<tr>
<td>Joint 16</td>
<td>9:45 A.M.</td>
<td>2:15 P.M.</td>
</tr>
<tr>
<td>Joint 17</td>
<td>6:45 A.M.</td>
<td>12:45 P.M.</td>
</tr>
<tr>
<td>Joint 18</td>
<td>11:30 A.M.</td>
<td>11:45 A.M.</td>
</tr>
<tr>
<td>Joint 19</td>
<td>5:00 P.M.</td>
<td>11:45 A.M.</td>
</tr>
<tr>
<td>Joint 20</td>
<td>12:30 P.M.</td>
<td>7:15 A.M.</td>
</tr>
<tr>
<td>Joint 21</td>
<td>10:45 A.M.</td>
<td>1:45 P.M.</td>
</tr>
<tr>
<td>Joint 22</td>
<td>1:15 P.M.</td>
<td>4:30 P.M.</td>
</tr>
<tr>
<td>Joint 23</td>
<td>8:45 A.M.</td>
<td>12:30 P.M.</td>
</tr>
<tr>
<td>Joint 24</td>
<td>5:15 P.M.</td>
<td>5:00 P.M.</td>
</tr>
</tbody>
</table>
Table 5.3 (Continued)

| Joint 25 | 9:15 A.M. | 10:30 A.M. | 12:30 P.M. | 8:15 A.M. |
| Joint 26 | 7:15 A.M. | 1:45 P.M.  | 2:15 P.M.  | 8:15 A.M. |

The average faulting for each joint was plotted so that the distribution of the average faulting through the test site could be assessed visually. The plot reveals that the faulting for the site is similar for most of the slabs. The most noticeable shift in the plot occurs at the 24\textsuperscript{th} joint where the average faulting is nearly double the rest of the average faulting for the site. Figure 5.2 shows the distribution of the average faulting at the initial I-16 test site.

![Figure 5.2 Average Faulting Distribution at Initial I-16 Site](image)

This led to further investigation of joint 24 to determine if the cause of the jump in the average faulting could be identified. Both the intensity and range data collected by the 3D Line Laser were reviewed along with the backward facing camera in the Geo3D
system to determine the cause of the high average faulting value. From this review it was
established that the cause of the high average faulting value is due to the fact that slab
number 24 is a broken slab. Since slab 24 is broken it caused the beginning of the slab to
settle more than any of the surrounding slabs in the test section. This indicates that if
the faulting of a concrete pavement section is analyzed with sufficient detail it may be
able to locate other forms of distress and provide aid when determining treatment options.
The faulting measurements that were taken at each position on joint 24 from each data
collection runs were average to verify that the results from the analysis did depict what
was actually observed in the field. The results indicated that the faulting grew roughly
linearly from left to right, which is logical because the broken slab is likely caused by
lack of support at the corner. So, when the slab breaks the corner is the lowest point on
the slab and the location of the highest faulting. Figure 5.3 shows the range and intensity
data collect by the 3D Line Laser, the video log image captured by the back facing
camera of the Geo3D system and the average faulting from each position for slab 24.
(b) 3D Line Laser Range Data for Joint/Slab 24

(c) Geo3D Back Camera Image for Joint/Slab 24
Figure 5.3 continued
The average faulting for joint 24 from all of the data collection runs were analyzed individually to determine if there was more affects from the thermal gradient on the broken slab. The average faulting variation that joint 24 exhibited during the data collection was 0.57 mm (0.022 in). This variation is only slightly larger than the 0.5 mm (0.02 in) accuracy of the 3D Line Laser sensors so it is likely that the thermal affects are not more severe on the broken slab than they are on a normal concrete slab. The average faulting properties of Joint 24 are given in Table 5.4. Figure 5.4 shows the distribution of the average faulting for Joint 24 throughout the data collection.
Table 5.4 Joint 24 Average Faulting Properties

<table>
<thead>
<tr>
<th></th>
<th>(mm)</th>
<th>(in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>4.34</td>
<td>0.17</td>
</tr>
<tr>
<td>Median</td>
<td>4.33</td>
<td>0.17</td>
</tr>
<tr>
<td>Maximum</td>
<td>4.59</td>
<td>0.18</td>
</tr>
<tr>
<td>Minimum</td>
<td>4.02</td>
<td>0.16</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.13</td>
<td>0.01</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>4.27</td>
<td>0.02</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>4.45</td>
<td>0.18</td>
</tr>
<tr>
<td>Variation</td>
<td>0.57</td>
<td>0.022</td>
</tr>
</tbody>
</table>

Figure 5.4 Joint 24 Faulting Distribution

The average faulting distributions for the joints were compared to the temperature variation between the top and bottom of the test slab at the weigh station to see if there was a relationship between them and to further test the repeatability of the system’s ability to measure the faulting. The results showed that both joints exhibited a level trend while the temperature variation showed a gradual increase through the data collection. This provides additional evidence that the temperature variations did not impact the faulting that was measured at the Initial I-16 test site. The variation on joint 1 was 0.37
mm (0.015 in) and the variation on joint 24 was 0.57 mm (0.015 in). These are minimal variations and show that the system is capable of repeatedly producing consistent faultring measurements on concrete pavement joints. Figure 5.5 shows the average faulting distributions for joint 1 and joint 24 at the initial I-16 test section.

![Figure 5.5 Joint 1 and Joint 24 Average Faulting Distributions at Initial I-16 Test Site](image)

After the average faulting distribution were examined to determine that they did not exhibit a trend that was correlated to the temperature variation the individual faulting measurements were evaluated to find out if there was a link between them and the change in temperature. For this joint 24 was selected because it had the greatest amount of faulting. The higher faulting is desired because it is expected that as the faulting increases the affects if the temperature variation will be accentuated and have a greater effect on the faulting. The particular profiles that were chosen were the ones collected at 6:45 A.M., 7:00 A.M, 9:15 A.M., and 3:00. These were chosen because the thermal data that was collected at the weigh station showed that these were the times that the critical
curvature conditions happened. These plots indicated that there was deviation in the faulting that was measured at individual points, but it is inconclusive as to whether it is caused by temperature changes or if it is due to slight shifts in the measurement position due to minor fluctuations in the pavement marking detection. It is suggested that this be further investigated to determine if the variation is due to the measurement position or if it is due to the temperature variations and whether or not it is significant enough to be concerned with. Figure 5.6 shows the faulting across joint 24 for the four critical collection runs.

![Figure 5.6 Faulting Measurements across Joint 24](image)

### 5.3 Initial I-16 Site Roughness Analysis

The longitudinal profiles that were defined at the initial I-16 test site started at the intersection of the first labeled joint and the wheel path. The longitudinal profiles that were used ended at the intersection of the last joint (26th Joint) in the test section and the wheel path. Just like the weigh station IRI data set the initial I-16 IRI data set was composed of 88 IRI values, 44 of which were for the left wheel path and 44 for the right
wheel path. The average IRI for the left wheel path was 1.05 m/km (66.41 in/mile) and was 1.08 m/km (68.51 in/mile). The IRI ranged from 0.94 m/km (59.55 in/mile) to 1.16 m/km (73.48 in/mile) in the left wheel path and ranged from 0.98 m/km (62.08 in/mile) in the right wheel path. Table 5.5 shows the results from the statistical analysis performed on the IRI values from the initial I-16 test section.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Initial I-16 IRI</th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>1.05</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>1.05</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>1.16</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>0.94</td>
<td>0.98</td>
</tr>
</tbody>
</table>

The variation in the IRI of the initial I-16 test section was examined to determine how much it varied throughout the data collection. The variation in the left wheel path was 0.22 m/km (13.94 in/mile) and was 0.34 m/km (21.54 in/mile) in the right wheel path. These results show that the IRI did vary throughout the day as the data was collected. The variation in the IRI results was less than the maximum variation of 0.47 m/km (29.77 in/mile), which was assessed as the possible variation that could be in the IRI results that are measured by the 3D Line Laser. However the initial I-16 test section was a smoother section and had an average IRI similar to that of FDOT test section 12 that was used to validate the IRI values measured by the sensing vehicle. The variation in the IRI results measured by the sensing vehicle for the FDOT test section 12 was 0.08
m/km (5.07 in/mile) for the left wheel path and 0.05 m/km (3.17 in/mile) for the right wheel path. Using these results it seems that the variation in the IRI results could be from the temperature changes during the data collection rather than from the accuracy of the sensing vehicle.

The distribution of the IRI for the left and right were compared to the recorded difference in the temperature of the top and bottom of the reference slab from the weigh station. It is expected that the IRI will increase as the magnitude of the temperature variation increases. The increase in the IRI is caused by the movement of the slabs which should be maximized as the temperature variation reaches a maximum magnitude. The trend of the IRI that was measured in the left and right wheel path followed this expected trend showing a gradual increase in the IRI as the temperature difference increased. However there were sudden spikes in the distribution which could more than likely be attributed to variation that is introduced by the accuracy of the IRI values measured by the sensing vehicle. Figure 5.7 shows the left and right IRI distribution for the initial I-16 test site and the difference in the top and bottom of the test slab at the weigh station.

![Figure 5.7 IRI Distribution at Initial I-16 Test Site](image-url)
The longitudinal profiles that were created and used to measure the IRI were examined in more detail to determine if the broken slab had a noticeable impact on the IRI values that were measured. It was observed that the spike in the longitudinal profile at joint 24 was indeed higher than the rest of the spikes in the profile that typically occur from the vehicle crossing a joint. For most of the profiles it was observed that the height of the spike at joint 24 was almost double the height of the spikes at the other joints. This is what is expected because the broken slab increases the faulting which in turn increases the IRI of the test section. So this indicates that shifts in the longitudinal profiles used to measure the IRI of a pavement section can also indicate other distresses, such as broken slabs like Slab 24, and can be beneficial to pavement condition evaluators. Figure 5.8 shows the longitudinal profiles that were created from the data collected at 2:30 P.M., the location of joint 24 is identified and the higher spike can clearly be identified.

![Figure 5.8 Longitudinal Profiles Collected at 2:30 P.M. used to indicate the Location of Broken Slab at Joint 24](image)

### 5.4 Summary

To determine if an in service concrete pavement section would behave similar to the weigh station an initial site was chosen on I-16. The particular site that was chosen was selected because of its close proximity to the weigh station which would minimize the data collection effort. After the data was collected at the site it was analyzed to
generate faulting and smoothness results that could be studied to evaluate how the characteristics changed as the temperature fluctuated. The key characteristics that were extracted from the analysis were the faulting of the joints and the smoothness of the entire test section.

Of the 26 joints inspected on the initial I-16 test section, 21 of them had a variation less than 0.5 mm (0.02 in) which is less than the accuracy of the 3D Line Laser sensors. Since it is likely that the variation in these particular average faulting values is caused by the sensors ability it is likely that the variation is not caused by the slabs response to the thermal gradient in it. However the remaining 5 joints did exhibit a variation in the average faulting that was greater than the possible variation caused by the accuracy of the sensors, but there was not a clear trend between the average faulting variation and the temperature change through the data collection. The individual faulting measurements were also evaluated to see if there was a noticeable trend with the temperature. There was some variation in the results, but it was inconclusive as to whether it was caused by the measurement position or the temperature variation. It is likely that the variation that was not due to the system accuracy was caused by the slight position changes between the faulting measurement locations. The location of the faulting measurement is dependent on how the algorithm detects the pavement marking which can vary a little between data collection runs and the surface texture could be a little different between the measurement locations or there could be some other form of distress interfering with the faulting measurement. It was also found that the thermal gradient in the slab does not have a more significant impact on the average faulting when the slab is broken because the variation in the average faulting on the broken slab (Slab
24) was not the greatest amount of variation that was observed. Although there is the possibility that the temperature will affect the faulting results it may not be detected in the automated faulting measurements using other devices because the variation is less than the 1 mm (0.04 in) requirement set forth in governing specifications.

The IRI results that were obtained indicated that there was a possibility of a slight variation in the results due to the temperature gradient in the slabs. The variation of the IRI in the left wheel path was 0.22 m/km (13.94 in/mile) and was 0.34 m/km (21.54 in/mile) in the right wheel path. These values seem to be accredited to the variability of the system’s ability to measure the IRI. This was assessed in Chapter 4 and it was found that the IRI measurements could vary up to 0.47 m/km (29.77 in/mile). This variation occurred in the roughest test section that was used for the validation of the IRI values obtained using the sensing vehicle. Since the initial I-16 test site was smoother than this test section it may be more valid to use the variation of the validation section that had an IRI closer to what was observed at the initial I-16 test site. The validation section that was similar to the initial I-16 test section was section 12 and it has a maximum variation of 0.08 m/km (5.07 in/mile). Based on this it is clear that there is a significant change in the IRI values, and it is very probable that it is due to the thermal effects on the slabs.
CHAPTER 6

FINAL I-16 INVESTIGATION

After the developed procedure was executed on an in service concrete pavement section, it needed to be performed on more in service test sections to encompass multiple pavement designs. This would determine if different concrete pavement designs behave differently when subjected to temperature variations. This section describes the sites that were selected for the final study on in service pavements and expounds on the analysis results and the findings that discovered.

6.1 Site Selection

Four test sections were chosen on Interstate 16 near Danville between milepost 37 and milepost 38.5 on the east bound travel lane. This particular location was chosen because in 2012 from milepost 32 to milepost 38, lane 2 was reconstructed. The pavement design at this site was different from all other concrete pavement sections in Georgia because it was the first to use a fabric interlayer between the concrete pavement and the base instead of an asphalt interlayer which is normally used. The fabric interlayer was of interest because it costs approximately 20% of what the typical 3 inch (76.2 mm) asphalt interlayer cost, so it is desired to determine if there is any impact on the concrete pavement characteristics from the interlayer.

The first test section (Section A) was selected in this new pavement segment and the other three were selected in the different pavement segments surrounding the new pavement segment. The next test section that was selected included the slabs in lane 1
that were adjacent to Section A, this section was named Section C. Sections A and C were located just before milepost 38. The next two test sections were selected between milepost 38, the end of the newly constructed pavement, and the off ramp for exit 39. The first of these sections was located in lane 2 and was identified as Section B and the final test section was adjacent to Section B in lane 1 and was identified as Section D.

Each of these test sections covered 25 slabs which consisted of 26 joints that were labeled so they could easily be located in each run of the data that was collected. These sections were selected in close proximity to each other so that the data that was collected could be collected on all of the sections within minutes of each other. This would help minimize the amount of temperature variation that would occur between the sections for the data collection runs that would be collected at each time. Figure 6.1 shows an aerial view of the four pavement test section that were labeled and used for the final I-16 analysis.

(a) Overhead View
Figure 6.1 Final I-16 Test Site
(b) Test Sections A, B, C, and D
Figure 6.1 continued
Section A was completed in 2012 and consisted of concrete slabs that were 11 inches (279.4 mm) thick. These slabs were 13.5 feet (4.115m) wide and the square joints were spaced 15 feet (4.573 m). The support for the slabs was an 8 inch (203.2 mm) cement modified based and this base was separated from the slabs by a fabric interlayer. The joints were reinforced with dowels and the slabs were enclosed by a concrete shoulder. Figure 6.2 shows an example image the front center video log that was collected to provide a visual idea of section A.

![Figure 6.2 Section A Video Log Image](image)

The pavement design of Sections B, C, and D are the same except for the type of shoulder that surrounds them. The three sections are composed of 9 inch (228.6 mm) thick slabs that were constructed in 1970. The joints are square and are spaced at 30 ft
(9.144 m). The slabs were 12 feet (3.66 m) wide and are supported by a 6 inch (152.4 mm) soil cement base that was not separated from the slabs with an interlayer. Dowels were not inserted to support the joints and to assist in the prevention of faulting. Sections B and D were both surrounded by a hot mix asphalt shoulder. While Section C was bordered by a concrete shoulder that was constructed during the construction project that include the reconstruction of lane 2 in 2012. Table 6.1 provides a summary of all of the pavement designs that were incorporated in this thesis. Another important note about Section D is that it had recently been diamond ground so it is expected that the faulting and roughness should be minimal for this site. Figure 6.3 shows an example image from the front center video log for Sections B, C, D, and milepost 38 that shows all of the different pavement designs. The CTE for the pavement designs at the Final I-16 test site were unknown so it is also assumed that they would have a CTE around 4.911 µε/°F (8.840 µε/°C) which has been measured for other Georgia pavements (Kim, 2012).
(b) Section C

(c) Section D
Figure 6.3 continued
(d) Milepost 38, Transition Between all Pavement Designs

Figure 6.3 continued

Table 6.1 Concrete Pavement Design Summary

<table>
<thead>
<tr>
<th></th>
<th>Weigh Station</th>
<th>Initial I-16</th>
<th>Section A</th>
<th>Section B</th>
<th>Section C</th>
<th>Section D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab Depth</td>
<td>12 in (304.8 mm)</td>
<td>10 in (254 mm)</td>
<td>11 in (279.4 mm)</td>
<td>9 in (228.6 mm)</td>
<td>9 in (228.6 mm)</td>
<td>9 in (228.6 mm)</td>
</tr>
<tr>
<td>Joint Spacing</td>
<td>20 ft (6.096 m)</td>
<td>30 ft (9.144 m)</td>
<td>15 ft (4.572 m)</td>
<td>30 ft (9.144 m)</td>
<td>30 ft (9.144 m)</td>
<td>30 ft (9.144 m)</td>
</tr>
<tr>
<td>Width</td>
<td>10 ft (3.048 m)</td>
<td>12 ft (3.658 m)</td>
<td>13.5 ft (4.115 m)</td>
<td>12 ft (3.658 m)</td>
<td>12 ft (3.658 m)</td>
<td>12 ft (3.658 m)</td>
</tr>
<tr>
<td>Joint Orientation</td>
<td>Square</td>
<td>Square</td>
<td>Square</td>
<td>Square</td>
<td>Square</td>
<td>Square</td>
</tr>
<tr>
<td>Interlayer</td>
<td>None</td>
<td>3 in (76.2 mm) (Asphalt)</td>
<td>Fabric</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>
Table 6.1 (Continued)

<table>
<thead>
<tr>
<th>Shoulder Type</th>
<th>Concrete/None</th>
<th>HMA</th>
<th>Concrete</th>
<th>HMA</th>
<th>Concrete</th>
<th>HMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dowels</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Base Depth</td>
<td>5 in (127 mm)</td>
<td>8 in (203.2 mm)</td>
<td>8 in (203.2 mm)</td>
<td>6 in (152.4 mm)</td>
<td>6 in (152.4 mm)</td>
<td>6 in (152.4 mm)</td>
</tr>
<tr>
<td>Base Type</td>
<td>PCC sub base or Asphaltic concrete base</td>
<td>Soil Base</td>
<td>Cement Modified</td>
<td>Soil Cement</td>
<td>Soil Cement</td>
<td>Soil Cement</td>
</tr>
<tr>
<td>Average Faulting</td>
<td>0.48 mm (0.019 in)</td>
<td>1.51 mm (0.06 in)</td>
<td>0.20 mm (0.008 in)</td>
<td>0.53 mm (0.021 in)</td>
<td>1.25 mm (0.049 in)</td>
<td>-0.06 mm (-0.002 in)</td>
</tr>
<tr>
<td>Average IRI Left WP</td>
<td>2.03 m/km (128.4 in/mile)</td>
<td>1.05 m/km (66.4 in/mile)</td>
<td>0.90 m/km (56.9 in/mile)</td>
<td>0.59 m/km (37.3 in/mile)</td>
<td>1.16 m/km (73.6 in/mile)</td>
<td>0.58 m/km (36.9 in/mile)</td>
</tr>
<tr>
<td>Average IRI Right WP</td>
<td>2.45 m/km (155.3 in/mile)</td>
<td>1.08 m/km (68.5 in/mile)</td>
<td>1.07 m/km (67.6 in/mile)</td>
<td>0.73 m/km (46.5 in/mile)</td>
<td>1.19 m/km (75.2 in/mile)</td>
<td>0.59 m/km (37.2 in/mile)</td>
</tr>
<tr>
<td>Collection Date</td>
<td>8/3/2013</td>
<td>8/3/2013</td>
<td>9/7/2013</td>
<td>9/7/2013</td>
<td>9/7/2013</td>
<td>9/7/2013</td>
</tr>
<tr>
<td>Lane</td>
<td>Main Truck Lane</td>
<td>Outside</td>
<td>Outside</td>
<td>Outside</td>
<td>Inside</td>
<td>Inside</td>
</tr>
<tr>
<td>Remarks</td>
<td>Has Thermal Devices</td>
<td>Contains 1 Broken Slab</td>
<td>New Pavement</td>
<td>Contains 2 Broken Slabs</td>
<td>Has Repaired Slab</td>
<td>Recently Diamond Ground</td>
</tr>
</tbody>
</table>

6.2 Final I-16 Site Faulting Analysis

Data was collected on all of the test sections simultaneously on September 7, 2013. All of the sensors on the sensing vehicle were utilized so that as much of the details of the section could be captured. Due to the amount of time required to collect all of the test sections the time interval between the data collection runs was 30 minutes. This was the shortest interval that could be used and ensure that all of the sections were collected. It would also provide sufficient data sets that could be used to determine if there were any changes in the concrete pavement characteristics due to temperature.
changes throughout the day. The data collection started at 8:00 A.M and each test section was collected every 30 minutes until 5:30 P.M. This resulted in 20 data sets for each test section and this subsection presents the faulting results that were generated for each of the test sections. The only test section that did not have 20 data sets was Section D and the data collected at 3:30 P.M was incomplete due to excessive speed during the collection, so this run was excluded from the Section D analysis.

For each test section there was between 10,000 and 11,500 faulting measurements taken on the 26 joints of each test section. These measurements were then aggregated into an average faulting value for each joint in each data collection run which produced a total of 520 average faulting values that could be used to analyze the faulting conditions of each test section.

For Section A the average faulting was 0.20 mm (0.008 in) and ranged from 0.01 mm (0.001 in) to 0.65 mm (0.026 in). The average faulting for Section B was 0.53 mm (0.021 in) and had a maximum average faulting of 2.22 mm (0.087 in) and a minimum average faulting of -0.49 mm (-0.019). The average faulting values of Section C ranged from 0.4 mm (0.016 in) to 3.48 mm (0.137 in) and had an average faulting of 1.25 mm (0.049 in). Section D had the lowest average faulting of -0.06 mm (-0.002 in) and the average faulting ranged from -0.50 mm (-0.02 in). Table 6.2 summarizes the statistics from the average faulting analysis performed on all of the test sections at the final I-16 test site.
The variation of the average faulting from all of the test sections was assessed to see if there was any significant variation throughout the day as the data was collected. Based on the preliminary analysis that was performed on the weigh station and the initial I-16 analysis it is expected that the faulting will only vary slightly throughout the data collection. The variation of the average faulting throughout the data collection was found by finding the maximum average faulting value for each joint and subtracting the minimum average faulting value for that joint from it. For Section A the maximum variation that occurred was 0.30 mm (0.01 in) and for Section D the maximum variation that occurred was 0.46 mm (0.02 in). Both of these are less than the accuracy of the 3D Line Laser so it is likely that this variation is not caused by the thermal gradient in the slab but by the accuracy of the sensors.

The maximum variation of the average faulting on the joints in Section B was 0.67 mm (0.03 in) and 4 of the 26 joints exhibited a variation that was greater than the 0.5 mm (0.02 in) accuracy of the 3D Line Laser sensors. Of the 26 joints in Section C two of them had a variation that was greater than the 0.5 mm (0.02 in) accuracy of the 3D Line Laser sensors.

### Table 6.2 Summary of Average Faulting for Final I-16 Test Site

<table>
<thead>
<tr>
<th></th>
<th>Section A</th>
<th>Section B</th>
<th>Section C</th>
<th>Section D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.20</td>
<td>0.53</td>
<td>1.25</td>
<td>-0.06</td>
</tr>
<tr>
<td>Median</td>
<td>0.19</td>
<td>0.38</td>
<td>1.12</td>
<td>-0.08</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.65</td>
<td>2.22</td>
<td>3.48</td>
<td>0.37</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.01</td>
<td>-0.49</td>
<td>0.40</td>
<td>-0.50</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.09</td>
<td>0.59</td>
<td>0.65</td>
<td>0.14</td>
</tr>
<tr>
<td>25th Percentile</td>
<td>0.13</td>
<td>0.15</td>
<td>0.83</td>
<td>-0.15</td>
</tr>
<tr>
<td>75th Percentile</td>
<td>0.24</td>
<td>0.72</td>
<td>1.37</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Laser sensors and the maximum variation that was observed was 0.57 mm (0.02 in). All of the average faulting variations are less than the 1 mm (0.04 in) accuracy requirement in the AASHTO R36-04 specification for automated faulting measurement methods, so if the variations were caused by thermal effects then it does not have a significant enough impact to affect the measured faulting results when following this specification. Table 6.3 shows the variation in the average faulting for all of the joints in the final I-16 test site.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Section A (mm)</th>
<th>Section A (in)</th>
<th>Section B (mm)</th>
<th>Section B (in)</th>
<th>Section C (mm)</th>
<th>Section C (in)</th>
<th>Section D (mm)</th>
<th>Section D (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint 1</td>
<td>0.21</td>
<td>0.008</td>
<td>0.34</td>
<td>0.013</td>
<td>0.19</td>
<td>0.007</td>
<td>0.28</td>
<td>0.011</td>
</tr>
<tr>
<td>Joint 2</td>
<td>0.16</td>
<td>0.006</td>
<td>0.26</td>
<td>0.01</td>
<td>0.41</td>
<td>0.016</td>
<td>0.29</td>
<td>0.011</td>
</tr>
<tr>
<td>Joint 3</td>
<td>0.12</td>
<td>0.005</td>
<td>0.67</td>
<td>0.026</td>
<td>0.37</td>
<td>0.015</td>
<td>0.17</td>
<td>0.007</td>
</tr>
<tr>
<td>Joint 4</td>
<td>0.16</td>
<td>0.006</td>
<td>0.38</td>
<td>0.015</td>
<td>0.35</td>
<td>0.014</td>
<td>0.26</td>
<td>0.01</td>
</tr>
<tr>
<td>Joint 5</td>
<td>0.12</td>
<td>0.005</td>
<td>0.36</td>
<td>0.014</td>
<td>0.38</td>
<td>0.015</td>
<td>0.35</td>
<td>0.014</td>
</tr>
<tr>
<td>Joint 6</td>
<td>0.21</td>
<td>0.008</td>
<td>0.41</td>
<td>0.016</td>
<td>0.34</td>
<td>0.013</td>
<td>0.18</td>
<td>0.007</td>
</tr>
<tr>
<td>Joint 7</td>
<td>0.16</td>
<td>0.006</td>
<td>0.30</td>
<td>0.012</td>
<td>0.27</td>
<td>0.011</td>
<td>0.31</td>
<td>0.012</td>
</tr>
<tr>
<td>Joint 8</td>
<td>0.18</td>
<td>0.007</td>
<td>0.31</td>
<td>0.012</td>
<td>0.27</td>
<td>0.011</td>
<td>0.46</td>
<td>0.018</td>
</tr>
<tr>
<td>Joint 9</td>
<td>0.16</td>
<td>0.006</td>
<td>0.35</td>
<td>0.014</td>
<td>0.45</td>
<td>0.018</td>
<td>0.32</td>
<td>0.013</td>
</tr>
<tr>
<td>Joint 10</td>
<td>0.12</td>
<td>0.005</td>
<td>0.20</td>
<td>0.008</td>
<td>0.24</td>
<td>0.009</td>
<td>0.28</td>
<td>0.011</td>
</tr>
<tr>
<td>Joint 11</td>
<td>0.24</td>
<td>0.009</td>
<td>0.40</td>
<td>0.016</td>
<td>0.32</td>
<td>0.013</td>
<td>0.26</td>
<td>0.01</td>
</tr>
<tr>
<td>Joint 12</td>
<td>0.14</td>
<td>0.005</td>
<td>0.37</td>
<td>0.015</td>
<td>0.20</td>
<td>0.008</td>
<td>0.26</td>
<td>0.01</td>
</tr>
<tr>
<td>Joint 13</td>
<td>0.11</td>
<td>0.004</td>
<td>0.32</td>
<td>0.013</td>
<td>0.32</td>
<td>0.013</td>
<td>0.19</td>
<td>0.007</td>
</tr>
<tr>
<td>Joint 14</td>
<td>0.14</td>
<td>0.006</td>
<td>0.31</td>
<td>0.012</td>
<td>0.24</td>
<td>0.009</td>
<td>0.22</td>
<td>0.009</td>
</tr>
<tr>
<td>Joint 15</td>
<td>0.17</td>
<td>0.007</td>
<td>0.34</td>
<td>0.013</td>
<td>0.57</td>
<td>0.023</td>
<td>0.25</td>
<td>0.01</td>
</tr>
<tr>
<td>Joint 16</td>
<td>0.16</td>
<td>0.006</td>
<td>0.35</td>
<td>0.014</td>
<td>0.20</td>
<td>0.008</td>
<td>0.24</td>
<td>0.01</td>
</tr>
<tr>
<td>Joint 17</td>
<td>0.20</td>
<td>0.008</td>
<td>0.32</td>
<td>0.013</td>
<td>0.30</td>
<td>0.012</td>
<td>0.31</td>
<td>0.012</td>
</tr>
<tr>
<td>Joint 18</td>
<td>0.18</td>
<td>0.007</td>
<td>0.49</td>
<td>0.019</td>
<td>0.23</td>
<td>0.009</td>
<td>0.27</td>
<td>0.011</td>
</tr>
<tr>
<td>Joint 19</td>
<td>0.14</td>
<td>0.006</td>
<td>0.41</td>
<td>0.016</td>
<td>0.54</td>
<td>0.021</td>
<td>0.22</td>
<td>0.009</td>
</tr>
<tr>
<td>Joint 20</td>
<td>0.26</td>
<td>0.01</td>
<td>0.40</td>
<td>0.016</td>
<td>0.50</td>
<td>0.02</td>
<td>0.33</td>
<td>0.013</td>
</tr>
<tr>
<td>Joint 21</td>
<td>0.19</td>
<td>0.008</td>
<td>0.58</td>
<td>0.023</td>
<td>0.43</td>
<td>0.017</td>
<td>0.19</td>
<td>0.008</td>
</tr>
<tr>
<td>Joint 22</td>
<td>0.22</td>
<td>0.009</td>
<td>0.38</td>
<td>0.015</td>
<td>0.32</td>
<td>0.013</td>
<td>0.26</td>
<td>0.01</td>
</tr>
<tr>
<td>Joint 23</td>
<td>0.23</td>
<td>0.009</td>
<td>0.49</td>
<td>0.019</td>
<td>0.42</td>
<td>0.016</td>
<td>0.28</td>
<td>0.011</td>
</tr>
<tr>
<td>Joint 24</td>
<td>0.23</td>
<td>0.009</td>
<td>0.42</td>
<td>0.016</td>
<td>0.20</td>
<td>0.008</td>
<td>0.24</td>
<td>0.009</td>
</tr>
<tr>
<td>Joint 25</td>
<td>0.30</td>
<td>0.012</td>
<td>0.59</td>
<td>0.023</td>
<td>0.31</td>
<td>0.012</td>
<td>0.29</td>
<td>0.012</td>
</tr>
</tbody>
</table>
Due to the traffic conditions at the final I-16 test sections it was not possible to install thermocouples in the pavement and actually measure the thermal gradient in the slabs, so the maximum and minimum average faulting occurrence time were summarized for each joint in each test section to see if there was clear pattern. If there were a clear pattern it would indicate that the faulting of the joints is affected similarly by the temperature changes. The results indicate that there is not an apparent pattern. However in some of the cases the maximum or minimum average faulting values for multiple joints in a section did occur at the same time. This did not happen often and the most joints that had the maximum average faulting occur at the same time was 7 and it was in Section A. Most of the other section would have between 4 and 6 joint that the maximum and minimum would occur in the same data collection run. Since the variation in the average faulting is less than the accuracy of the sensors it is likely that these occurrences are not related to thermal effects. Table 6.4 displays the occurrence times for the maximum and minimum average faulting for each joint in all of the test sections.

Table 6.4 Maximum and Minimum Average Faulting Occurrence Times

<table>
<thead>
<tr>
<th>Joint 26</th>
<th>MAX</th>
<th>MIN</th>
<th>MAX</th>
<th>MIN</th>
<th>MAX</th>
<th>MIN</th>
<th>MAX</th>
<th>MIN</th>
<th>MAX</th>
<th>MIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.3 (Continued)
<table>
<thead>
<tr>
<th>Joint 5</th>
<th>3:30 P.M.</th>
<th>10:30 A.M.</th>
<th>2:30 P.M.</th>
<th>9:00 A.M.</th>
<th>3:00 P.M.</th>
<th>8:30 A.M.</th>
<th>8:00 A.M.</th>
<th>10:00 A.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint 6</td>
<td>2:30 P.M.</td>
<td>8:30 A.M.</td>
<td>9:30 A.M.</td>
<td>1:00 P.M.</td>
<td>1:00 P.M.</td>
<td>5:00 P.M.</td>
<td>10:00 A.M.</td>
<td>8:00 A.M.</td>
</tr>
<tr>
<td>Joint 7</td>
<td>1:30 P.M.</td>
<td>8:30 A.M.</td>
<td>10:30 A.M.</td>
<td>11:30 A.M.</td>
<td>5:00 P.M.</td>
<td>12:30 P.M.</td>
<td>9:30 A.M.</td>
<td>4:30 P.M.</td>
</tr>
<tr>
<td>Joint 8</td>
<td>2:30 P.M.</td>
<td>8:00 A.M.</td>
<td>8:30 A.M.</td>
<td>4:30 P.M.</td>
<td>3:30 P.M.</td>
<td>10:00 A.M.</td>
<td>10:30 A.M.</td>
<td>5:30 P.M.</td>
</tr>
<tr>
<td>Joint 9</td>
<td>1:30 P.M.</td>
<td>3:30 P.M.</td>
<td>10:00 A.M.</td>
<td>4:00 P.M.</td>
<td>3:30 P.M.</td>
<td>10:30 A.M.</td>
<td>4:00 P.M.</td>
<td></td>
</tr>
<tr>
<td>Joint 10</td>
<td>1:00 P.M.</td>
<td>9:30 A.M.</td>
<td>11:30 A.M.</td>
<td>4:30 P.M.</td>
<td>3:30 P.M.</td>
<td>4:00 P.M.</td>
<td>9:00 A.M.</td>
<td>2:00 P.M.</td>
</tr>
<tr>
<td>Joint 11</td>
<td>2:30 P.M.</td>
<td>10:00 A.M.</td>
<td>3:00 P.M.</td>
<td>12:30 P.M.</td>
<td>2:00 P.M.</td>
<td>12:30 P.M.</td>
<td>4:00 P.M.</td>
<td>9:00 A.M.</td>
</tr>
<tr>
<td>Joint 12</td>
<td>4:00 P.M.</td>
<td>10:00 A.M.</td>
<td>8:00 A.M.</td>
<td>5:00 P.M.</td>
<td>9:30 A.M.</td>
<td>1:00 P.M.</td>
<td>1:00 P.M.</td>
<td>8:00 A.M.</td>
</tr>
<tr>
<td>Joint 13</td>
<td>2:00 P.M.</td>
<td>8:00 A.M.</td>
<td>8:30 A.M.</td>
<td>2:00 P.M.</td>
<td>12:30 A.M.</td>
<td>11:00 A.M.</td>
<td>12:30 A.M.</td>
<td>12:00 P.M.</td>
</tr>
<tr>
<td>Joint 14</td>
<td>2:00 P.M.</td>
<td>8:30 A.M.</td>
<td>9:00 A.M.</td>
<td>4:00 P.M.</td>
<td>1:30 P.M.</td>
<td>10:00 P.M.</td>
<td>10:30 A.M.</td>
<td>2:30 A.M.</td>
</tr>
<tr>
<td>Joint 15</td>
<td>12:00 P.M.</td>
<td>9:30 A.M.</td>
<td>9:00 A.M.</td>
<td>11:00 A.M.</td>
<td>2:00 P.M.</td>
<td>9:00 A.M.</td>
<td>8:00 A.M.</td>
<td>11:00 A.M.</td>
</tr>
<tr>
<td>Joint 16</td>
<td>2:30 P.M.</td>
<td>9:00 A.M.</td>
<td>9:00 A.M.</td>
<td>2:00 P.M.</td>
<td>8:30 A.M.</td>
<td>4:30 P.M.</td>
<td>9:00 A.M.</td>
<td>4:30 A.M.</td>
</tr>
<tr>
<td>Joint 17</td>
<td>12:00 P.M.</td>
<td>8:00 A.M.</td>
<td>10:00 A.M.</td>
<td>5:00 P.M.</td>
<td>4:00 P.M.</td>
<td>2:30 P.M.</td>
<td>8:00 A.M.</td>
<td>1:00 P.M.</td>
</tr>
<tr>
<td>Joint 18</td>
<td>3:30 P.M.</td>
<td>9:00 A.M.</td>
<td>5:30 A.M.</td>
<td>8:00 A.M.</td>
<td>2:30 P.M.</td>
<td>2:00 P.M.</td>
<td>12:00 A.M.</td>
<td>8:00 A.M.</td>
</tr>
<tr>
<td>Joint 19</td>
<td>2:30 P.M.</td>
<td>2:00 P.M.</td>
<td>8:30 A.M.</td>
<td>2:00 P.M.</td>
<td>4:30 P.M.</td>
<td>1:00 P.M.</td>
<td>5:00 P.M.</td>
<td>9:00 A.M.</td>
</tr>
<tr>
<td>Joint 20</td>
<td>2:00 P.M.</td>
<td>8:30 A.M.</td>
<td>10:00 A.M.</td>
<td>12:30 P.M.</td>
<td>4:30 P.M.</td>
<td>1:30 P.M.</td>
<td>9:00 A.M.</td>
<td>3:00 P.M.</td>
</tr>
<tr>
<td>Joint 21</td>
<td>11:00 A.M.</td>
<td>9:30 A.M.</td>
<td>10:00 A.M.</td>
<td>3:30 P.M.</td>
<td>1:00 P.M.</td>
<td>12:30 P.M.</td>
<td>10:00 A.M.</td>
<td>8:00 P.M.</td>
</tr>
<tr>
<td>Joint 22</td>
<td>1:00 P.M.</td>
<td>11:30 A.M.</td>
<td>9:30 A.M.</td>
<td>2:00 P.M.</td>
<td>9:00 A.M.</td>
<td>1:30 P.M.</td>
<td>11:00 A.M.</td>
<td>2:00 P.M.</td>
</tr>
<tr>
<td>Joint 23</td>
<td>5:00 P.M.</td>
<td>8:00 A.M.</td>
<td>9:00 A.M.</td>
<td>2:00 P.M.</td>
<td>4:30 P.M.</td>
<td>1:30 P.M.</td>
<td>10:00 A.M.</td>
<td>3:00 P.M.</td>
</tr>
<tr>
<td>Joint 24</td>
<td>2:30 P.M.</td>
<td>8:30 A.M.</td>
<td>9:00 A.M.</td>
<td>3:00 P.M.</td>
<td>12:00 P.M.</td>
<td>1:30 P.M.</td>
<td>2:30 P.M.</td>
<td>9:30 P.M.</td>
</tr>
<tr>
<td>Joint 25</td>
<td>12:00 P.M.</td>
<td>10:30 A.M.</td>
<td>9:30 A.M.</td>
<td>5:30 P.M.</td>
<td>10:30 A.M.</td>
<td>1:30 P.M.</td>
<td>10:00 A.M.</td>
<td>12:00 A.M.</td>
</tr>
</tbody>
</table>
Table 6.4 (Continued)

<table>
<thead>
<tr>
<th>Joint</th>
<th>2:30 P.M.</th>
<th>9:00 A.M.</th>
<th>11:30 A.M.</th>
<th>2:00 P.M.</th>
<th>2:30 P.M.</th>
<th>4:00 P.M.</th>
<th>9:00 A.M.</th>
<th>4:30 P.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The average faulting distribution for each test section was plotted so that it could be visually assessed. The distribution of the average faulting for Sections A and D showed that the faulting for all of the joints in each test section was similar and varied less than 0.5 mm (0.02 in) through each test section. The distribution for Section B showed the most changes in faulting through the section and ranged from -0.49 mm (-0.019 in) to 2.22 mm (0.087 in). The average faulting distribution for Section C showed the largest amount of variation through the test section, which was 3.08 mm (0.121 in). Most of the joints in Section C were between 0.5 mm (0.02 in) and 1.5 mm (0.059 in), but there was 4 joints that had faulting outside this range. Figure 6.4 shows the faulting distributions for all of the test sections at the final I-16 test site.

(a) Section A

Figure 6.4 Final I-16 Test Site Average Faulting Distributions
Figure 6.4 continued

(b) Section B

(c) Section C

Figure 6.4 continued
Section A, B and C were analyzed further to determine if there was an identifiable cause of the changes in the distribution of the average faulting. The joint in section A that was an outlier was joint 25 so the video log image was extracted to see if there was a noticeable cause for the jump in the faulting distribution. Figure 6.5 shows an image of joint 25 in Section A.
Figure 6.5 Joint 25 in Section A

(a) Joint 25

(b) Slab 25
All of the joints in Section B were looked at in further detail and there was no obvious cause of the higher faulting values. Slabs 6 and 12 in Section B were broken slabs but the average faulting for the joints of these slabs (Joints 6 and 7 for Slab 6 and Joints 12 and 13 for Slab 12) were not the outliers that were observed in the average faulting plots. From the faulting distribution it appeared that joints 3, 17, 18, and 26 were outliers in the section. The video log images of these joints were pulled out to see if a cause for their abnormality could be seen visually. The review of the images did not reveal a clear source for the change in the faulting for these joints. Figure 6.6 shows the abnormal joints from Section B.

(a) Joint 3

Figure 6.6 Joints with Abnormal Faulting in Section B
(b) Joint 17

(c) Joint 18
Figure 6.6 continued
The four joints in Section C that were different from all of the other joints were Joints 15, 19, 20, and 22. The slabs that are separated by these joints were looked at to see if there was a palpable cause for the higher average faulting at these joints. It was found that for joints 15 and 22 there was no apparent cause for the higher average faulting on these joints. However for joints 19 and 20 it was found that slab 19 was a slab that had been partially replaced. The end of slab 19 had been removed and repaired. It was also found that the repaired part of the slab had cracked. The part of slab 19 that was separated by joint 19 was the part of the old slab and it was longer than the repaired part which is probably why the faulting at joint 20 (3.22 mm (0.127 in)) was higher than the faulting at joint 19 (2.50 mm (0.098 in)). Figure 6.7 shows the damaged repaired slab from Section C.
The joints that had the highest and lowest average faulting were selected from each test to see if there was any relationship between the average faulting and the temperature variation during the data collection. The evaluation of the average faulting through the data collection would also provide additional evidence to whether or not the system faulting measurements were repeatable. Of the 8 joints that were inspected only 2 had a variation greater than 0.5 mm (0.02 in) and the two that were greater were both less than 0.55 mm (0.022 in). Based on this it can be concluded that the average faulting that is measured by the 3D Line Laser is repeatable. Figure 6.8 shows the faulting distributions for each joint that was analyzed to determine if there was a relationship between the temperature changes and to test the repeatability of the system.
Figure 6.8 Individual Joint Average Faulting Distributions for Final I-16 Test Site
None of the average faulting distributions showed a definite trend with the temperature, but it was noticed that Joint 26 in Section B showed a slight decrease in average faulting from approximately 12:00 P.M. to 4:00 P.M where it began to gradually increase and then level out. The variation in the average faulting during this time period for Section B was 0.53 mm (0.0207 in). Joint 20 in Section C also showed a slight up and down trend that started after 12:00 P.M. and continued for the remainder of the data.
collection. The amount of variation that was exhibited by joint 20 in Section C was 0.47 mm (0.0185 in). These cases are interesting because during this time frame the temperature rose and reached a maximum and then began to gradually decrease for the day. Due to the amount of variation being 0.53 mm (0.0207 in) for Section B and 0.47 mm (0.0185 in) there is not enough evidence to conclude that the changes in temperature were the direct cause of the change however a more accurate faulting measurement technique should be employed to actually quantify and determine the exact impact of the temperature variations. Figure 6.9 shows Joint 26 in Section B and Joint 20 in Section C.
Since Joint 20 from Section C had the highest average faulting the individual faulting measurements that were taken on it through the data collection were compared to see if there was an evident variation in the faulting measurements. There were slight deviations in the measurements, but most of them follow the same trend. A clear relationship between the faulting profiles could not be established. If there was a definable relationship with the temperature it would be expected that there would be a gradual change in the profiles. It is suggested that this procedure be extended and exact points on the joints be labeled in the field prior to the data collection which would allow exact faulting measurements to be compared rather than approximate ones. Figure 6.10 shows the faulting measurement distributions for each data collection run collected on Section C.
6.3 Final I-16 Site Roughness Analysis

Longitudinal profiles were created for each test sections at the final I-16 test site, these profiles were then used to calculate the IRI for each wheel path of each test section. The starting point of each profile was defined as the intersection of the first joint in the test section and the wheel paths. The end of the profile was defined as the intersection of the 26\textsuperscript{th} joint in the test section and the wheel paths. For each of the 4 test sections there were a total of 40 IRI values calculated, 20 for the left wheel path and 20 for the right wheel path.

The average IRI for the left wheel path in Section A was 0.9 m/km (56.885 in/mile) and was 1.07 m/km (67.591 in/mile) for the right wheel path. The range of the IRI in the left wheel path for Section A was from 0.79 m/km (50.044 in/mile) to 1.00 m/km (63.346 in/mile) and for the right wheel path the IRI ranged from 0.94 m/km (59.546 in/mile) to 1.27 m/km (80.45 in/mile). Section B had an average IRI of 0.59 m/km (37.311 in/mile) in the left wheel path and an average IRI of 0.73 m/km (46.496 in/mile) in the right wheel path. The range of the IRI in the left wheel path of Section B
was 0.52 m/km (32.940 in/mile) to 0.71 m/km (44.976 in/mile) and was between 0.53 m/km (33.574 in/mile) to 1.01 m/km (63.980 in/mile) in the right wheel path.

Section C had an average IRI of 1.16 m/km (73.609 in/mile) in the left wheel path and 1.19 m/km (75.192 in/mile) in the right wheel path. The IRI from the left wheel path ranged from 1.11 m/km (70.315 in/mile) to 1.21 m/km (76.649 in/mile) and from 1.12 m/km (70.948 in/mile) to 1.25 m/km (79.183 in/mile) in the right wheel path. Section D had the lowest average IRI in both wheel paths. The average IRI for the left wheel path was 0.58 m/km (36.917 in/mile) and the average IRI for the right wheel path was 0.59 m/km (37.234 in/mile). The range of the average IRI values in the left wheel path was between 0.55 m/km (34.841 in/mile) to 0.61 m/km (38.641 in/mile). The average IRI values in the right wheel path were from 0.52 m/km (32.940 in/mile) to 0.68 m/km (43.076 in/mile). Table 6.5 summarizes the statistical analysis results from the IRI values calculated from all of the sections at the final I-16 test site.

<table>
<thead>
<tr>
<th>Section</th>
<th>Left {m/km}</th>
<th>Left {in/mile}</th>
<th>Right {m/km}</th>
<th>Right {in/mile}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Median</td>
<td>Standard Deviation</td>
<td>Max.</td>
</tr>
<tr>
<td>Section A</td>
<td>0.9</td>
<td>0.92</td>
<td>0.05</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>56.885</td>
<td>57.962</td>
<td>3.181</td>
<td>63.346</td>
</tr>
<tr>
<td></td>
<td>1.07</td>
<td>1.07</td>
<td>0.06</td>
<td>1.27</td>
</tr>
<tr>
<td></td>
<td>67.591</td>
<td>67.781</td>
<td>4.033</td>
<td>80.45</td>
</tr>
<tr>
<td>Section B</td>
<td>0.59</td>
<td>0.59</td>
<td>0.05</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>37.311</td>
<td>37.058</td>
<td>2.963</td>
<td>44.976</td>
</tr>
<tr>
<td></td>
<td>0.73</td>
<td>0.7</td>
<td>0.11</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>46.496</td>
<td>44.026</td>
<td>7.273</td>
<td>63.98</td>
</tr>
<tr>
<td>Section C</td>
<td>1.16</td>
<td>1.17</td>
<td>0.03</td>
<td>1.21</td>
</tr>
<tr>
<td></td>
<td>73.609</td>
<td>73.799</td>
<td>1.763</td>
<td>76.649</td>
</tr>
<tr>
<td></td>
<td>1.19</td>
<td>1.19</td>
<td>0.03</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>75.192</td>
<td>75.382</td>
<td>2.157</td>
<td>79.183</td>
</tr>
</tbody>
</table>
Table 6.5 (Continued)

<table>
<thead>
<tr>
<th>Section D</th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>{m/km}</td>
<td>{in/mile}</td>
</tr>
<tr>
<td></td>
<td>0.58</td>
<td>36.917</td>
</tr>
<tr>
<td></td>
<td>0.02</td>
<td>1.082</td>
</tr>
<tr>
<td></td>
<td>0.61</td>
<td>38.641</td>
</tr>
<tr>
<td></td>
<td>0.55</td>
<td>34.841</td>
</tr>
<tr>
<td></td>
<td>0.06</td>
<td>3.801</td>
</tr>
</tbody>
</table>

The variation of the average IRI in Section A was 0.21 m/km (13.303 in/mile) in the left wheel path IRI values and was 0.33 m/km (20.904 in/mile) in the IRI values measured in the right wheel path. This section had the second highest overall IRI of all of the test sections and also had the second highest amount of variation in the results. The IRI in this section is most similar to the IRI in the FDOT test Section 12 which had an average IRI of 1.27 m/km (79.833 in/mile) in the left wheel path and 1.02 m/km (64.200 in/mile) in the right wheel path. The variation for the IRI values measured with the 3D Line Laser for Section 12 was 0.08m/km (5.070 in/mile) for the left wheel path and was 0.05 m/km (3.170 in/mile) for the right wheel path. Since the IRI measured at these sites is similar it is assumed that the variation in the results caused by the system would be similar, so it appears that some of the variation in the IRI from Section A could be due to thermal effects on the concrete pavement.

To determine if there was a relationship between the IRI and temperature the distributions were plotted on the same plot and compared. The temperature data from the day of the data collection (September 7, 2013) was downloaded from the National Oceanic and Atmospheric Administration (NOAA) website. The IRI from the right wheel path shows what is expected it shows a slight drop in the IRI in early in the morning when it is expected that the slabs would be going from a curled up state to a flat state when the temperature gradient in the slabs would be zero. Then the IRI gradually
increases as the temperature rises and the slabs begin to enter a curled down state and as
the temperature begins to decrease toward the end of the data collection the IRI starts to
level out. If the data was collected the remainder of the day then the right wheel path IRI
would probable gradually decrease until the temperature variation between the top and
bottom of the slab reached zero then the same cycle would be repeated if the
environmental conditions were the same for the following day. The IRI trend from the
left wheel path showed a progressive increase in the IRI measurements throughout the
data collection until the temperature reached a maximum and then the IRI began to
decrease gradually. Figure 6.11 shows the IRI distribution Section A along with the air
temperature that was recorded for the day of the data collection.

![Figure 6.11 Section A IRI Distribution](image)

Section B exhibited the most variation in the average IRI out of fall of the test
section. It had 0.19 m/km (12.036 in/mile) of variation in the left wheel path and 0.48
m/km (30.406 in/mile) in the right wheel path. The IRI of this section is most similar to
the FDOT section 11. The IRI of the left wheel path for FDOT section 11 was 0.52 m/km (32.500 in/mile) and was 0.61 m/km (38.400 in/mile) in the right wheel path. This site had a variation of 0.10 m/km (6.330 in/mile) in the left wheel path and 0.09 m/km (5.700 in/mile) in the right wheel path. Since these two test sections had similar IRI values it was assumed that the results calculated by the 3D Line Laser would have the same amount of variation in the results. The variation in the results from Section B was 2 to 5 times higher than the results from FDOT Section 11, so the IRI distribution was compared to the air temperature distribution on the day of the data collection to see if there was a correlation between the two. Both the left and right wheel paths show a gradual increase in the IRI as the temperature increases and when the temperature begins to decrease during the later part of the data collection the IRI begins to gradually decrease. Figure 6.12 shows the IRI distribution for Section B and the air temperature during the data collection.

![Figure 6.12 Section B IRI Distribution](image-url)
Section C had the highest average IRI of the four test sections, but had the second to the lowest variation of the results. The variation of the left wheel path was 0.10 m/km (6.335 in/mile) and was 0.13 m/km (8.235 in/mile) for the right wheel path. The IRI is most similar to the FDOT section 12 and Section A from the final I-16 test site. So, it is expected that the variation in the IRI values caused by the ability of the 3D Line Laser would be close to the variation in the results from FDOT section 12 which was 0.08m/km (5.070 in/mile) for the left wheel path and was 0.05 m/km (3.170 in/mile) for the right wheel path. The variation in the IRI values measured on Section C were very close to the one’s from section 12 so it is likely that the thermal changes in the concrete slab did not have a significant impact on the IRI values from Section C. The IRI distribution for each wheel path was compared to the temperature change to determine if there was a connection between the two. This comparison showed that the IRI distribution was relatively flat during the data collection. Figure 6.13 shows the IRI distribution for Section C and the air temperature from the day of the data collection.

![Figure 6.13 Section C IRI Distribution](image-url)
Section D had the lowest average IRI and lowest variation of all of the test sections. The variation of the IRI values in the left wheel path was 0.06 m/km (3.801 in/mile) and was 0.16 m/km (10.135 in/mile) in the right wheel path. The IRI for this section was similar to FDOT section 11 so the variation in the results caused by the system accuracy should be similar to the variation in Section B. The variation is almost the same in Section D so it is probable that the temperature change during the data collection did not have an impact on the IRI measured from Section D. The IRI distribution was compared to the air temperature that was recorded on the day of the data collection. These results revealed that the IRI distribution was reasonably flat throughout the data collection and did not follow the same trend as the air temperature. Figure 6.14 shows the distribution of the IRI measurements taken from Section D along with the air temperature that was recorded that day.

Figure 6.14 Section D IRI Distribution
Due to the findings from Chapter 5 where the broken slab caused a significant spike in the longitudinal profiles the replaced slab in Section C was evaluated to determine if its impact could be depicted in the longitudinal profiles. The repaired slab can be identified in the profiles that are collected by the system and it appeared as multiple spikes in the profile within the length of the slab. Figure 6.15 shows an example of the longitudinal profiles that were generated for Section C and it shows that the location of slab 19 can clearly be seen.

![Figure 6.15 Example Longitudinal Profiles Collected on Section C to Show Repaired Slab](image)

The review of the longitudinal profiles also revealed that there were other locations in the profiles that could indicate other forms of distress. The indicators that were observed were larger spikes in the profiles. The joints that correspond to these spikes were identified as joints 10, 11, and 12. The video log images of these joints were reviewed along with the average faulting distribution. The average faulting distributions showed that these joint had faulting conditions similar to the majority of the section and the images did not reveal a clear cause for the spike in the longitudinal profiles. Figure 6.16 shows the back facing video log images for the joints that caused the high spikes in the longitudinal profiles and the part of slab 19 that had been repaired.
Figure 6.16 Joints Causing Irregularities in Section Cs Longitudinal Profiles

(a) Joint 10 Section C

(b) Joint 11 Section C
(c) Joint 12 Section C

(d) Joint 20 Section C (End of Slab 19)
Figure 6.16 continued
6.4 Summary

To further the investigation of the thermal effects on concrete pavement behavior to include additional pavement designs another final test site was chosen on I-16 near Danville, Georgia. The exact location of the test sections at this site were chosen because of the unique pavement design in Section A and the other 3 sections were chosen because of their location relative to Section A, Section B was a different pavement design but in the same lane, Section C was beside section A in the neighboring lane, and Section D was in the next to Section B in the adjoining lane. Data was collected on all of the sections concurrently then it was analyzed to see if the faulting and roughness of each section fluctuated with the temperature.

Out of the four test sections, none of the joints in Section A or Section D had a variation in the average faulting results that were greater than the 0.5 mm (0.02 in) so if there were any affects from the temperature variation there were less than what could be detected by the sensors. In Section B there were 4 joints that had a variation greater than the 0.5 mm (0.02 in) accuracy of the sensors and in Section C there were only 2 joints that had a variation greater than the accuracy. These joints were further investigated by determining the times that the maximum and minimum average faulting occurred for each joint. These times were then studied to see if there was a correlation between them that could be linked to the air temperature changes during the data collection. There were slight trends in some of the joints that indicated there were fluctuations in the average faulting but the variations were approximately the same as the accuracy of the sensors. An exact relationship between the two was unattainable, so it was concluded that the
effects of the thermal gradient in the concrete pavement on the average faulting were less than what could be detected by the sensing vehicle.

The IRI results in Section A indicated that it did not have the lowest IRI which was expected since it was a new pavement section. It is possible that the shorter slab length could be the attributing factor because as the slabs begin to curl they would produce a shorter wavelength causing more up and down movement of the vehicle. It also means that there are more joints in a shorter distance which could also cause more up and down vehicular motion. There could also be an impact from the length of the test section. Section A was the shortest test section used in the analysis because it had a shorter slab length which caused it to be 114.3 m (375 ft) while the other test sections were 228.6 m (750 ft). The shorter section length could cause the IRI to be higher because it is calculated as a unit per distance so Section A should be further analyzed to determine if there is some definite cause of the higher IRI.

The IRI results from Sections C and D did not vary more than what was expected. Based on the validation results from the FDOT test sections the variation in the results from these test sections was more than likely due to the accuracy of the system rather than due to the changes in the thermal gradient in the slab. Section D had the lowest average IRI of all of the test sections and Section C had the highest average IRI, but these two sections had the lowest amount of variation in the IRI results of the four sections. These results do not match the findings from the analysis on the FDOT test sections which were that the rougher sections had more variation than the smoother sections. Since these results from the two analyses do not align the 3D Line Laser’s ability and accuracy needs to be evaluated in greater detail. The thermal effects on the slabs did not
have a significant enough impact on these two sections to cause a detectable amount of variation in the IRI results. Section A and Section B did show more variation than what was expected based on the results from the FDOT validation section. The comparison of the IRI distribution through the day with the change in temperature did indicate that there was a relationship between the IRI and the temperature. The IRI from both of these sections indicated that as the temperature rise during the data collection the IRI also gradually increases.

Since Section D had recently been diamond ground it would be beneficial to expand the study and select a section that does have some level of faulting. The diamond grinding makes Section D unique and it influences the relationship between the Sections. The results from each section were collected concurrently so that the behavior in each section could be correlated and if there were similarities or differences between them they could be assessed.
CHAPTER 7
CONCLUSIONS

The study performed in this thesis was conducted to gain better understanding of how concrete pavement behaves when subject to thermal variations. The goal of the research was to develop and implement a methodology that would utilize advanced technology to capture the pavement characteristics, use the collected data to generate useful results and to interpret them to determine the impact of temperature changes on the concrete pavement. This section outlines the conclusions that were made during this research and the suggestions for future research.

7.1 Conclusions

To accomplish the goals of this thesis six test sections were selected to study the concrete pavement characteristics. The key characteristics that were focused on were the faulting and the IRI because these are the typical distresses that are used to rate concrete pavement sections. Each of these sections covered 25 slabs and 26 joints that provided a total of 150 slabs and 156 joints that were analyzed. It is noted here that all of the conclusions that are drawn from limited data sets, both of which were collected toward the end of the summer season in middle Georgia. One data set was collected on August 3, 2013 and the other on September 7, 2013. Based on this the conclusions are only valid for data that was collected and do not apply to all other situations that may be encountered.
To study how the temperature in the slab was distributed a single slab at the weigh station was selected as a test specimen. Three positions on the slab were selected and thermocouples were inserted at four depths at each of these positions. The depths that were evaluated were 0.5 in (12.7 mm) from the slab surface, 6 in (152.4 mm) from the slab surface (mid-depth of the slab), 11.5 in (292.1 mm) from the slab surface (bottom of the slab) and 13 in (330.2 mm) from the slabs surface (base) The following are the conclusions that were drawn from the thermal data that was collected on October 19, 2012.

(1) The thermal data from the three positions was compared to determine if there was a big deviation in the temperature that was measured at each depth. It was concluded that the thermal profiles from each depth followed a similar trend and that the main difference was that the profiles were shifted slightly. It was found that the center of the slab (Position C) always had the highest temperature distribution, the middle of the slab at the joint (Position B) was the second highest distribution, and that the corner of the slab (Position A) always had the lowest temperature distribution of the three. Since the variation would be used to draw the remainder of the conclusions is drawn from the data collected in the corner of the slab on October 21, 2013.

(a) The surface temperature of the slab reached a maximum of 97.7°F (36.5°C) and a minimum of 60.3°F (15.7°C). The observed variation through the day was 37.4°F (20.8°C).

(b) The temperature in the bottom of slab ranged from 81.1°F (27.3°C) to 73°F (22.8°C) producing a variation of 8.1°F (4.5°C).
(c) The temperature from the base and the bottom were compared to determine how much they varied from each other. The average temperature for each depth was found and the difference was 0.4°F (0.2°C), so it is concluded that the average temperature in the base was approximately the same as the average temperature in the bottom of the slab.

(d) It was found that the maximum positive temperature variation in the slab occurred at 2:50 P.M and had a magnitude of 21°F (11.7°C). This condition occurred simultaneously with the maximum surface temperature in the slab and the maximum ambient temperature during the day.

(e) The maximum negative temperature variation occurred at 6:50 A.M and had a magnitude of -14.3°F (-7.9°C). This condition occurred approximately an hour prior to the minimum ambient temperature for this day.

(f) The zero variation conditions occurred at 10:20 A.M. and 6:50 P.M.

(g) It was also found that the surface temperature in the slab follow a trend similar to the ambient air temperature that was measured that day. The surface temperature of the slab was greater than the air temperature throughout the entirety of the day.

In order to establish whether or not the faulting was affected by the temperature changes approximately 91,452 faulting measurements were taken on the 156 joints in the selected test sections. The faulting measurements were aggregated by averaging the faulting measurements for each joint in each data collection run to form a data set of
4,368 average faulting values that were used to evaluate how the faulting changed throughout the data collections. Of the 156 joints only 15 exhibited a variation in the average faulting that was greater than the 0.5 mm (0.02 in) accuracy of the sensors used to collect the concrete pavement surface data. The occurrence times of the maximum and minimum average faulting were then studied to see if there was any correlation that could be linked to the temperature changes that occurred during the data collection.

(2) The individual faulting measurements taken by the 3D line lasers were evaluated to determine if the faulting of a joint could be detected. One particular joint that showed the 3D line lasers ability to depict the faulting of a joint was Joint 24 in the Initial I-16 test section, which separated a broken slab from an intact slab. The faulting measurements indicated that the faulting increased almost linearly from left to right which is what was observed from the image data and what was expected.

(3) There were a total of 13 joints inspected and 10 of them had an average faulting variation less than 0.5 mm (0.02 in) and the 3 that were higher were all less than 0.57 mm (0.022 in). The three sections that had the greater average faulting variation were the Initial I-16 test section and Sections B and C from the final I-16 test site. Based on these results it was concluded that the 3D Line Laser could repeatedly produce consistent average faulting results for a joint.

(4) All of the 156 joints were studied to determine if a relationship could be defined between the average faulting and the temperature variation. It was found that there was no clear pattern between the average faulting and the temperature in any of the joints. The average faulting variation was less than the 0.5 mm (0.02 in) in
90.4% of the joints that were analyzed, which is less than the accuracy of the sensors. The remaining 9.6% of the joints analyzed had a variation in the average faulting values that were less than 1 mm (0.04 in) which is the specified accuracy in the AASHTO R36-04 specification, which governs the required equipment accuracy when measuring faulting. Based on these results it is concluded that the affects of the temperature variations do not have an impact on the average faulting for the data sets that were evaluated in this study.

(5) It is likely that there is not a definable trend between the temperature and the faulting because the affect that the changes in temperature has on the faulting is less than what can be detected by the sensors.

(6) The variation in the average faulting that was greater than the 0.5 mm accuracy of the sensors was probably caused by some other form of error which could include minor shifts in the faulting measurement locations, random error in the data, or because the data was not collected in a controlled environment.

(7) The comparison of the average faulting results from Section C and Section D at the final I-16 test site reveals that the diamond grinding technique does improve the faulting conditions. Both of these sections are in the inside lane and are the same design so it is expected that they would exhibit similar faulting conditions, but the diamond grinding on Section D caused it to have significantly better faulting conditions.

For all of the data collection runs a longitudinal profile was created for the left and right wheel path and was used to measure the IRI. This resulted in a data set of 336 IRI values, half for the left wheel path and half for the right wheel path. These IRI values
were then used to create an IRI distribution for the left and right wheel path in each test section.

(8) The amount that the IRI results varied was evaluated to determine if there was sufficient quantitative variation that could be caused by the thermal changes rather than the accuracy of the sensors. The quantitative results revealed that 4 out of the 6 IRI distributions from both the left and right wheel paths had variation that was very likely caused by the thermal effects on the concrete slabs, but the system’s ability needs to be investigated further.

(9) The longitudinal profiles created to measure the IRI values of the test sections were evaluated and it was found that they could be used to identify other forms of distress. The forms of stress that were identified in the longitudinal included the broken slab in the Initial I-16 test section which was indicated by larger spikes in the profile and the repaired slab in Section C at the final I-16 test site which caused several small fluctuations in the profile.

(10) Out of the 12 wheel paths studied, 7 showed a relationship with the temperature fluctuations that occurred during the data collection, but the correlation was weak and it could not be concluded with absolute confidence that the temperature had a significant effect on the IRI results.

(11) It was also found that the amount of variation in the IRI results from the test sections used in this study did not increase with the magnitude of the IRI. It was expected that sections with higher IRI values might be impacted more by the temperature variation which could have introduced more variation in the IRI results.
It can be concluded that the diamond grinding technique used on Section D at the final I-16 test site did improve the IRI conditions at the site. This conclusion is based on the comparison of the IRI results from Section C and Section D, where Section D had a much lower IRI than section C.

7.2 Recommendations for Future Research

Additional research is required to fully determine the effects of the temperature variations on the concrete pavement behavior. The suggestions to expand this research are:

(1) It is suggested that the temperature data that was recorded from the weigh station test site be used to validate the current methods in the Mechanistic-Empirical Pavement Design Guide (MEPDG) used to estimate the temperature gradient in concrete pavements.

(2) Although a variety of pavement designs were incorporated into the current research it is suggested to expand the research by using the methodology that was developed here to further investigate how temperature variations affect concrete pavement characteristics of an assortment of pavement designs. The key pavement features that should be focused on are the slab thickness and the slab length because it is expected these will have the most significant impact on how the slab deflects when subjected to thermal variations. This would allow it to be determined if the temperature variation has a more significant impact on particular pavement designs or if all pavement designs behave in the same manner. This would allow concrete pavement experts to determine if their
particular pavement designs could be impacted by thermal fluctuations and if their faulting evaluation practices needed to be adjusted on a pavement design basis.

(3) It is also suggested that the research be extended to cover a broader spectrum of faulting conditions. The sites used in this research only covered sites that consisted mainly of joints with minimal faulting. It is expected that more severe faulting may accentuate the impact of the thermal gradient on the faulting.

(4) This research was performed on data that was collected on a single day toward the end of the summer season so the conclusions are based on a limited data set. This research should be extended and data should be collected seasonally at the test sites to cover more temperature fluctuation conditions to determine if there is any effect due to seasonal changes at the sites.

(5) Since Section D at the final I-16 test site had been diamond ground an alternate test section needs to be selected so that a sufficient comparison of the results from all of the sections at the final I-16 test site can be made.

(6) In some of the cases it was noted that the variation in the faulting results was more than the accuracy of the sensors, so it needs to be further assessed to determine where the additional variation is coming from. It is possible that the variation in the average faulting that is higher than the accuracy of the sensors is caused by minor shifts in the locations of the faulting measurements. When the faulting measurements are shifted the surface texture could be slightly different and cause the height readings used to calculate the faulting to be faintly different. The developed procedure could be adjusted to identify an exact location on the slabs surface and manually identify the faulting measurement locations on the
joint during the analysis, which would reduce the variation in the results if it were
caused by the change in the faulting measurement location. If the variations in
the results were not found to be caused by the measurement locations then the
system should be further assessed to determine if the additional variation is
casted by a drop in the system accuracy due to the data not being collected in a
controlled environment or if they were due to thermal variations in the pavement.
The accuracy of the sensors used to collect data is assessed in a controlled
environment so when the sensors are operated outside a controlled environment
there could be additional factors that could introduce error into the faulting
measurements. Some of these factors include random irregularities in the data,
dust or other debris could interfere with the laser as it is measuring the surface
data, and the vibrations of the sensors or frame supporting the sensors. Additional
research should be performed to better assess the accuracy of the sensors when
used in an uncontrolled environment.

(7) Due to the lack of documented validation of the 3D Line Lasers ability to measure
the IRI it is suggested that the system be further investigated to determine what
accuracy the measured IRI can be expected to have. One possible method to
validate the IRI from the 3D line laser could be collect data simultaneously with a
road profiler on the same section of pavement and to compare the IRI results from
the two.

(8) The 3D Line Laser data should also be used to extract the curvature of the slabs.
A preliminary investigation was performed in this study to obtain the curvature
information from the data, but due to the amount of time and effort required to
fully develop the procedure it is suggested that it be further evaluated and improved. Once the procedure can provide reliable curvature results the data from this study can be used to study how the curvature changes with respect to the temperature fluctuations.

(9) After the curvature that is derived from the 3D line laser data is validated it should be compared to other existing curvature computation methods, from equipment such as road profilers or LIDARS, and ground truths, from strain gauges or other curvature measuring techniques, to determine if it is sufficient to measure the curvature or if it is a better method to compute the curvature.

(10) The sensing vehicle used for this thesis is also equipped with LIDARs that could be used to capture the curvature of the concrete pavement. It is suggested that the ability of the LIDAR to measure the curvature be evaluated to determine if it is capable of depicting a change in the curvature. After the curvature measurement ability of the LIDAR is validated then the curvature can be extracted from the 3D line laser data and the LIDAR data for comparison. This would determine if both systems are capable to measure the curvature or if one system is superior to the other.

(11) The Geo3D system is equipped with an IMU that measures the changes in the vehicles position. Among these measurements include the vertical acceleration of the vehicle during the data collection. The vertical acceleration measured by the Geo3D IMU should be compared to the vertical accelerations measured by the IMU devices that are attached to the 3D line lasers. This would assist in validating the accuracy of the IRI that is measured by the 3D line lasers.
Joint 20 from Section C at the final I-16 test section showed a lot of variation in the faulting that is measured along the joint. It is suggested that actual faulting at the joints be measured using a faultmeter to establish ground truths for the joint. Then the ground truths should be compared back to the results from the 3D line laser to determine if they were valid.

The faulting results used in this analysis were generated using faulting measurements taken across the joint which may not be a sufficient representation of how faulting is measured during actual field surveys. So it needs to be extended to determine if the faulting results generated during field surveys are impacted by the thermal gradient in the slabs. Current faulting techniques, such as road profilers and faultmeters, typically select a single point on the joint to measure the faulting. For instance, the GDOT concrete survey manual specifies that the faulting be measured 6 inches (152.4 mm) from the pavement marking using a faultmeter. One way to determine if the GDOT survey would be impacted would be to adjust the parameters used by the faulting computation algorithm to ensure that a faulting measurement would be taken 6 inches (152.4 mm) from the lane marking. Then the data collected for this research could be reanalyzed to get faulting measurements for the desired point on each joint. The changes in the single faulting measurement could be compared to determine if there is an affect from the temperature changes and if the results taken during the GDOT surveys could be impacted.
APPENDIX A

THERMOCOUPLE INSTALLATION
APPENDIX A

THERMOCOUPLE INSTALLATION

Thermocouple Installation at Weigh Station on I-16 (West Bound)

Submitted to:
James Tsai, Ph.D., P.E.
Georgia Institute of Technology

By:
Zach Lewis
School of Civil and Environmental Engineering
Georgia Institute of Technology
{zllewis@aol.com}
Spring 2013
Table of Contents

A.1 INTRODUCTION ................................................................................. A-1
A.2 DEVICE SELECTION ................................................................. A-1
A.3 SITE SELECTION ................................................................. A-3
A.4 SLAB LOCATIONS AND DEPTHS TO MONITOR ............... A-1
A.5 INSTALLATION TIME SELECTION ........................................ A-4
A.6 THERMOCOUPLE INSTALLATION PROCEDURE .......... A-4
   A.6.1 Shoulder Preparation for Housing and Protective Piping .... A-5
   A.6.2 Groove Cutting ................................................................. A-7
   A.6.3 Hole Drilling ................................................................. A-9
   A.6.4 Thermocouple Labeling ................................................. A-11
   A.6.5 Housing Preparation and Thermocouple Placement in
       Protective Pipe ................................................................. A-13
   A.6.6 Thermocouple Placement in Slab ................................. A-18
   A.6.7 Excess Thermocouple Placement and Electrical Box
       Sealing ................................................................. A-23
   A.6.8 Soil Replacement ........................................................... A-24
   A.6.9 Data Logger Placement .................................................. A-26
A.1 Introduction

In order to know the temperature variation throughout the slab sensors are required to monitor the temperature. There are several methods out there that explain how to install these sensors while the concrete is being poured, but there were none that gave a detailed description of how to install the sensors into concrete that had already been placed. Since the test sections that were chosen for this study were in service and had already been placed a method had to be developed to install the required sensors into the slabs. This section starts by giving the details of the devices that were selected to monitor the temperature, it then describes which locations were selected to monitor, and finally provides a detailed procedure of the steps taken to install the sensors.

A.2 Device Selection

Several temperature monitoring devices were considered for use during the planning of this study. The types of devices that were considered for use included thermocouples, iButtons, and USB thermal data loggers. Of these three devices the thermocouples were selected for this study. Thermocouples were chosen because of the three they were the only device that could be placed in the concrete and log the temperature information to a data logger. The iButton and the USB device would have to be removed from the concrete and connected to computer in order to retrieve the thermal data. This would not be possible because it would require that some form of removable adhesive be used to hold the devices in the concrete which would more than likely be removed by the traffic and could cause the thermal logging device to be damaged while logging the temperature. The removable adhesive could have also had different thermal
properties than the concrete which could have given inaccurate readings, and would not have been a good representation of the actual slab temperature. The size of the device was also considered when selecting the device for the study. The thermocouples were the smallest of the devices that were considered so they would require the smallest hole to be drilled into the concrete. The exact thermocouples that were used to measure the temperature in the slabs were Omega hermitically sealed thermocouples with a temperature range from \(-400^\circ F\) to \(450^\circ F\). These devices only measure the temperature, but cannot record the temperature so they have to be connected to a data logger in order to record the temperature of the slab. The data logger that was used in this study was just a standard Omega programmable data logger that had the capability of logging 10,000 thermal readings with a timestamp for up to four thermocouples. So we could record up to 40,000 readings without returning to the test sites. After deciding which device was the best fit for our application we then had to determine where to put the devices into the slab.

A.3 Site Selection

After the depths and locations in the slab were defined a test site had to be located to develop a procedure to install the thermocouples into the concrete pavement. It was decided to use a slab at a Weigh Station that was nearby the Georgia Tech Savannah campus on I-16. Originally the plan was to select a slab in the back parking lot since it would be out of the way and would not interrupt their day to day operations. After communicating with the local department of transportation to find the pavement design for the back parking lot it was found that this pavement design was no longer in their
records, but they did have the pavement design for the main lane and the bypass lane. Although it seemed that not having the back parking lot design was a downfall it actually turned out to be a benefit because it would allow the sensor installation site to be exposed to traffic. Which would show how well the installation procedure would perform if it were used on an in service highway. Reviewing the plans allowed an approximate location to be defined for the installation; it would have to be in the main lane or the bypass lane. To select an exact slab the weigh station personnel were contacted and consulted and they suggested a slab, which would not affect their daily duties, to monitor. The slab that was proposed was located on the main lane and was just past the section that had an extended shoulder. The extended shoulder is used by the personnel when they are inspecting trucks, so a slab past this section was selected so that the data logger housing would not intrude on their inspections. Figure A.1 shows the aerial view of the weigh station with the considered locations and the exact location that was selected.

Figure A.1 shows the aerial view of the weigh station with the considered installation locations labeled and the slab that was selected for the installation.
A.4 Slab Locations and Depths to Monitor

To establish the locations in the slab to monitor several concrete experts were consulted and they made some suggestions on where to monitor the thermal data for the slab. It was determined that the corner of the slab at the joint (location 1 in Figure A.2) would be the most critical, because it is where the most curling and warping movement should take place. In order to see if there is any heat loss due to edge effects the center of the slab was also selected (location 2 in Figure A.2). Since we were there and it would only require one more hole to be drilled we also selected the center of the slab at the joint (location 3 in Figure A.2). Having these three locations would show how the temperature varied through the slab and to determine if the location of the sensors in the slab would have a major impact on the variation between the top and bottom. It would also show if there was a significant change in the temperature variation or if there was just a shift in the temperatures. Figure A.2 shows the locations on the slab that were selected to monitor.

Figure A.2 shows the locations that were selected to monitor in the preliminary test section.

It was also necessary to see how the temperature varied through the depth of the slab at each of these locations. Since the data loggers that were being used could log the
temperature data from four thermocouples, four depths were selected. Since the focus of this study is the curling and warping of the slab then the two most critical depths to measure are ½ an inch from the top of the slab (location 1 in Figure A.3) and ½ an inch from the bottom of the slab (location 3 in Figure A.3). These two depths will give the variation between the top and bottom of the slab and these values can be used to determine the times that the maximum positive, maximum negative, and zero curvature occur. This will determine the times that data needs to be collected on the test sections. Since there were two depths left to measure the center depth of the slab (location 2 in Figure A.3) was selected so that the distribution of the temperature throughout the depth of the slab could be evaluated. The final depth that was selected was 1 inch into the base (location 4 in Figure A.3), this would show if there was any deviation between the bottom of the slab and the base. Figure A.3 shows the depths that were selected to place the thermocouples.
A.5 Installation Time Selection

Once the slab and locations were selected the time to install the thermocouples had to be coordinated with the weigh station personnel. During the planned period to install the thermocouples the weigh station was in operation so it required careful planning to avoid interrupting the functions of the weigh station. The operation time for the weigh station during this period was from 6:00 a.m. to 12:00 a.m. The weigh station personnel were consulted to determine which day had the least amount of trucks that traveled through the weigh station. Saturday was the day that was suggested since there

Figure A.3 shows the depths that the thermocouples were placed into the concrete slab.
was only one to two hundred trucks that passed through the weigh station on that day. In order to minimize the amount of time that the main lane was closed to truck traffic it was decided to start the installation at 12:00 a.m. on Saturday morning. This would only cause the main lane to be closed for a few hours after the scheduled opening. The actual time of the installation started at 12:00 a.m. and it was finished at 10:00 a.m. on Saturday October 6, 2012.

A.6 Thermocouple Installation Procedure

This section presents the detailed procedure that was used to install the thermocouples into the slab and the data logger housing into the shoulder at the weigh station. This section is broken into several subsections and is organized as follows: the first subsection describes how the shoulder was prepared for the data logger housing and protective pipe, the second subsection tells where and how the grooves were cut into the top of the slab, the third subsection explains where and how the holes were drilled into the slab, the fourth subsection presents how the thermocouples were labeled, the fifth subsection gives the details of how the housings were prepared and how the thermocouples were placed in the housings and the sixth subsection tells how the thermocouples were placed in the concrete, the seventh subsection describes how the excess thermocouple was coiled into the electrical box and how the electrical box was sealed, the eighth subsection explains how the housing and pipe were covered and the final subsection shows how the data loggers were placed in the housings.
A.6.1 Shoulder Preparation for Housing and Protective Piping

The first step that was taken to install the thermocouples at the weigh station was to prepare the shoulder beside the selected slab by removing the grass and soil where the data logger housing was going to be stored and where the protective pipe would be placed. For the data logger housing grass was carefully peeled away so that it could be placed back after the installation was finished. Figure A.4 shows the shoulder after the grass was removed.

![Figure A.4](image)

(a) The Location where the Data Logger would be housed after the grass was peeled off.

(b) Pictures of the grass that was carefully removed so that it could be replaced after the installation.
Figure A.4 shows the shoulder after the grass was removed.

In order to house the data loggers and keep them, an irrigation box was chosen to protect the data logger. The irrigation box would protect the data from everything except precipitation, because the irrigation box is not water tight. So it was also decided to place
the data loggers in a sealed electrical box to shelter them from rain. It was necessary to
remove enough soil so that the irrigation box could be installed to house the electrical
box containing the data logger. Enough soil had to be extracted so that the top of the
irrigation valve box is flush with the bottom of the layer of grass (the top of the box
should be at the same level as the root system of the grass). This will ensure that the top
of the irrigation valve box is recessed under the grass which will prevent the box from
being damaged during routine maintenance at the site (i.e. having the box recessed will
keep it from being struck by the blades of a lawnmower when the grass is cut on the site).
Figure A.5 shows the shoulder after the soil was removed so that the irrigation box could
be recessed into the ground.

(a) The hole that was dug to hold the data logger.

(b) The irrigation valve box that will be used to house the data logger.

Figure A.5 shows the hole that was dug for so that the irrigation box could be below
the ground surface.
After the shoulder was prepared for the irrigation box it also had to be prepared so that the protective pipe could be inserted. A protective pipe is used because the thermocouples would have to go to the center of the slab from the irrigation box. In order to keep the thermocouples out of the way they would need to be ran underground, so to provide more protection and try to prevent damage it was decided to place them into a piece of pipe. This would prevent the thermocouples from being cut if anyone ever dug beside the slab, they would only strike the pipe with their shovel instead of cutting the thermocouples in half. To prepare the shoulder for the pipe a trench was dug from the irrigation box to the center of the slab using a shovel. Figure A.6 shows the trench where the pipe would be placed.

![Figure A.6 shows the trench that was dug to hold the protective pipe.](image)
A.6.2 Groove Cutting

The next step of the installation was to cut the grooves into the slab using a grinder with a masonry blade. These grooves will later be used to hold the thermocouple wires that go to the data loggers. Both grooves ran parallel to the joint. The first groove was cut 0.5 feet from the joint and the second groove was cut 10 feet from the joint. The grooves were 5 feet long and started at the center of the slab and went all of the way to the edge of the slab at the shoulder. Figure A.7 shows the schematics of the slab that show where the grooves were cut into the slab.

(a) Schematic of the concrete slab before any modifications were made.

(b) Schematic of the slab after the grooves were cut using the grinder.
The depth of grooves closest to the joint was approximately 1 inch from the center of the slab to 1 foot form the edge. One inch was used because it would allow all of the thermocouples to fit into the grooves and allow for about ½ of an inch of concrete adhesive to cover them. Since a second hole was to be drilled in this groove at 1 foot from the edge of the slab, the groove had to be deeper in order to account for the four additional thermocouples that would need to be placed in the groove. In the last 1 foot section of the groove it was cut to approximately 1 ½ inches. The second groove that was 10 feet from the joint was cut to a depth of 1 inch because it would only have to conceal four thermocouples. Figure A.8 shows one of the grooves being cut into the slab with the grinder.
A.6.3 Hole Drilling

After the grooves were cut into the slab surface then the holes had to be drilled into the concrete. A hammer drill with a ½ inch high strength concrete bit was selected as the tool to use to drill into the concrete with. Before the holes were drilled the grinder was used to cut an ‘x’ into the slab at the locations where the holes were to be drilled. This was done to help keep the bit from trying to walk along the groove that had been cut. It would help get the hole started and ensure that the hole’s location was not shifted. The first hole was drilled 5 feet from the edge and 10 feet from the joint (in the center of the slab), the second hole was drilled 0.5 feet from the joint and 5 feet from the edge (the center of the slab along the joint), and the third hole was drilled 0.5 feet from the joint and 1 foot from the edge (near the corner of the slab). Figure A.9 shows the schematic of the slab after the holes were drilled and their locations in the slab.
Figure A.9 shows the schematic of the slab to illustrate where the holes were drilled. It was already determined that the holes needed to be 13 inches deep to ensure that the thermocouples could be inserted 1 inch deep into the slab. To check the depth of the holes a 3/8 inch wooden dowel rod was measured and labeled with a 13 inch mark. Then periodically during the drilling of each hole the dowel was inserted into the hole to check the depth. Figure A.10 shows the dowel rod that was used to measure the depth of the holes. Figure A.11 shows one of the holes as it was being drilled.
(a) The 3/8 inch dowel rod was marked at 13 inches

(b) The dowel rod being used to check the depth of the hole.
Figure A.10 shows the dowel rod that was used to measure the depth of the holes that were drilled.
A.6.4 Thermocouple Labeling

In order to know which thermocouple was located where they had to be labeled. To label the thermocouples red electrical tape was used to make a tag on the end of the thermocouple that had a plug on it. (The other end will be labeled later, but was not labeled here because the tag would have to be removed to insert the thermocouple into the housing) Then a marker was used to write a number and letter designation on each tag.

The letter that was written on the tag was used to indicate which hole the thermocouple was to be placed in. The hole in the corner of the slab was labeled as A, the hole along the joint and in the center of the slab was labeled as B, and the center of
the slab was labeled as C. The number that was written on the tags was to indicate what depth the thermocouple was placed at. T4 was used to indicate the thermocouple that was placed $\frac{1}{2}$ inch from the top surface of the slab, T3 was used to indicate the thermocouple that was placed at center depth of the slab, T2 was used to indicate the thermocouple that was placed $\frac{1}{2}$ inch from the bottom of the slab and T1 was used to indicate the thermocouple that was inserted 1 inch into the base below the slab. Figure A.12 displays where the letters and numbers used to label the thermocouples were located.

Figure A.12 shows the letter locations and number depths used when labeling the thermocouples.
Since two different length thermocouples were used it was necessary to select the proper length thermocouples when labeling them. The two lengths that were used were 10 feet and 25 feet. For location A and B the 10 feet cables were used and for location C the 25 feet cables were used. There were a total of 12 thermocouples labeled and they were A-T1, A-T2, A-T3, A-T4, B-T1, B-T2, B-T3, B-T4, C-T1, C-T2, C-T3, and C-T4. Figure A.13 shows one of the labeled thermocouples.

![Image of labeled thermocouple]

**Figure A.13 shows one of the labeled thermocouples.**

**A.6.5 Housing Preparation and Thermocouple Placement in Protective Pipe**

After the shoulder and the slab were prepared the housings had to be prepared. The electrical box was only big enough to hold two data loggers, so two electrical boxes had to be prepared. To prepare the electrical boxes a drill with a 1/8 inch drill bit was used to drill holes for the thermocouples to run through. The box that would house 2 data loggers had to have 8 holes drilled in it and the box that would house one data logger had to have 4 holes drilled in it. Figure A.14 shows the holes being drilled into one of the boxes.
Figure A.14 shows the 1/8 inch holes being drilled into one of the electrical boxes.

After the electrical boxes were prepared the irrigation box also had to have 2 holes drilled in it to allow the thermocouples to run through it. The holes in the irrigation box were ½ inch in diameter so that pipe fittings could be attached. There were two holes drilled in the irrigation box one on the side facing the slab and one on the side facing the pipe. Figure A.15 shows the holes being drilled into the irrigation box.

Figure A.15 shows one of the holes being drilled into the irrigation box.
After the holes were drilled in the housings the wires had to be run through them. The wires were run through the electrical box first, and the ends of the thermocouples that were on the exterior of the box (these are the ends without the plugs the ends with the plugs were labeled earlier in section 6.4) were labeled so that they could be run to their designated locations. The ends without the plugs were given the same labels as the end with the plugs, so that both ends of the thermocouples had matching labels. Then they were run through the irrigation box. Figure A.16 shows one of the electrical boxes and the irrigation box after some of the thermocouples were run through it.

(a) The exterior of the electrical box with the thermocouples ran through it

(b) The interior of the electrical box with the thermocouples ran through it
(c) The interior of the irrigation box after the thermocouples were ran through it

Figure A.16 shows the housings after some of the thermocouples were run through them.

Once the thermocouples were run through the housings the four that were going to be placed in the center of the slab had to be fished through the protective pipe. The protective pipe that was used consisted of the three pieces one was a 10 foot piece, the second was a 90 degree elbow, and the third was a short piece about 1.5 feet. To get the thermocouples through the longer pipe a piece of masonry twine was fed all of the way through the pipe and the four thermocouple ends were taped to the twine. Then the twined was pulled on the opposite end in order to pull the thermocouples through the pipe. Figure A.17 shows the 10 foot pipe with the twine run through it and after the thermocouples were pulled through.
(a) The protective pipe with the masonry twine ran through it

(b) The protective pipe after the thermocouples were ran through

Figure A.17 shows the 10 foot protective pipe with the twine and the thermocouples ran through it.

Since the elbow and 1.5 foot piece of pipe were short it was easy just too directly feed the thermocouples through it. So the thermocouples were pushed were pushed through and the pieces of pipe were connected to each other and then the 10 foot piece of pipe was connected to the irrigation box. Figure A.18 shows the pipe as the thermocouples were being run through it.
(a) The 90 degree elbow after the thermocouples were pushed through

(b) The 1.5 foot piece after the thermocouples were pushed through
(c) The 10 foot piece of pipe where it connects to the irrigation box

(d) The overall view of the pipe and housings after the thermocouples were run through them

Figure A.18 shows the pipe at different stages as the thermocouples were ran through it.
A.6.6 Thermocouple Placement in Slab

The next step of the installation procedure was to insert the thermocouples into the slab and secure them in with concrete with concrete anchoring adhesive. In order to know how deep the thermocouple was supposed to go into the slab they were measured and marked using a piece of black electrical tape. For each hole three of the thermocouples had to be measured and marked. These three were the one that was to be placed at mid depth of the slab (T3- 6 inches from the slab surface), the one that was to be ½ an inch from the bottom of the slab (T2- 11.5 inches from the slab surface), and the third one was the one that was to be 1 inch into the base under the slab (T1- 13 inches from the slab surface). Figure A.19 shows the depths being measured and marked on the thermocouples.

(a) The thermocouple that would be placed 1 inch into the base under the slab (13 inches deep)

(b) All three thermocouples for one hole after they were measured and marked. Figure A.19 shows the depths being measured and marked onto the thermocouples.
Now that the thermocouples were marked and there depths measured they were bundled together and the bottom of the electrical tape on each was aligned. The bottom of the electrical tape represented where the slab surface would be when the thermocouples were inserted into the slab. So this would be the relative positions of the thermocouples when inserted in the slab so a cable tie was used to fasten them together. The cable tie was used because once the bundle was inserted to the hole it would create a stop that would hold the thermocouples in their designated location. Then black electrical tape was used to hold the thermocouples together throughout the bundle. After the thermocouples were bundled and fixed together they were inserted into the slab. Figure A.20 shows the thermocouples being bundled together and inserted into the slab.

(a) The thermocouples after they were aligned and taped together (the labels were removed before the thermocouples were inserted into the slab)

(b) The thermocouples fastened by the cable tie
The thermocouples inserted into the slab. Figure A.20 shows the thermocouples being bundled together and inserted into the slab.

Next the remainder of the hole was filled with the concrete anchoring adhesive. The hole was filled in three stages the first was to fill the hole with approximately 8 inches of the adhesive, which would allow all three of the thermocouples to be in the adhesive. Then the adhesive was allowed to set fixing the thermocouples into the slab. Then the cable tie was removed and the thermocouples were laid over into the groove that had been cut for them. Now the second stage of the filling process was performed and it was to fill the hole until it was only ½ an inch deep, and then the adhesive was allowed to set. This would allow the forth thermocouple to just be laid in the trench and it would be in its proper place. Once the adhesive was hardened enough the forth
thermocouple was put into place. Then the third stage of the hole filling process was executed and it was to fill the remaining ½ inch of the hole. Once the third stage of the filling was complete the adhesive was allowed to fully set to ensure that the thermocouples position was not altered when the groove was filled with the adhesive. Figure A.21 shows one of the holes being filled with the concrete anchoring adhesive.

![Figure A.21 shows one of the holes being filled with the concrete anchoring adhesive.](image)

When the adhesive was set the thermocouples were situated into the groove using a flat head screwdriver to push them to the bottom of the groove. This was done from the filled holes to the edge of the slab all along the groove. Cardboard was used to make shims to hold the thermocouples in the bottom of the groove and to keep them from rising up while the adhesive was drying. The groove was then filled with adhesive in two stages. The first stage of the groove filling process was to fill the entire groove with the exception of the locations that were occupied by the cardboard shims. Once these spaces
were filled and the adhesive had set the cardboard shims were removed and the remainder of the groove was filled. Figure A.22 shows one of the grooves as it is being prepared to be filled, as it is being filled and after it has been completely filled.

(a) The thermocouples as they were laid into the groove

(b) The cardboard shims used to temporarily hold the thermocouples into the bottom of the groove
Figure A.22 shows the different parts of the groove filling process.

(c) Close up view of the cardboard shims

(d) The groove as it is being filled with the adhesive

(e) The groove after it was totally filled

Figure A.22 shows the different parts of the groove filling process.
A.6.7 Excess Thermocouple Placement and Electrical Box Sealing

Once the thermocouples were secured into the slab the excess had to be pulled back to the irrigation box. When the excess was pulled back through the irrigation box it was also pulled into the electrical boxes. Where it was then coiled and tied to keep it neat and organized so that when the data loggers would be placed in the boxes the plugs could be easily accessed and the labels could be seen clearly. After all of the excess thermocouple was pulled into the electrical box the holes that they passed through had to be sealed to help prevent water from entering the box. To seal the holes in the electrical box silicone was used. Large amounts of the silicone were spread around the thermocouples where they passed through the walls of the box on both the interior and exterior. Enough silicone was applied to ensure that there was no gap between the thermocouple and the wall of the electrical box. Figure A.23 shows the excess thermocouple that was coiled in the electrical box and the holes after they were sealed with the silicone.

(a) The excess thermocouple coiled in the electrical box
(b) The sealed holes where the thermocouples pass through the walls of the electrical box

Figure A.23 shows the thermocouples after they were coiled in the electrical and the holes after they were sealed with the silicone.

A.6.8 Soil Replacement

After the thermocouples were secured and fastened in the housing and the slab then the soil and grass that was removed needed to be replaced. The trench holding the protective pipe was filled first. When the soil was removed it was removed in triangular wedges so it was easily replaced just by putting the wedges back into place. Once the wedges were back in their places they were compacted down by stepping on them. The next step in the soil replacement process was to fill the soil back in around the irrigation box. When it was removed it was placed beside the hole so it just had to be shoveled
around the box. (The lid was placed on the irrigation box during this step to prevent the inside of the box from filling up.) It was also compacted by stepping on it as the hole was filled. Once the soil was almost level with the box then the grass that was carefully rolled away in the beginning was placed back on top of the soil so that it could continue to grow and prevent a mud hole from forming around the box. Since the box took up some of the space that was previously occupied by the soil there was some excess soil left over, but it was just scattered in the surrounding grass so that it would be washed away in the future by rain. Figure A.24 shows the shoulder during and after the soil replacement.
A.6.9 Data Logger Placement

Now that the thermocouples were installed the data loggers had to be set up in order to record the thermal data from the slab. The data loggers had to be programmed to the required specifications. Since the data collection plan was to collect data every fifteen minutes for this particular site the loggers were programmed to collect a thermal reading for each location every fifteen minutes. After the three data loggers were programmed they also were labeled to ensure that the thermal data was correctly analyzed in the future. The data loggers were labeled A, B, and C and the labels correspond to the three holes that were drilled in the slabs. Figure A.25 shows the data logger being programmed and one of the labeled data loggers.
The matching thermocouples were then plugged into their data loggers and the data loggers were set to record. After the data loggers were set to record they were placed into the electrical boxes. Since the temperature fluctuations and humidity would
cause moisture to build in the electrical boxes damp rid was also inserted into the boxes to soak up any moisture that formed in the box. After everything was in the box then the lids were placed on the electrical boxes and fastened to them using Phillips head screws and a drill with a Phillips head bit. To add an extra layer of protection to the data loggers the electrical boxes were inserted into large plastic bags and then these bags were tied shut using a cable tie. The wrapped electrical boxes were then inserted into the irrigation box and the lid was placed on it. Figure A.26 shows the data loggers being inserted into the electrical boxes, wrapped in the plastic bags, and then being placed into the irrigation box. Figure A.27 shows the site after the installation was complete.

(a) The data loggers in the electrical box with the damp rid
(b) The screws being inserted to seal the lid on the electrical box

(c) The electrical boxes after they were put in the plastic bags
(d) The electrical boxes after they were placed into the irrigation box Figure A.26 shows the data loggers as they are being placed into their protective housings.

Figure A.27 shows the site after the thermocouples were installed.
APPENDIX B

DATA EXTRACTION PROCEDURE
Procedure to Extract Curvature, Faulting, and Roughness from the 3D Line Laser data

Submitted to:
James Tsai, Ph.D., P.E.
Georgia Institute of Technology

By:
Zach Lewis
School of Civil and Environmental Engineering
Georgia Institute of Technology
{zlewis@aol.com}
Summer 2013
Table of Contents

B.1 INTRODUCTION………………………………………………………………………………… B-1

B.2 PROCEDURE TO GENERATE THE IRI RESULTS USING THE 3D LINE LASER SOFTWARE………………………………………………………………………………… B-1

B.3 PROCEDURE TO GENERATE THE FAULTING RESULTS USING THE 3D LINE LASER SOFTWARE………………………………………………………………………………… B-7

B.3.1 Faulting Parameters ………………………………………………………………………… B-7

B.3.1.1 How the LcmsRoadInspect Software Calculates the Faulting of a Joint………………………………………………………………………………………… B-7

B.3.1.2 The Faulting Parameters Described……………………………………………… B-8

B.3.1.3 How to Adjust the Faulting Parameters…………………………………………… B-9

B.3.2 Single Joint Faulting Processing………………………………………………………… B-10

B.3.3 Multiple Joint Faulting Processing…………………………………………………… B-13

B.3.4 Faulting Result……………………………………………………………………………… B-15

B.4 PROCEDURE TO PRODUCE CORRECTED LONGITUDINAL PROFILES FROM PROVAL………………………………………………………………………………… B-18

B.5 PROCEDURE TO PRODUCE LONGITUDINAL AND TRANSVERSE CURVATURE FROM RAW 3D LINE LASER DATA………………………………………………………………………………… B-22

B.5.1 File Conversion …………………………………………………………………………… B-23

B.5.2 Locating Slab Extents Using LcmsRoadInspect Software…………………. B-25

B.5.3 Using MATLAB to Extract Slab Profiles from Binary Files………. B-31

B.5.4 Using Excel to Analyze the Slab Profiles…………………………………………… B-35

B.6 PROCEDURE TO EXTRACT THE RAW IMU DATA…………………………………… B-40
B.7 **PROCEDURE TO EXTRACT THE TEMPERATURE DATA FROM THE DATA LOGGERS** ....................................................... B-41

B.8 **CONCLUSION** ........................................................................................................... B-42
B.1 Introduction

The results required from the analysis of the 3D Line Laser data has to come from different locations and call for several processing steps to be taken. The roughness or International Roughness Index (IRI) is a direct output from the 3D Line Laser software and can be viewed in the software as soon as the data is processed. The faulting for each joint is also an output of the 3D Line Laser software but is produced into a separate file (html file) that has to be opened in another program (Internet Explorer) in order for it to be viewed. The transverse profiles can be viewed in the 3D Line Laser software, but only half of the profile can be seen at a time because each sensor captures approximately half of the slab and the software only allows one sensor to be viewed at a time. Although the transverse curvature can be seen it cannot be accurately quantitatively accessed within the 3D Line Laser software so the data has to be extracted and combined in a separate program (MATLAB or Excel) in order to establish sufficient results.

For the longitudinal profile extraction there are two types of profiles that can be extracted and used for analysis, the first is the longitudinal profiles created from the 3D Line Laser data that has been corrected by the IMU data and the second is the longitudinal profile created from just the raw 3D Line Laser range data. The reason that the second longitudinal profile is used at this point in the research is because the IMU data is affected by drift during the data collection which causes a small height variation over the traveled distance during data collection. Currently the only way to remove the drift in the profile is to use a high pass filter which also removes the curvature from the slab, so the raw and corrected profile are both extracted for comparison. Thermal data for the concrete slabs at the weigh station is collected using thermocouples installed in
the slab at different locations and a data logger to store the time and temperature readings. In order for this data to be examined and reviewed it has to be downloaded from the data logger and analyzed using Excel.

The following procedure is divided into seven sections the first is the detailed process to generate the IRI results from the 3D Line Laser software, the second section tells how to produce the faulting results from the 3D Line Laser software, the third section explains how to get the corrected longitudinal profile that is created by correcting the 3D Line Laser data using the IMU data from the PROVAL software, the fourth section gives the detailed procedure to extract the raw 3D Line Laser data using MATLAB and how to use Excel to analyze the data, and the fifth section shows how to obtain the raw IMU data, the sixth section describes how to acquire the temperature data from the thermal logging devices, and the final section is the conclusions from the procedure.

**B.2 Procedure to Generate the IRI Results Using the 3D Line Laser Software**

The IRI results are a direct output of the 3D Line Laser longitudinal profile processing and they are given to the user immediately after the processing is complete. There are two values given one for the right wheel path and one for the left wheel path. After the results are generated the IRI values have to be manually recorded, because they are not stored in a separate file like the other results that are produced by the 3D Line Laser software. This section of this Appendix provides the detailed procedure to use the 3D Line Laser software to obtain the IRI values for a selected section of pavement.
The first step that should be taken is to open the LcmsRoadInspect software. Once the program is open then use the open button in the top right corner to open the file selection window. Then navigate to the folder containing the data that the user wants to process and double click on the file that starts the pavement section that is going to be processed. It is important to follow this step because if the user navigates to the desired file and double clicks it and allows the computer to automatically open the LcmsRoadInspect software then the processing options will not be available to the user. Figure B.1 shows the user interface for the LcmsRoadInspect software when the desired data is opened in the program using both options described above. The processing options are indicated by the red circles it can be seen that they are not available in figure B.1 (b).

(a) LcmsRoadInspect software when the software is opened first then the desired data is selected using the software’s open function.
After the software is opened correctly then the user needs to scroll through the data and find the desired starting and end points. There are two options that the user can use to select the starting and ending points of the longitudinal profiles that are created. The first option is to record the file that contains the starting point and the file that contains the ending point. The second option is to record the exact starting and ending points based on the distance from the beginning of the data collection. Once the beginning and ending points are known then the user needs to click on the start button just under Long Profile (this is an abbreviation for the longitudinal profile) in the lower right corner of the user interface. Figure B.2 shows the location of the start button that is used to start the longitudinal profile processing.
When this button is clicked then the user will be prompted to select the beginning and ending points for the longitudinal profile that the user wants to create. Figure B.3 shows the window that pops up when the start button is clicked and allows the user to define the starting and ending files for the longitudinal profiles.
Figure B.3 shows the window that allows the user to define the starting and ending files to be processed for the longitudinal profiles.

Once this window is open select the user can input the beginning and ending points by clicking on the drop down box under “First Section”, this will be the file that the user wants the longitudinal profiles to begin in. After the beginning file is selected click on the drop down box beneath “Last Section”, and select the file that the user wants to end the longitudinal profiles in. The user can also select the exact beginning and ending points that they want to create a longitudinal profiles from. To define the beginning and ending points using this option the user needs to enter the exact beginning point in the box under “Start Position” and the desired length of the profile in the box below “Profile Length” in the center of the window. The value in the “End Position” box should the exact ending position that the user selected previously. The user also has the option to select the destination folder that the longitudinal profiles are stored in. This is done by clicking on the “Select Folder” button and then navigating to the preferred
location, once the desired folder is selected then click save in the lower right corner of the navigation pane and the destination folder will be changed to the selected folder. This location is not important for the IRI values but will be when the user needs to view or analyze the corrected longitudinal profiles which will be discussed in more detail later in this Appendix. After all of the options are set to what the user prefers then the longitudinal profiles can be created by clicking the start button in the lower right corner of the window.

When the start button is clicked the software will begin creating the longitudinal profiles and will also begin calculating the IRI for the defined section of pavement. The progress of the processing can be observed in the main interface of the LcmsRoadInspect software. Figure B.4 shows where the progress is shown on the user interface.

![User interface showing progress in the main interface](image)

Figure B.4 shows the location where the status of the processing is reported.
Once the processing is complete then the IRI values will be displayed in a separate window. The user has to manually record these values because they are not stored anywhere. After the processing in complete there are also four files that are created and saved in the destination folder that the user defined earlier in this procedure. Figure B.5 shows the IRI values that are produced from the LcmsRoadInspect software.

![Image showing the IRI results generated from the longitudinal profiles created.]

**Figure B.5 shows the IRI results that were generated from the longitudinal profiles that were created.**

Below is a list of the files that are created and saved they include the left and right wheel path longitudinal profiles that were created by correcting the 3D Line Laser data with the IMU data and the left and right raw IMU data is also stored there in a binary file.

- LcmsLongProfile_80121601_B200m_L900m_s5mm_L.ppf
- LcmsLongProfile_80121601_B200m_L900m_s5mm_R.ppf
- LcmsLongProfile_80121601_B200m_L900m_s5mm_IMU_L.bin
- LcmsLongProfile_80121601_B200m_L900m_s5mm_IMU_R.bin
These files will be used for other procedures that will be described in further detail later in this Appendix.

This section of the Appendix has given the detailed explanation of how the IRI results can be obtained using the LcmsRoadInspect software. These results are a direct output from the software and only require the user to select a starting and ending point and the software then produces the longitudinal profiles and calculates the IRI values that the user can instantly see and acquire immediately after the processing is complete.

**B.3 Procedure to Generate the Faulting Results Using the 3D Line Laser Software**

After the IRI results are obtained then the faulting values for each joint can be obtained. Within the LcmsRoadInspect there are two ways to process the faulting for a section of pavement the first is to analyze one joint at a time and the second is to process multiple joints at time. The procedure to process a single file will be described and the procedure to process multiple files at a time will also be given. The most important thing to note is that when using the faulting computation method provided in the LcmsRoadInspect software is that there are three parameters that can be adjusted and will impact the faulting values that are produced by the software. This section will begin by describing these parameters and how to change them then it will give a detailed procedure on how to generate the faulting results using the software then how to get these results so that they can be used to represent the faulting on the joint.
B.3.1 Faulting Parameters

Since different agencies have different requirements to follow when measuring the faulting of a joint, a variety of methods and devices are available to measure the faulting. So to make the software more versatile three common factors where made variable so that the software could be customized by the particular agency that is performing the faulting measurements. This subsection will start by briefly describing how the LcmsRoadInspect software calculates the faulting, then it will explain the faulting parameters that can be adjusted, and then it will give the process that needs to be followed so that the user can modify these parameters and customize the faulting calculations to fit the method of their choice.

B.3.1.1 How the LcmsRoadInspect Software Calculates the Faulting of a Joint

In order to calculate the faulting of a joint the LcmsRoadInspect software will locate the joint and begin performing the faulting calculations either at the lane marking or the end of the joint depending on what the user specifies when starting the processing. Before beginning the processing the user can select whether the software detects the lane markings in the data or not. If the user specifies that the software needs to identify the lane marking then the faulting calculations will start at the lane markings. If the user does not select this option then the software will begin the faulting calculations at the start of the joint. After the program defines where to start the faulting calculations then it will begin by going to the specified location in the data (this is a point on the joint) and then it will select points that are a set distance past the joint and a set distance before the joint, the distance between these points is known as the footprint, once these two
locations are found in the data the software will then compute a height reading at each point. To obtain this height reading the profile uses a certain number of the readings that are the set distance away from the joint, the amount of points used is defined as the average window width. Once the program finds all of the points on each end it takes the average of the points and produces two values which are height readings for each side of the joint. The faulting is then calculated as the difference between these two height readings. After this faulting value is calculated then the program moves a set distance along the joint and repeats the same process again until it reaches the next lane marking or the end of the joint. Figure B.6 shows a schematic of how the faulting is typically measured and how the LcmsRoadInspect software measures the faulting.

![Diagram](image)

Figure B.6 shows a schematic of how the faulting is calculated in the LcmsRoadInspect software.
B.3.1.2 The Faulting Parameters Described

The three parameters that can be adjusted are the footprint, the interval between the locations that the faulting measurements are performed and the width of the window of 3D Line Laser data points used to measure the height on each side of the joint. The software defines the footprint as the measurement distance, it defines the interval between points as the evaluation position distance and it defines number of point used to find the average height readings as the averaging window width. Figure B.7 presents a figure that shows these parameters and how they are used to calculate the faulting in the software. In the figure the pink line indicates the lane marking that is detected by the software, the red I’s indicate the locations where the faulting is calculated, A is the footprint, B is the averaging window width, and C is the interval between the calculation locations.

Figure B.7 shows the parameters that are used by the software to calculate the faulting.
B.3.1.3 How to Adjust the Faulting Parameters

This section describes the steps required to change the parameters that are described in the previous section to the ones that the user needs to ensure that the program is calculating the faulting based on their desired technique. The first step of this process is to navigate to the LcmsAnalyser folder which is in the Pavemetrics folder and it contains the LcmsAnalyserParam.cfg file. This folder location could be different depending on the computer and the operating system that is on the computer. The computer being used to write this procedure has Windows 7 and the path to the LcmsAnalyser folder is C:\Program Files (x86)\Pavemetrics\LcmsAnalyser. Once the LcmsAnalyserParam.cfg is located then the user needs to right click on the file and select edit from the options that appear. Figure B.8 shows what the user should see after the configuration file is opened so that it can be edited; the faulting parameters are highlighted in blue.

![Configuration file with faulting parameters highlighted](image)

Figure B.8 shows the configuration file as it is being edited; the faulting parameters are highlighted in blue.

The exact names of the parameters are given below with the description that corresponds to the ones given in the previous section:

JointModule_EvalPositionDistance_mm Interval between the faulting calculations
JointModule_AveragingWindowWidth_mm Width of the array of data points used to calculate the average height readings
JointModule_MeasurementDistance_mm Footprint

All of the units for the parameters are in mm and the user can adjust the parameters by changing the number that follows the parameter’s name and is separated by a tab. Once the user defines these values then the user needs to save the changes and close the configuration file. If the LcmsRoadInspect software is open then it needs to be closed and reopened so that the new parameters will be used in the faulting calculations.

### B.3.2 Single Joint Faulting Processing

After the parameters are set to the desired values and the software is open then the user can begin analyzing the faulting of the joints. This can be done one of two ways the user can go to each joint individually and process them one at a time or the user can select to process multiple joints at a time. This subsection lays out the procedure to process a single joint. The first step that the user needs to perform is to use the file open function on the LcmsRoadInspect software to open the desired data set. Then the user should travel through the data until the joint that they want to process is shown in the data viewing section of the software window. When the software is opened all of the data processing options are automatically selected. The user has the choice to allow the software to process the data using all of the options or to only process for faulting. To process just the faulting the user should unselect all of the boxes in the process selection except the Joints Conc. box. After the user has selected the process options then they need to click the process button above the process selection section of the software window. The software will then begin processing the data and generating the results, the progress of the processing can be observed in the status box close to the center of the
Figure B.9 shows the LcmsRoadInspect software window that the viewer sees when it is open, the key features that are utilized during the data processing are labeled to show where they are located.

When the processing is finished then the user can view the qualitative results in the software. To do this the user needs to go to the results display section in the lower right side of the software window. The user can then select the results that they want to display. All of the boxes are selected by default when the program is opened but if the user wants to only view the faulting results then they have to unselect all of the other boxes and only select the Joints Conc. box. After the results that the user wants to
display are selected then the user should click the view results button and the qualitative results will appear in a separate window to the right of the main window and the results are shown. Figure B.10 shows the LcmsRoadInspect software with the qualitative results shown and the key features used to view the results are also indicated.

Figure B.10 shows the qualitative results in the LcmsRoadInspect software, it also indicates some of the features that are used to view the results.

After the user has the results viewing window open, then they have the option to save both the qualitative results that they have seen here and they can also save the quantitative results that were calculated by the software. To do this the user has to click on the save results button. When this button is clicked a Save Analysis Results window will come up and the user can specify the results that they want to save. By default in the Save options section of this window there are only two boxes that are checked and they
are the Save Overlay Image -Intensity and the Save Overlay Image – Range. The user can select any of the options that they would like to, but in order to save the quantitative results the user will have to select the Save XML Data option. The rest of the options in this section of the window are for the images that the user viewed in the results viewing window of the software. The user also has the option to select which qualitative results they would like to overlay onto the images that are saved. This is done by selecting the options in the Overlay Options section of this window, by default all of these options are selected but the user can unselect the ones that they do not want to display. After all of the options are specified the user needs to click the select folder button to navigate and select the destination folder to save the results into. After these steps are complete then the user needs to click the Save button and the results will be saved to the folder they specified the files that are saved will be discussed in the subsection of this section that describes how to get the results and use them. Figure B.11 shows the Save Analysis Results window that appears and allows the user to stipulate what results the software will save for later use.

![Save Analysis Results window](image)

Figure B.11 shows the Save Analysis Results window that allows the user to save the particular results that they want to use for further analysis.
B.3.3 Multiple Joint Faulting Processing

As mentioned in the previous section the user can process multiple joints at a time the steps required to do this will be laid out in this subsection of this Appendix. To process multiple joints using the LcmsRoadInspect the user needs to first locate the starting and ending points that they would like for the software to process. To do this the user need to navigate to the file that contains the first joint that they want to process and record the distance that is listed to the right of the right image in the column that displays the survey parameters. This distance indicates the distance at the beginning of the file so when the processing begins it will start searching for joints at the beginning of this file. After the beginning point is established then the ending point needs to be determined, to do this the user needs to navigate to the last joint in the section they plan to evaluate. After this joint is located then the user needs take the distance from this file and add the file length, which is located just above the distance value, to it. If the user only selected this distance then the software will stop processing at the beginning of this file and would miss the joint, so the file length is added so the software will process this entire file. Figure B.12 shows where the user can attain the distance value and the file length values.
Figure B.12 shows where the file length and distance values are located in the LcmsRoadInspect software window.

Once these values are recorded the user has to click on the Start button in the Proc. Multiple section in the main window of the software (this button is shown in figure B.12 above). Once the start button is clicked then multiple road section analysis parameters window pops up allowing the using to specify the extent of the data processing. This window is similar to Save analysis results window that appeared during the single file processing. It has the Save options selection section allowing the user to select the file formats that are saved during the multiple file processing, it also has the Overlay options section allowing the user to specify the results that are displayed on the saved images, and it has the Select folder button that lets the user choose where to save the results. The differences between this window and the one in the previous section are
that there is a Current Selection section and a Survey Info. section which provides the user with information about the data set that is located in the current folder that they are processing. There is also a Road section selection section that allows the user to specify a file to begin the processing in and a file to stop the processing with. By default the entire section in the data set is selected but the user can change this by changing the distance that the processing starts at and changing the distance that the processing ends at. These are the values that were recorded in the beginning of this section, the first section is the distance of the file that contains the first joint and the last section is last file distance plus the file length value. Figure B.13 shows the multiple road section analysis parameters window that allows the user to set up the data processing for multiple files.

Figure B.13 shows the multiple road section analysis parameters window that allows the user to adjust the processing that the software will perform and the results that will be saved.
After the user has defined all of the parameters for the data processing that they want the software to perform then they have to click the start button to make the software begin processing the data. Once the start button is clicked then the multiple road section analysis parameters window will close and the main software window will appear. The status of the data processing can be viewed in the Status section in the main window near the center; this is the same status section that was shown in figure B.9. When the software is finished processing the data then the files that the user specified previously will be saved into the destination folder. The files that are saved will be described in the next section and it will also describe how these values can be extracted and used.

### B.3.4 Faulting Result

This section describes what results were used for this particular analysis and how they were attained and used. Although there are several options that the user can select to view the results, but there were only three that were used for this analysis. The three that was used were the XML file, the intensity image with the results overlaid onto it, and the range data with the results overlaid onto it. The intensity and range images with the results overlaid onto them were used to visually see where the faulting values were calculated and to quickly assess if there was anything abnormal about the results. For instance these images were used to see if the lane marking was detected properly or if the joint detection that was performed properly by the software because in some cases only half of the joint was detected or the joint was not detected at all. These images were also used to check and see if there were multiple joints in one file and to check and see if they
were detected correctly. Figure B.14 shows an example intensity and range image with the faulting results overlaid onto them.

Figure B.14 shows the intensity and range images overlaid with the faulting results.

These images were also used to determine if there were any faulting measurements taken outside the desired joint sections. In most cases the data that was collected would be wider than the joint that was processed and there is not a function in the software that allows the user to stop the faulting calculations at the end of the joint, so in most cases a few faulting values had to be removed. For instance in figure B.14 above the joint starts at the white pavement marking (pink line) and ends at the longitudinal joint (it can be seen best in the range image), but the red I’s indicate that the faulting computations were continued past the end of the joint. So these values had to be removed from the quantitative results. To do the number of red I’s was counted and recorded and would be used a little later in this section. For the joint in figure B.14, four
I’s are past the joint so when the faulting values were extracted the last four would be deleted because they were calculated past the joint limits.

The XML file is the file that actually contains the quantitative results so these values had to be extracted out and evaluated in another program. The XML file contained the calculated faulting values and the x and y positions where they were calculated. For this analysis the faulting values were the only values that were of concern so they were the only values that were extracted. To extract the faulting values the XML file was opened then the faulting values were located and copied. There is a section with faulting values for each joint that is detected and each joint is divided into a left and right section. For example if there are two joints in one file there will be a left faulting value set and a right faulting value set for the first joint and there will also be a left faulting value set and a right faulting value set for the second joint that was detected, resulting in four total faulting value sets. The amount of faulting value sets was determined by reviewing the overlaid images, for example the image in figure B.14 there would be two faulting value sets. To determine which joints correspond to each other in the XML file the x and y position information was used. Figure B.15 shows the faulting values being copied from the XML file.
Figure B.15 shows the faulting values being extracted from the XML files.

If these values were directly pasted into Excel then the multiple values would be put into the same cell and no statistics could be generated from them. So to get the values into a usable format they were pasted into a notepad file. This is where the left and right values were stitched together and if there were multiple joints they were differentiated in the notepad file. Once the values were pasted into notepad then this is where the values that were calculated outside the joint limits were removed (four values for the example in figure B.14). After the values were in the notepad file they were then imported into Excel where statistics where generated. The statistics that were generated were the average, median and the variation of the faulting across the joint. For this analysis multiple runs were collected throughout the day so the same joint was collected several times. After all of the faulting values for each run were gathered then the average
faulting was plotted against the time of the data collection to visually show the change of the faulting throughout the day. Then the temperature variation through the day was also plotted on the same plot so that it could be seen how the faulting changed with the temperature. Figure B.16 shows an example plot of the faulting versus time and of the temperature versus time.

**Figure B.16** shows the faulting and temperature versus time plots generated in the faulting analysis.

### B.4 Procedure to Produce Corrected Longitudinal Profiles from PROVAL

After the faulting results are completed then the corrected longitudinal profiles need to be extracted. These are the profiles that are generated from using the raw 3D Line Laser range data and correcting it using the IMU data. The first step to pull these profiles out is to open the LcmsRoadInsect software and navigate to the first joint in the slab that the user wants to extract the profile for. The next step is to locate the starting point of the profile which is the location where the center of the wheel path intersects the
joint. This is an approximate location, but once it is located then the profile number needs to be recorded. Once this profile is found the starting point is found by multiplying this profile number by the resolution of the data collection and then adding it to the distance that is in the survey information column of the software. Below is the previous arithmetic written into an equation:

Starting Point = (Profile Number)\times(Resolution) + Distance

Figure B.17 shows where the values required to determine the starting point of the longitudinal profile are located. The example in the figure below has a starting point of 104.595 m, the units is meters which is what is required when inputting the starting point into the software. Here is the equation for calculating the starting point for the example:

\[
919\times(5\text{ mm})/(1000\text{ mm/m}) + (0.100\text{ km})/(0.001\text{ m/km}) = 104.595\text{ m}.
\]
Figure B.17 shows where the values used to calculate the starting point on the profile are located in the software window.

After the starting point is established then the profile length needs to be determined, this is done in a similar way as finding the starting point. To find the profile length travel to the ending joint on the slab that the profile is being generated for. Once this joint is found find the ending position the same way that starting position was found. Then subtract the starting point from the ending point to get the profile length. Ending Point – Starting Point = Profile Length. For the example shown in figure B.17 the ending joint parameters are: profile number = 137, the distance is 0.110 km, and the resolution is the same (5 mm) so the ending point is

\[ 110.685 \text{ m} = 137 \times (5 \text{ mm}) / (1000 \text{ mm/m}) + (0.110 \text{ km}) / (0.001 \text{ m/km}) = 110.685 \text{ m}. \]

The profile length for the example is 6.09 m (110.685 m – 104.595 m = 6.09 m) which is 19.98 feet. Since the design length of the
slabs is known to be 20 feet a quick check is performed to make sure that the slab length is correct. It is important to record these values if multiple slabs are being evaluated in a continuous section because the ending point of the first slab will be the starting point of the following slab. Once these values are identified then the Start button in the Long Profile box on the lower right corner of the software interface needs to be clicked. This will cause another window to pop up and allow the user to enter these values that were just found and to select a path to save the longitudinal profiles that will be created by the software. Figure B.18 shows the window that pops up and allows the user to define the parameters for generating the corrected longitudinal profiles. This is the same window that was shown in section 2, but a different section is used to specify the exact location of the profile instead of just running through multiple files.

![Longitudinal profile data selection](image)

**Figure B.18 shows the window that pops up and allows the user to input the parameters for generating the corrected longitudinal profiles.**

After everything is filled in then the start button is pressed and the four files that were described in section 2 are created for the slab. When the software has finished creating the profiles then a dialog box will pop up and display the IRI values for the slab.
Once the files are created the results can be viewed using the ProVAL software and can be converted into a different file format. To open the profile in ProVAL the user has to navigate to the ppf file that was created and right click and select open with then click ProVAL. Once the profile is open in the ProVAL software the user can view it there and choose to perform some of the operations and analysis that are available there or they can choose to extract the corrected profiles and use other software to analyze the data. For this analysis the ProVAL software was not used to do any analysis but the data was converted to an Excel file. To do this the user had to click the project box in the top left corner of the ProVAL window and select the Report icon. When this is clicked the user has three options PDF, Excel, and Text. If PDF is clicked then a PDF file containing an image of the profile and other survey information is created. If Excel in clicked then an excel file is created comprising of the profile distance and elevation. If Text I selected then a text file is created and it has the same information as the Excel file. Figure B.19 shows the ProVAL user interface and the location of the report button that is used to reproduce the profile data into other file formats.
Figure B.19 shows the ProVAL user interface and the location of the report button that is used to reproduce the profile data into other file formats.

If the data is extracted into Excel it will be in a text format instead of a number format, so the format will have to be changed to a number format. To change the format select all of the values in the spreadsheet then a yield sign with an exclamation mark will appear click on this and select the convert to number option. After the values are converted to a number format then the data can be plotted. Figure B.20 shows an example profile that was plotted using Excel.
Figure B.20 shows an example profile that was plotted using Excel.

When the plot was generated in Excel the trend line function was used to get a smooth profile and an equation that could be used to generate quantitative results. To get a trend line select the profile on the plot then right click on the plot of the profile and select the add trend line function. Then a box will pop up and allow the trend line function parameters to be set. For this analysis a polynomial trend line of the second order was used. After the type of trend line is selected and the order is set to 2, then the check box beside the display equation on the chart function needs to be checked to ensure that the equation is displayed on the chart. Once the equation is on the chart it is then used to calculate quantitative values to assess the curling and warping. To get a numerical value for the curling and warping the beginning and ending distance measurements were substituted into the trend line equation to get two end height readings. Then these values were averaged to level out the profile. The center point on the profile was found and the distance position at this location was plugged into the trend
line equation to get a height for the center of the slab. The difference of these two values is the quantitative value used to assess the curling and warping for the slab.

**B.5 Procedure to Produce Longitudinal and Transverse Curvature from Raw 3D Line Laser Data**

Since the longitudinal and transverse curvature of the concrete pavement is not a direct output from the 3D Line Laser software the data that is collected needs to be extracted and processed in order to observe these properties. There are several steps that need to be taken to get this data and they are broken into four sections. The first section is the explanation of how to get the data into a usable format so that it can be read by other software other than the 3D Line Laser software, the second section gives the detail on how to locate the starting and ending points on the slab using the 3D Line Laser software, the third section tells how to use MATLAB to read the data from the binary files and transfer it into Excel, and the final section gives the details on how to correct the profiles and to get the necessary results from the analysis. Figure B.21 shows the flow of the analysis that is performed on the range data to extract the curvature.
Figure B.21 Curvature Analysis Flow

3D Range Data

Convert to Binary Data

Transverse Profile

Isolate Slab within Profile

Remove Outliers

Shift Profiles (Align data from two sensors)

Trend Line

Level Trend Line

Curvature Value

Longitudinal Profile

Isolate Slab within Profile

Remove Outliers

Trend Line

Level Trend Line

Curvature Value
B.5.1 File Conversion

Before the 3D Line Laser data can be read by other programs, such as MATLAB, it needs to be converted into a different file format. The 3D Line Laser software uses .fis files, but they have to be converted to binary files (bin) so that the data can be manipulated as needed. To change the file a convertor is used. There are several files that must be present in order for the software convertor to work. Figure B.22 shows a screenshot of the files that must be present in the folder in order for the convertor to function.

After the thirteen files shown in figure B.21 are in the same folder with the data that needs to be converted then the file name test.bat needs to be edited so that it contains all of the files that are to be converted. To edit this file right click and select the edit option. Once the file is open then the list of filenames needs to be change to match the filenames that need to be converted. Figure B.23 shows the contents of the test.bat file as
it is being edited. In the file the filename is placed after the executable filename that converts the file. The filenames are then followed by the number of profiles that are in the fis file. Then the final character in each line of the file is a 0 or a 1 and these indicate that the data is for the left or right sensor (0-left, 1-right).

Figure B.23 shows the contents of the test.bat file as it is being edited.

After the changes have been made to the test.bat file then the changes need to be saved then the file needs to be closed. When the file is saved the file icon needs to be double clicked to start the file conversion. As the file conversion process begins the files will begin to appear in the folder with the convertor and 3D Line Laser data. Figure B.24 shows the files that are created by the convertor. There are a total of four files that are created and they include: a binary file for the range data from the left sensor, a binary file for the intensity data from the left sensor, a binary file for the range data from the right sensor, and a binary file for the intensity data from the right sensor.
Figure B.24 shows the files that are created by the convertor when it is run.

B.5.2 Locating Slab Extents Using LcmsRoadInspect Software

After the files are converted then they can be read by other programs. For this analysis a MATLAB function was created that would read the files and stitch them together because the slab profiles were too long to be collected into one file. Before the MATLAB code could be used to read the code there were several parameters that had to be determined. The parameters that need to be determined are the slab extents so that just the one slabs profile is extracted, the filenames of the fis files containing the slab, and the slab profiles numbers that need to be extracted. To find these parameters the files containing the slab had to be opened in the LcmsRoadInspect software so that it can be viewed. Once the software is open navigate to the beginning joint on the slab that the profiles are being extracted for. Then move the mouse pointer to the left sensor data viewing pane and position it over the intersection of the white line and the joint. This will cause the x value at this location to appear in the position information line between the data viewing pane and the profile viewing pane. Figure B.25 shows where to position the mouse pointer and where the x value is displayed.
Figure B.25 shows where to position the mouse pointer and where the x values are displayed so that the center point of the slab can be located.

After the left extent of the slab is found then the right extent of the slab needs to be located. To find the right extent of the slab the mouse needs to be moved over the right sensor data and positioned at the location that the longitudinal joint intersects the transverse joint. Once the numerical x values are found for both of the slab edges they are used to find the center longitudinal profile of the slab. To do this the left x values is subtracted from 2080 which is the total number of points in the transverse direction. This will give the number of points that are between the white line and the end of the left sensor data set. Then this value is averaged with the right x value and the left x value is added to this number to get the center longitudinal profile. The equation to find the center longitudinal profile (CLP) is:
Center_Longitudinal_Profile = ((2080 – Left_X) + Right_X)/2 + Left_X

For the example file in figure B.5.2.1 the center longitudinal profile is 1815

(Center_Longitudinal_Profile = ((2080 – 350) + 1200)/2 + 350 = 1815). This value needs to be recorded and will be used later when the data is being taken out of the MATLAB software. After the center longitudinal profile is found then the center transverse profile (CTP) needs to be located.

To find the center transverse profile then the transverse profile that intersects the end of the joint in the left data sets and the end of the left data sets needs to be selected (this is Y_1). When this profile is selected the profile number will be displayed in the lower left hand corner of the LcmsRoadInspect software interface. After this number is recorded then the user needs to navigate to the joint at the end of the slab. Once this joint is located then the profile that intersects the end of the joint in the left data set and the end of the left data set needs to be selected (this is Y_2). Once this is selected then the profile number will be displayed in the lower right corner of the window and it needs to be recorded. After the starting and ending profiles are found then the number of files that contain parts of the slab needs to be determined. This is done by simply navigating through the files in the software and counting the number of files that have the slab in them. Figure B.26 shows which profiles needs to be selected in order to find the center transverse profile and where the profile number is displayed in the software.
(a) Screenshot of the LcmsRoadInspect software as the first profile number is being determined
Figure B.26 shows where the user has to click to determine the profile numbers and where they are displayed in the software.

When these three numbers are found then they need to be used to determine the center transverse profile (CTP). To do this the following equation is used:

$$CTP = \frac{\left(\text{# of Files} \times \text{# of Profiles per file}\right) - Y_1 - \left(\text{# of Profiles per file} - Y_2\right)}{2} + Y_1$$

For the example presented in figure 5.2.2 the center transverse profile is 899, this is the transverse profile that approximately crosses the center of the slab

$$(CTP = \frac{(2 \times (1000)) - 287 - (1000 - 511)}{2} + 287 = 899).$$

To find the number of profiles per
Next the ends of the profiles need to be recorded so that the single slab profiles can be isolated and only a single slab is analyzed. This has to be done because the MATLAB code is structured to read the entire file into the program and a matrix is created. Then the row and column from the matrix that contains the center longitudinal and transverse profile are copied and pasted into Excel where the partial parts of the preceding and following slab are removed. To find the ends of the profiles take the center longitudinal and transverse profile numbers that were just found and look at the data using the LcmsRoadInspect software. First the ends of the longitudinal profile were found. To do this navigate to the file containing the starting joint of the slab then scroll over the joint with the mouse until the center longitudinal profile number is the X values in the position information line between the data image and the selected profile. When the X value appears then the corresponding Y value should be recorded (This will be referred to as Y_1 later in the paper) because this will be used later when the data is copied from MATLAB to Excel. After this value is attained then navigate to the ending joint on the slab and scroll along the joint until the X value in the position information line is the center longitudinal profile. Then record the Y value that corresponds to it (This will be referred to as Y_2 later in the paper). Figure B.27 shows how the ends of the center longitudinal profiles are found.
Figure B.27 shows how the starting point of the longitudinal profile is found.

After the longitudinal profiles ends are located then the center transverse profile ends need to be found. This is performed by navigating to the file that contains the center transverse profile and selecting this profile in the left data set by either entering the Y value in the box that displays the selected profile number in the lower right hand corner or by clicking on the image until the center transverse profile is selected. After the profile is selected scroll along the blue line, that indicates the profile that is selected, until it is positioned over the intersection of the blue line and the longitudinal joint (or the pavement marking if the shoulder is on the left and the end of the slab cannot be clearly located) at the left edge of the slab. When the mouse is positioned here then the corresponding X value needs to be recorded (This will be referred to as X_1 later in the
Next the center transverse profile needs to be selected in the right sensor data set. When the profile is selected position the mouse over the intersection of the right longitudinal joint (or the pavement marking if the edge of the slab cannot be clearly identified) and the blue line that indicates and then record the corresponding X value (This will be referred to as X_1 later in the paper). Figure B.28 shows where to position the mouse to get the end values for the center transverse profile and where the values can be seen.

There are a few notes that need to be included here about identifying the profile ends. The first is that when looking for the left end of the center transverse profile if the joint extends past the left data set (i.e. the edge of the slab was not collected and there is
no left longitudinal joint or pavement marking) then use zero for the X_1 value. When trying to locate the right end of the center transverse profile if the joint extends past the right side of the data set (there is no right longitudinal joint or pavement marking) then use 2080 for the X_2 value. If the center transverse profile number is greater than the number of profiles per file then the number of profiles should be subtracted and this value will be the center transverse profile number in the second file containing the slab. If the center longitudinal profile is greater than the number of points per profile (2080) then the center longitudinal profile will be located in the right data set. The X value that corresponds to the center longitudinal profile in the right data set then becomes the number of points per profile subtracted from the original X value (CLP_Right = CLP_original – 2080).

Now that the profile parameters are known there is one more requirement to read the data using the MATLAB code. This requirement is the filenames of the files that contain the slab that the profiles are being extracted for. This can be performed by looking at the path of the file that is displayed on the top of the LcmsRoadInspect software. The filename is the last entry in this line it will be located between the last backslash (“\”) and the file type (.fis). Record just the filename not the type because the fis file will not be used by MATLAB but the binary files will be and the code is set up to use the filename and not the type. Figure B.29 shows where the filenames can be seen and recorded from.
B.5.3 Using MATLAB to Extract Slab Profiles from Binary Files

After the required parameters are gathered for the slab that is going to be extracted, the MATLAB software needs to be opened. Once the software is open the m-file named Bin_Extraction. When the file is open then all of the parameters need to be inserted into the code. The first change that needs to be made is to change the path to the folder containing the files that were converted in section B.5.1. To get this navigate to the folder containing these files using Windows Explorer, then copy the path in the address bar and paste it into line 7 of the m-file. This is what line 7 should look like when the path is inserted

```
Folder='H:\Faulting\Curling_Warping\Data_Analysis_Spring_2013\700\Weigh_Station\';
```

Here it is important to make sure that the folder name, which is the last name in the path, is followed by a backslash. If this is not followed by a backslash then the code will not run. The next line that needs to be changed is line 12. This line contains the number of profiles that are in the files that the slab profiles are going to be extracted from. This is the same number of profiles that was used in section B.5.2 when locating the ends of the slabs. For all of the cases used in this study the number of profiles per file was 1000, but it could vary depending on the
parameters that were used during the data collection. This is what line 12 should look like “ProfNum =1000; %number of profiles per fis file”.

The next change that has to be made to the m-file is to insert the filenames of the binary files that contain the slab that the profiles are being extracted for. In some cases the slab is contained in two files and in others it is contained in three files. The amount of files that the slab is in depends on two factors and they are the length of the slab and the starting position of the data collection with respect to the individual slab. So to account for the varying number of files containing the slab the code was set up to be easily adjusted to accommodate either case. If the slab is within two files then lines 54-59 need to be commented out of the code. This is the section that reads the third binary file. Line 64 also needs to be commented out and line 63 needs to be uncommented. Lines 63 and 64 are where the code stitches the data together from the left and right sensors and from multiple files then writes the values into ne matrix. Line 63 does this for two files and line 64 does this for three files. If the slab is in three files then lines 54-59 need to be uncommented to make the code read the third file that contains the slab. Line 64 also needs to be uncommented to ensure that the matrix contains all of the slab data. Line 63 needs to be commented out since line 64 will stitch the data and put it into a single matrix.

Once the proper lines are commented and uncommented then the filenames need to be entered into the code. The code is set up to read each file in individually so each file name has to be entered for both the left and right sensors. Since each the left and right sensor data is split into separate files the filename has to be entered twice. The first file name that needs to be changed is located in lines 40 and 43, the second file name is
Figure B.30 shows the code where the file names are located and what it should look like when the slab is contained in two files.

After the code has been modified to meet the requirements to extract the particular slab that is being analyzed then the save and run button needs to be clicked. If prompted the directory in MATLAB may need to be changed here. After the save and run button is pressed then switch to the main MATLAB window and in the Workspace portion of the window where the variables are displayed. Locate the All_Profile_Range_Data matrix and double click it to open it in the Variable Editor pane of the main window. In this matrix the rows correspond to the transverse profiles and the columns correspond to the longitudinal profiles. Now the profile numbers that were found in section B.5.2 are needed. For the center longitudinal profile select the entire
column that corresponds to the center longitudinal profile number found in section B.5.2. For our example in section B.5.2 the center longitudinal profile number was 1815 (CLP=1815), so the 1815th column in the All_Profile_Range_Data needs to be copied. After the data is copied it needs to be pasted into Excel where it will be edited later.

Next the center transverse profile needs to be extracted. This is done by taking the center transverse profile number found in section B.5.2, the center transverse profile in our example was 899 (CTP=899). So the 899th row in the matrix needs to be selected. After the entire row is selected the values need to be copied and pasted into Excel where it will be edited. Figure B.31 shows the MATLAB main window as the center profiles are being selected.
Figure B.31 shows the center profiles being extracted from the main MATLAB window.

Now that the full profiles are in Excel then the ends need to be cut off so that only the slab profiles are there. To do this the X and Y values that were found in section B.5.2 will be used. The X values correspond to the transverse profile and the Y values correspond to the longitudinal profile. To isolate the slab in the longitudinal profile then values need to be removed from the beginning and end of the profile. The amount of values that need to be removed from the beginning of the longitudinal profile is the Y_1 value from section B.5.2. For our example the Y_1 value is 274, so we need to delete the
first 274 values from the longitudinal profile. The number of values that needs to be removed from the end of the profile is found by subtracting the $Y_2$ value from the number of profiles in the file. For our example the $Y_2$ value is 500 ($Y_2=500$), so the number of values that would need to be removed from the end of the profile is the number of profiles in the file (1000 for this case) minus 500 which is 500. ($1000-500=500$) So the last 500 values need to be deleted from the end of the longitudinal profile. Now the center longitudinal profile is completely extracted.

To isolate the slab in the transverse profile then the X values are used to determine how many of the values need to be removed. The $X_1$ value is the amount of the values that need to be deleted from the beginning of the profile. For our example the $X_1$ value is 350 ($X_1=350$), so 350 values need to be deleted from the beginning of the profile. The $X_2$ value is then used to determine the amount of values that need to be removed from the end of the profile. To do this the $X_2$ value is subtracted from 2080, which is the number of points that are on the full transverse profile. For the example in section B.5.2 the $X_2$ value is 1200 ($X_2=1200$), so the number of values that need to be removed from the end of transverse profile is the number of points on the profile minus the $X_2$ value, which is 880. ($2080-1200=880$). After these values are removed then the transverse profile is completely extracted.

**B.5.4 Using Excel to Analyze the Slab Profiles**

Now that the profiles are in Excel then they can be analyzed by plotting them so that they can be visually assessed, by adjusting the profile to account for shifts at the locations where the profiles were stitched together by removing the built in curvature,
and by quantifying the curvature so that the variation through the day can be determined so the thermal effects can be seen. This section will describe how to plot the slab profiles, how to shift the profiles how to remove the built in curvature and how to quantify the slab curvature.

The first step to analyze the slab profiles was to plot them using the scatter plot function in Excel. Before the values were plotted they were inverted by multiplying them by negative one (-1). This was necessary because the height readings are the distance measurements from the sensor to the pavement surface so a larger value indicates a lower point. So if the original readings were plotted then the larger values would be plotted as higher points which require the profile to be inverted for the plot to correctly portray what the slab profile is. After the profiles were inverted then they were shifted so that all of the profiles for one slab would have the same starting position. This was necessary because the height readings taken by the sensors are relative readings and could vary slightly between runs because of temperature effects on the frame, the path the vehicle takes, or the rate of acceleration of the vehicle as it passed over the slab. This variation was not much but could cause the profiles to be incorrectly assessed and having the same starting point also allowed the profiles to be plotted on the same plot and the variation of the slab profile through the day could be seen.

To make the shift the starting point on the profile was subtracted from the entire profile this ensured that the starting point on every profile was zero. In some cases the starting point of the profile was not the first value in the column or row that was imported into Excel; this was because the starting and ending points in the slab were roughly estimated using the LcmsRoadInspect software so the beginning of the extracted profile
could have started in the joint. When this point was incorrect there would be a spike in
the beginning of the profile so when this was noticed then the mouse was positioned over
the point that followed the spike and the profile was shifted so that this was the new
starting point on the profile. In some cases there would also be spikes on the end of the
profile which were probably also caused by height readings that were in the joint near the
end of the slab so these were also removed. Figure B.32 shows an example profile that
had to be shifted and what the shifted profile looks like.

![Original_Profile vs Shifted_Profile](image)

**Figure B.32 shows an original profile and a shifted profile that had spikes on the
beginning and end of the profile.**

Once the plots of the actual slab profiles were obtained they were also visually
evaluated to look for spikes and to look for shifts in the profiles that were caused by
stitching the data from the two sensors, this typically occurred in the transverse profiles.
The spikes could be caused by several factors that could include an irregular reading form
the sensor or could possibly be a small depression in the slab caused by a pop out of other
defect, but either case does not accurately depict the actual slab profile for the means of curvature analysis so they were removed. When a spike was seen in the plot of the profile then the mouse could be position over the point to get the point information. After the point information was found then it was located in the data set and removed and replaced by the average of the height reading before it and the height reading that followed it. In some cases there were multiple invalid readings in a row so they were all deleted and replaced with the average of the first valid height reading before and after the cluster. Figure B.33 shows an example profile that contained an invalid point.
Figure B.33 shows an example profile that contained an invalid point that needs to be removed.

After all of the spikes were removed in the profiles then the transverse profiles had to be shifted due to the elevation difference between the two sensors. To do this the X-1 value found in section 5.2 is used to find the location that the shift occurs. To find this location subtract the X_1 values from 2080 which is the number of points on the transverse profile (2080-X_1=Stitch_Point). Once the stitch point value is found then it needs to be located in the data set the values need to be evaluated to determine the last point on the left sensor and the first point on the right sensor. Once these two values are obtained then the difference needs to be found. Then the difference needs to be added or subtracted from the right sensor readings to shift them to match the left sensor readings and create a smooth profile. Figure B.34 shows a profile that had to be shifted to account for the height difference between the left and right sensors.
Figure B.34 shows an example profile that had to be adjusted due to the elevation difference between the two sensors.

The built in curvature is the curvature that the slab will have at all times no matter what the environmental conditions are. The built in curvature is caused by temperature
variations in the slab during the construction process (Lederle, et. al. 2011). For this study the focus is on how the temperature impacts the concrete slabs so to find the built in curvature then data needed to be collected on the slabs when the temperature variation between the top and bottom of the slab were zero. Data was collected on the site for two full days, once during August and one in October. The thermal data for the slab was reviewed and the time that the variation was approximately zero was recorded. This was then compared to the data collection runs, which were collected every fifteen minutes throughout the day, and the data collection run from the same time that the temperature variation was zero was selected. Then the procedure described in sections B.5.1-B.5.3 was used to extract the built in curvature profiles. These profiles were then subtracted from the original slab profiles that were extracted so that only the curvature caused by the temperature variation between the top and bottom of the slab could be assessed.

Once the plot of the slab was corrected and the actual slab profile was obtained then the trend line function in Excel was used to get a smooth profile. To get a trend line select the profile on the plot then right click on the plot of the profile and select the add trend line function. Then a box will pop up and allow the trend line function parameters to be set. Since the slab profiles are parabolic in shape a polynomial trend line to the second order was used. After the type of trend line is selected and the order is set to 2, then the check box beside the display equation on the chart function needs to be checked to ensure that the equation is displayed on the chart. Once the equation is on the chart it is then used to calculate quantitative values to assess the curling and warping. Figure B.35 shows one of the plots of the slabs that were generated using the raw 3D Line Laser range data with the trend line on the plot, the corrected slab profile and the slab profile.
without the built in curvature.

Figure B.35 shows one of the slab profiles that were generated from the raw 3D Line Laser data with the trend line, original corrected profile and the profile after the built in curvature was removed.

To get a numerical value for the curling and warping the beginning and ending distance measurements were substituted into the trend line equation to get two end height readings. Then these values were averaged to level out the profile. The center point on the profile was found and the distance position at this location was plugged into the trend line equation to get a height for the center of the slab. The difference of these two values is the quantitative value used to assess the curling and warping for the slab.

### B.6 Procedure to Extract the Raw IMU Data

The IMU data that is used to correct the profiles that were obtained in section 4 of this appendix may also need to be extracted and the procedure to get this data is given in
this section. This data may be needed when trying to pull out a long section that contains multiple slabs. In this case there is random error that is introduced into the IMU data called drift (French 2009). In the ProVAL software the drift can be filtered out of the entire longitudinal profiles but it also filters out the slab curvature, so a method is needed to filter the drift out without filtering out the slab curvature. It has been suggested to filter the raw IMU data then use the filtered data to correct the raw 3D Line Laser data, but 3D Line Laser does not currently offer this option. This procedure is provided in case a method is developed or provided in the near future and the IMU data is needed.

To read the raw IMU data the same MATLAB code from section 5.3 is used. The binary files that contain the raw IMU data were created in section 2 when the IRI values were calculated using the LcmsRoadInspect software. To read the files they either need to be placed in the same folder as the binary files used in section 5 or the path in line 7 of the code needs to be changed to the path of the folder containing the IMU binary files. To read only the IMU binary data with the code then lines 40-74 need to be commented out and lines 75-84. If lines 40-74 are not commented out then they must also be formatted correctly or the code will stop before it gets to the section that reads the IMU data. Once the code reads the IMU data it will write all of the data into a single matrix. Figure B.36 shows the section of the code that reads the IMU data and outputs it into a single matrix.
Figure B.36 shows the code where the IMU data is read and wrote into a matrix.

The matrix that is produce into the Workspace pane of the main MATLAB window contains the left IMU vertical acceleration values in column one, the timestamps from the left IMU in the second column, the vertical accelerations from the right IMU in the third column and the timestamps from the right IMU in the fourth column. This data can be copied from the Variable editor pane in the main MATLAB window and pasted into excel or it can be written into a test file if lines 86-94 are uncommented.

B.7 Procedure to Extract the Temperature Data from the Data Loggers

This section presents the procedure to extract the temperature data that is logged on the data loggers. The temperature readings that are on the data logger are measured using the thermocouples that were installed in the pavement (More information on these can be found in Appendix A which gives the procedure that was used to install them into the pavement.). The first step to download the temperature data is to connect the data logger to the computer using the USB cable that came with the logging device. When the device is connected turn it on by pressing and holding the power key until it beeps. Now
that the hardware component is connected the software needs to be opened, to do this
double click on the Temp Monitor_S2 software icon. The window will open then the
DataLogger(D) button on the menu bar needs to be clicked. Only one option is available
in this menu and it is ON so click it and the temperature data will start to download
automatically. If the data logger is not connected then an error message will appear and
the data logger needs to be disconnected and the procedure needs to be restarted. When
the data finishes downloading a message box will appear to notify the user that the data
has finished, click OK when it appears. The temperature data will be tabulated in the
lower pane and the plot of the logged information will be displayed in the upper pane.
Figure B.37 shows the Temp Monitor_S2 software window after the temperature data is
downloaded.

![Temp Monitor_S2 software window](image)

Figure B.37 shows the Temp Monitor_S2 after the temperature data was
downloaded.
Then click on the save button (disk icon) that is located in the upper left corner of the main software window to save the temperature data that was downloaded. There will be two options available under this menu; the first is SaveData which will save the tabulated values into a text file and SaveBmp which will save an image of the temperature plots. When the desired option is selected then another window will pop up allowing the destination to save the file to be defined and the file name to be changed. When the path and file name have been designated then click the Save button. Then a text file will be created that can be imported into excel or an image of the graph will be saved that can be viewed later. Now the temperature data is ready to be analyzed to determine when to collect data or when certain temperature variations occurred.

B.8 Conclusions

This document was prepared to give the details that of the procedures that were used to extract the data out for the curling and warping analysis. There were several methods that were introduced and described. These methods included how to generate the IRI values using the LcmsRoadInspect software, how to calculate the faulting values using the LcmsRoadInspect software and read them using Internet Explorer, how to produce longitudinal profiles that were corrected by the IMU data using the LcmsRoadInspect software how to view them in the ProVAL software and how to export these corrected profiles into Excel for further analysis. Since the IMU data was affected by drift the uncorrected longitudinal profiles were also extracted to compare to the corrected longitudinal profiles. The transverse profiles were also pulled out to determine how they changed with temperature. Then the raw IMU data was also taken out so that it
could be processed separately. Finally the procedure to acquire the temperature data from the data loggers was laid out.
(a) Weigh Station Main Lane Typical Section

5' Binder Course, Full Part Gravel, Groove 1 of 2, I-10.

Required: 1.1" PLAN PAVEMENT COURSE, COMBINED WITH DOWELS EXaggerated.

5' Binder Course, Full Part Gravel, Groove 1 of 2, I-10.

5' Binder Course, Full Part Gravel, Groove 1 of 2, I-10.

5' Binder Course, Full Part Gravel, Groove 1 of 2, I-10.

See Details

Shoulder

12

Curb Line

Shoulder

12

Curb Line

Shoulder

12
(b) Weigh Station Scale and Bypass Lane Typical Section
Figure C.2 Close up View of Each Lane Typical Station
Figure C.4 Weigh Station Grade Profile Eastbound Lanes
APPENDIX D

FIRST PRELIMINARY INVESTIGATION
APPENDIX D

FIRST PRELIMINARY INVESTIGATION

Several attempts were made to successively collect data and implement the developed procedure on the weigh station test section. Three attempts were made to collect the data the first of which the thermal data logger was damaged and all of the logged thermal data was lost, during the second data collection the thermal variation between the top and bottom of the slab was minimal so this led to a third attempt to collect the data which was successful. The data from the third data collection was used for this thesis however the data from the first data collection was used to test the developed procedures for the data collection and analysis. These results were originally used to write Chapter 4 and this appendix contains the original chapter 4 of this thesis.

D.1 Introduction

To accomplish the objectives of this thesis a method had to be developed to ensure that all of the data was collected and processed in the same manner so that the comparison of the results was adequate. This method would include how to install thermal monitoring devices and how to use them to collect and analyze pavement temperature data. It would also entail developing a method to correlate this thermal data to the data collected by the sensing vehicle and how to best utilize the capabilities of the sensing vehicle. To develop this methodology a site was selected and the thermal devices were installed, thermal data was collected along with the sensing vehicle data and the developed analysis procedure was used to generate results for the preliminary
investigation. This chapter summarizes the procedure that was produced and the logic and considerations that were deliberated when developing it. The resulting concrete pavement characteristics for the preliminary investigation site are also summarized in this chapter.

**D.2 Site Selection**

When selecting a site to perform a preliminary investigation the main goal was to find a location that would provide a safe environment to install the thermocouples into the pavement and during the data collection. The site that was selected was the Weigh Station located approximately at mile 143 on I-16. Several site visits were made to coordinate with the personnel and determine a location that would be suitable and not interfere with their daily operations. Originally it was decided to select a slab in the overflow parking area behind the weigh station, but the pavement design for this location was not recorded in the plans. The plans only consisted of the main truck lane, the scale lane, and the bypass lane, so another site visit was made to further discuss with the staff and finalize the location of the test section.

It was finally decided to use the main lane in front of the structure on site. This lane was chosen because it had a grass shoulder that was needed to install a housing for some of the thermal equipment that was used. Twenty five slabs in front of the guard station were selected as the actual test section that would be used for analysis. The twentieth slab was selected as the test slab to install the thermocouples into, because it was out of the way and would not obstruct any of the functions of the weigh station. Figure D.1 shows the aerial view of the weigh station with the key features labeled.
The pavement design at the weigh station consisted of a 20 feet (6.1 m) lane that was made up of two 10 feet (3.05 m) wide slabs. The slab length in the travel direction was 20 feet (6.1 m). These slabs were composed of a 12 inch deep Portland cement concrete cross section with doweled joints and rested on a 5 inch Portland cement concrete sub base or a 5 inch asphaltic concrete base. The plans for the weigh station can be found in Appendix C of this thesis.

D.3 Thermocouple Installation

After the test slab was identified the positions to monitor the temperature in the slab needed to be located. To determine these locations concrete experts were consulted and their inputs were used to find which positions and which depths to install the sensors. Three positions were decided upon. The first was the corner of the slab at the joint (location 1 in Figure 4.2), which would be the most critical, because it is where the most curling and warping movement should take place. The second location that was selected
was the center of the slab (location 2 in Figure 4.2) so that it could be compared to the corner to see if there is any heat loss due to edge effects. The third and final location that was selected was the center of the slab along the joint (location 3 in Figure 4.2). The thermal data collected at these three locations would show how the temperature varied through the slab and to determine if the location of the sensors in the slab would have a significant impact on variation of the pavement temperature. Figure D.2 shows the locations in the slab that were selected to monitor and where the thermocouples were installed.

(a) Relative Monitoring Locations
The depth that each sensor would be inserted into the pavement also had to be established. This was necessary to see how the temperature varied through the depth of the slab at each of these locations. The data loggers that were used could log the temperature data from four thermocouples, so four depths were selected. Since the focus of this study is the curling and warping of the slab then the two most critical depths to measure are $\frac{1}{2}$ an inch (12.7 mm) from the top of the slab (location 1 in Figure 4.3) and $\frac{1}{2}$ an inch (12.7 mm) from the bottom of the slab (location 3 in Figure 4.3). These two depths will give the variation between the top and bottom of the slab and these values can be used to determine the times that the maximum temperature variation, maximum
temperature variation, and when there was no variation between the bottom of the slab and the top of the slab. This will determine the times that data needs to be collected on the test sections. There were two depths left to measure the center depth of the slab (location 2 in Figure 4.3) was selected so that the distribution of the temperature distribution throughout the depth of the slab could be estimated. The final depth that was selected was 1 inch (25.4 mm) into the base (location 4 in Figure 4.3), this would show if there was any deviation between the bottom of the slab and the base. Figure 4.3 shows the depths that were selected to place the thermocouples.

Figure D.3 Thermocouple Depths in the Test Slab

Once all of the planning was complete the thermocouples were installed into the pavement. Due to the weigh station being an operating facility the installation had to be
coordinated with the staff. At the time of the installation the weigh station was open seven days a week. The day with the least truck traffic was Saturday. The weigh station opened at 6:00 A.M. and closed at 12:00 A.M., so in order to reduce the amount of time that their operation was interrupted the installation started at 12:00 A.M. on a Saturday morning. The detailed procedure that was developed and implemented to install the thermocouples into the existing concrete pavement at the weigh station can be found in Appendix A of this thesis.

D.4 Thermal Data

After the thermocouples were installed in the pavement then the thermal data needed to be collected and analyzed. This analysis would provide a basis for determining when to collect data using the sensing vehicle. This section describes the how the thermal data was collected, interpreted and the conclusions that were made.

D.4.1 Thermal Data Collection at Weigh Station

The thermal data was collected at all 12 locations in the slab for four weeks prior to collecting the pavement surface data using the sensing vehicle. The interval between the readings was set to 15 minutes, which would provide sufficient detail to capture the gradual change in the pavement temperature. The day before the data collection was scheduled the thermal data was downloaded and analyzed to determine the data collection windows when the slabs would be experiencing the most curvature. During the data collection the thermal data was logged using an interval of 1 minute, this would provide
detailed data and would ensure that there would be a thermal reading to correspond to each data collection run collected by the sensing vehicle.

**D.4.2 Thermal Data Analysis**

The thermal data was analyzed to determine two things. The first of which was to determine if the position that the thermal data was logged from would impact the amount of variation between the top and bottom of the slab. The second analysis was to determine when different variations between the top and bottom of the slab were observed.

**D.4.2.1 Position Analysis**

To see if there was a lot variation in the pavement temperature between the positions that were measured the same depth from each location was plotted. Figure D.4 shows the plot of the thermal data from the bottom of the slab for all of the positions.
This plot shows that the temperature at all of the positions follow the same trend. The plots are slightly shifted from each other. This was the case for all of the data that was collected so it was concluded that when determining the temperature difference between the top and bottom of the slab the positioned the data was taken from was not critical. Since the position was not critical it was decided to use the data that was collected in the edge of the slab because it is where the most slab movement would occur.

D.4.2.2 Variation Analysis

The desired curvature conditions were the maximum positive curvature (center of the slab rises and edges go down), the maximum negative curvature (center of the slab goes down and edges rise), and when there is zero curvature (the slab is flat). The maximum positive curvature occurs when the temperature in the top of the slab is greater than the temperature in the bottom of the slab. Using the formula $\Delta T = T_{Top} - T_{Bottom}$, this would occur at the same time as the maximum positive $\Delta T$. The maximum negative curvature occurs when the temperature in the top of the slab is less than the temperature in the bottom of the slab, this occurs at the same time as the maximum negative $\Delta T$. The zero curvature condition occurs when $\Delta T$ is equal to zero. For the thermal analysis the temperature data was segmented into daily data sets and each of these conditions was identified in the data. Then the corresponding time was recorded. The occurrence time for these events did not happen at the same time each day. For each category all of the recorded times were evaluated and used to determine the time windows that the sensing vehicle data should be collected to cover all of the
desired conditions. Figure D.5 shows an example of the daily thermal plots used to
determine the occurrence time of the desired curvature conditions.

![Figure D.5 Daily Thermal Data Example](image)

For this example the maximum positive curvature occurred around 2:00 P.M. and
the temperature difference ($\Delta T$) was $23.2 \, ^\circ\text{F}$ ($12.89 \, ^\circ\text{C}$). The maximum negative
curvature occurred around 6:00 A.M. and the temperature difference ($\Delta T$) was $-7.4 \, ^\circ\text{F}$ ($-4.11 \, ^\circ\text{C}$). In all cases the zero curvature occurred twice each day, once in the morning as
the slab surface heated and once in the evening as the surface began to cool. For this
example the zero curvature condition occurred at 9:30 A.M. and 3:30 P.M.

This process was completed for all of the four weeks of thermal data that was
collected to determine what the data collection time windows would be. These results
showed that the optimal time to collect the maximum negative curvature was early in the morning, the maximum positive curvature was in the early afternoon, and the zero curvature was between 8:30 A.M. and 10:30 A.M or between 3:00 P.M. to 8:00 P.M. To
reduce the amount of time at the test site it was decided to only collect the zero curvature during the morning window. For capturing the maximum negative curvature and zero curvature the data needed to be collected between 5:45 A.M. and 10:30 A.M. To capture the maximum positive curvature the data needed to be collected from 12:30 P.M. to 3:00 P.M.

There was no further analysis performed on the thermal data that was collected on the day that the sensing vehicle was used to collect data which was on August 11, 2012. This was due to the occurrence of an afternoon thunder storm that happened just after 2:00 P.M., which damaged the data logger and rendered the thermal data unrecoverable. However, the actual observed temperatures that are recorded by the National Oceanic and Atmospheric Administration (NOAA) were compared for the day of the data collection and the days preceding it. This comparison was done to approximate the temperature variation for the day of the data collection. Out of all of the days prior to the data collection the day that showed the most similar thermal properties was August 3, 2012. So the variation between the top and bottom of the slab for this day was used as a rough estimate for the magnitude of the variation on the day of the data collection. The maximum positive variation on August 3, 2012 was 28.1 °F (15.61 °C) and the maximum negative variation was -9.9 °F (-5.5°C).

**D.5 Sensing Vehicle Data**

After the results from the thermal analysis were used to decide when the sensing vehicle should be used to collect data a strategy was devised to collect this data and
analyze it. This section will describe the plan used to collect the data, how it was analyzed and the conclusions that were drawn.

D.5.1 3D Line Laser Data Collection at Weigh Station

Data was collected using the sensing vehicle at the weigh station during the specified time periods. It was decided to use a fifteen minute interval between the data collection runs. Since the temperature change in the slab is gradual the fifteen minute interval should provide sufficient data to capture each of the curvature conditions. During the collection all of the sensors on the vehicle were used, so that as much detail as possible could be captured. Even though not all the data was utilized for this thesis the rest was collected so that if future research required the other data it would already be possessed and would not require more effort. The 3D Line Laser data was the main focus of the data collection since it would be used for this thesis.

The first data collection was performed on August 11, 2012. The first run of data was collected at 5:45 A.M. and continued every fifteen minutes after that until 10:30 A.M. The data collection then resumed at 12:45 P.M. and continued until 2:00 P.M. when an afternoon thunder storm interrupted the data collection for the day. During this collection there were 26 data collection runs collected that spanned 25 labeled slabs and 26 identifiable joints.

A second data collection was performed on October 27, 2012, but the temperature variation between the top and bottom of the slab was minimal (-6°F (-3.34°C) and 4.3°F (2.39°C)) so the effect of the curling on the pavement characteristics would be reduced.
Though this data was used to analyze the built in curvature at the site, which occurs when there is no temperature variation between the top and bottom of the slab ($\Delta T=0$).

### D.5.2 3D Line Laser Data Analysis

The 3D Line Laser data was processed and analyzed several ways to produce results that depict the characteristics of the concrete pavement. Some of the required results were direct outputs of the 3D Line Laser software while others required more in depth manual processing. The results that were generated included the faulting, the roughness, and the transverse and longitudinal curvature. The methods used are summarized here, but are described in greater detail in Appendix B of this thesis.

#### D.5.2.1 Weigh Station Faulting Analysis

The faulting is computed by the 3D Line Laser software. To compute the faulting, the joint and lane marking have to be located within the data. After these are found then the algorithm goes a set distance before and after the joint to find elevation readings to use to calculate the faulting with. The distance between these two points is known as the footprint of the measuring method. For this thesis a 50 mm (1.97 in) footprint (Dimension A in Figure D.6) was used, since the study was performed in Georgia and this is approximately the footprint of the Georgia Faultmeter. After the position that the elevation readings will be taken are found then the algorithm selects a set length of elevation readings parallel to the joint (Dimension B in Figure D.6). The readings are also centered on the point established by the footprint. The average of these readings is then taken as the height for that side of the joint. For this thesis 100 mm (3.94
in) was used as the length of the elevation readings used to find the height for each side of the joint. After the height of each side of the joint was found then the difference between the two values were taken and the result is the faulting at that position.

With most automated methods the single faulting value is all that could be obtained, but with the detailed joint information that the 3D Line Laser provides multiple faulting measurements along the joints. To generate multiple faulting values for the joint the algorithm will move along the joint and repeat the faulting computation until the joint ends or intersects pavement markings. The locations that the faulting measurements are taken is a variable and can be manipulated to produce as many faulting measurements for a joint as desired. The first fault measurement is taken this interval away from the beginning of the joint or where it intersects the pavement marking. Then the algorithm moves along the joint and computes the faulting using this value as an interval between the measurements. For this thesis the interval between the faulting measurements that was used was 150 mm (5.91 in) (Dimension C in Figure D.6). Figure D.6 shows the parameters that the faulting computation algorithm uses when computing the faulting.
This process was performed on all the joints in the weigh station test section. There were a total of 26 data collection runs that covered 26 joints for a total of 676 joints that were analyzed. The results from the processing that the 3D Line Laser software performs can produce a variety of results. For this faulting study the calculated faulting values and the intensity images that indicate where the faulting measurements were taken were used.

The images were used to determine if faulting measurements were invalid. An invalid faulting measurement was one that did not depict the actual faulting that the joint is exhibiting. The cases that were encountered in the weigh station analysis were that vegetation was included in the elevation readings used to compute the faulting; the longitudinal joints were included in the elevation readings used to compute the faulting
and some of the faulting values were calculated outside the travel lane. These values had to be removed so that the final results were not affected by these irregularities.

Another problem that affected the faulting statistics was the joint detection performed by the algorithm. In some cases the joints were falsely detected and in some cases all or part of the joint was not detected. If there were false detections then they had to be deleted from the final values and if there were joints that were not detected they had to be considered to ensure that when interpreting the results the conclusions that were drawn were not based on inaccurate results.

The faulting values were used to find the average faulting for each joint in each data collection run. This resulted in 626 average faulting values for which the statistics are presented in Table D.1. These results show that there is minimal faulting at the site with an average faulting of 0.45 mm (0.018 in), a standard deviation of 0.30 mm (0.012 in), and a range from -0.03 mm (-9.8 x 10^{-4} in) to 1.36 mm (0.054 in).

<table>
<thead>
<tr>
<th>Average Faulting</th>
<th>(mm)</th>
<th>(in)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average</strong></td>
<td>0.45</td>
<td>0.018</td>
</tr>
<tr>
<td><strong>Standard Deviation</strong></td>
<td>0.30</td>
<td>0.012</td>
</tr>
<tr>
<td><strong>Maximum</strong></td>
<td>1.36</td>
<td>0.054</td>
</tr>
<tr>
<td><strong>Minimum</strong></td>
<td>-0.03</td>
<td>-0.00098</td>
</tr>
<tr>
<td><strong>Median</strong></td>
<td>0.34</td>
<td>0.013</td>
</tr>
</tbody>
</table>

After an overall idea of the faulting conditions at the weigh station test site were obtained then each joint was isolated and analyzed. This analysis used the average faulting values for a single joint from all data collection runs to see how the faulting of an individual joint changed throughout the day. This provided 26 average faulting values to
represent each joint from which the maximum and minimum average faulting values were found. Then the variation of the average faulting was found by taking the minimum from the maximum (Faulting_Variation = Maximum Average Faulting –Minimum Average Faulting). This produced 26 variation values to show if there was a significant change in the faulting throughout the data collection. Table D.2 shows the variation in the average faulting values for each joint.

Table D.2 Weigh Station Average Faulting Variation

<table>
<thead>
<tr>
<th>Weigh Station Variation</th>
<th>Average Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint</td>
<td>(mm)</td>
</tr>
<tr>
<td>Joint 1</td>
<td>0.18</td>
</tr>
<tr>
<td>Joint 2</td>
<td>0.24</td>
</tr>
<tr>
<td>Joint 3</td>
<td>0.20</td>
</tr>
<tr>
<td>Joint 4</td>
<td>0.18</td>
</tr>
<tr>
<td>Joint 5</td>
<td>0.18</td>
</tr>
<tr>
<td>Joint 6</td>
<td>0.27</td>
</tr>
<tr>
<td>Joint 7</td>
<td>0.19</td>
</tr>
<tr>
<td>Joint 8</td>
<td>0.58</td>
</tr>
<tr>
<td>Joint 9</td>
<td>0.26</td>
</tr>
<tr>
<td>Joint 10</td>
<td>0.28</td>
</tr>
<tr>
<td>Joint 11</td>
<td>0.55</td>
</tr>
<tr>
<td>Joint 12</td>
<td>0.71</td>
</tr>
<tr>
<td>Joint 13</td>
<td>0.63</td>
</tr>
<tr>
<td>Joint 14</td>
<td>0.21</td>
</tr>
<tr>
<td>Joint 15</td>
<td>0.3</td>
</tr>
<tr>
<td>Joint 16</td>
<td>0.28</td>
</tr>
<tr>
<td>Joint 17</td>
<td>0.48</td>
</tr>
<tr>
<td>Joint 18</td>
<td>0.2</td>
</tr>
<tr>
<td>Joint 19</td>
<td>0.17</td>
</tr>
<tr>
<td>Joint 20</td>
<td>0.33</td>
</tr>
<tr>
<td>Joint 21</td>
<td>0.16</td>
</tr>
<tr>
<td>Joint 22</td>
<td>0.2</td>
</tr>
<tr>
<td>Joint 23</td>
<td>0.13</td>
</tr>
<tr>
<td>Joint 24</td>
<td>0.36</td>
</tr>
<tr>
<td>Joint 25</td>
<td>0.25</td>
</tr>
<tr>
<td>Joint 26</td>
<td>0.24</td>
</tr>
</tbody>
</table>
The maximum variation that was observed was 0.71 mm (0.028 in) and the minimum was 0.13 mm (0.005 in). The variation is less than 1 mm (0.04 in), so it is within the limits of the AASHTO R36-04 specification. Since this variation is less than the required accuracy then it will not have a significant impact when measuring the faulting using an automatic method. Out of the 26 joints only 4 had a variation greater than 0.5 mm (0.02 in) which is lower than the accuracy of the 3D Line Laser. In most cases the variation in the faulting caused by the temperature gradient in the slab is not substantial enough to be of concern.

D.5.2.2 Weigh Station Roughness Analysis

Like the faulting the roughness is a direct output from the 3D Line Laser software. The roughness is quantified using the International Roughness Index (IRI). The IRI is found by first defining the starting and end points of the test section then a longitudinal profile is created for each wheel path. These profiles are created from the 3D Line Laser range data and then are corrected using the IMU data so that the vehicles up and down motion could be removed. The corrected profiles are then used to generate the IRI values for each wheel path. An algorithm simulates how a reference vehicle would respond if it traveled the profile. As this profile is traversed the algorithm accrues the suspension movement which is the IRI. For the 3D Line Laser this value is reported in meters or suspension travel per kilometer that the sensing vehicle traveled (m/km).

For the weigh station test section there was one IRI values for each wheel path in each data collection run. This resulted in 52 IRI values or 26 IRI values for the left wheel
path and 26 IRI values for the right wheel path to use to study how the IRI changed through the data collection. The average IRI for the left wheel path was 2.10 m/km (133.3 in/mile) and 2.37 m/km (150.5 in/mile). Table D.3 shows the statistics for the IRI results.

**Table D.3 Weigh Station IRI Statistics**

<table>
<thead>
<tr>
<th>Weigh Station IRI</th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>{m/km}</td>
<td>{in/mile}</td>
</tr>
<tr>
<td>Average</td>
<td>2.10</td>
<td>133.3</td>
</tr>
<tr>
<td>Median</td>
<td>2.11</td>
<td>133.4</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.07</td>
<td>4.4</td>
</tr>
<tr>
<td>Maximum</td>
<td>2.27</td>
<td>143.8</td>
</tr>
<tr>
<td>Minimum</td>
<td>1.91</td>
<td>121.0</td>
</tr>
<tr>
<td>Variation</td>
<td>0.36</td>
<td>22.8</td>
</tr>
</tbody>
</table>

The variation was found by subtracting the minimum IRI from each wheel path from the maximum IRI from each wheel path. The variation for the left wheel path was 0.36 m/km (22.8 in/mile) and for the right wheel path it was 0.26 m/km (16.5 in/mile). This indicates that the temperature gradient through the slab does have an impact on the IRI and should be considered when evaluating the smoothness of a concrete pavement section. The IRI values were then plotted to see how they varied during the course of the day. Figure D.7 shows the plot of the IRI values versus time for each wheel path and the plot of the recorded air temperatures from NOAA versus time. This was included to see how the IRI correlated to the temperature variation.
These results exhibit what is expected because the IRI shows a slight upward trend until around 10:00 A.M. when it jumps up slightly. Then the IRI in begins to decrease after the temperature peaks for the day. The slight upward trend (nearly flat) is probably caused by the accuracy of the 3D Line Laser to calculate the IRI. It is expected that this trend would be flat because in the early morning the temperature variation between the top and bottom is not that significant so as the slab goes from a slight negative curvature condition, the temperature in the top of the slab is less than the temperature in the bottom of the slab, to a zero curvature condition. Then once the zero curvature condition is achieved the temperature in the top of the slab increases while, the temperature in the bottom of the slab stays the same causing the slab to begin to exhibit a positive curvature condition. This causes the flat trend in the IRI plot because as the slab goes from a slight negative curvature to a slight positive curvature there is not much change, probably less than the system accuracy. The jump in the IRI plot is caused by
the positive curvature of the slab increasing due to the increase in the temperature in the top of the slab which creates a much larger temperature gradient between the top and bottom of the slab. Then as the temperature of the top of the slab begins to decrease the positive curvature begins to decrease which in turn decreases the IRI.

D.5.2.3 Weigh Station Curvature Analysis

After it was determined that the curvature did have an impact on the IRI, it was analyzed to see if the 3D Line Laser could be used to measure the curvature. There is not a function in the 3D Line Laser software that allows the curvature of a slab to be assessed so a procedure had to be developed that would use the 3D Line Laser data to measure the curvature. This procedure would extract both the longitudinal and transverse curvature. This section briefly describes the steps that were taken to quantify the curvature and the conclusions that were made from it. The detailed method to extract the curvature from the 3D Line Laser data is in Appendix B of this thesis.

D.5.2.3.1 Longitudinal Curvature

There are two options to get longitudinal profiles from the data that was collected; the first is to use the raw 3D Line Laser range data. The second is to use the corrected profiles that were created from the raw 3D Line Laser range data and the IMU data. These are the same profiles that were used to calculate the IRI.

An algorithm was created to read the raw 3D Line Laser range data and to combine the data from multiple files to create a complete profile. After the profile was attained then it had to be manually filtered to remove irregularities. Some of the
irregularities that were encountered in the profiles include spikes caused by the joints, spikes caused by anomalies in the data (i.e. random error from the sensors), and large steps in the profiles that were caused by data from multiple sensors being combined together. Once the profiles were filtered then they were plotted in Excel and the trend line function was used to get a smooth profile for the slab. Then the trend line equation was used to get a numerical value for the curvature of the slab. To get a numerical value for the curvature the x position values were substituted into the trend line equation to get a y value for the beginning, middle and end of the profile. The beginning and end points were averaged to level out the profile and then the difference between this average value and the middle y value was taken as the quantitative curvature value.

For the weigh station three slabs were selected as test slabs to be examined for the curvature analysis. The slabs that were selected were the first slab, the thirteenth slab, and the twenty fifth slab. Since the center of the slab would undergo the most curvature the center longitudinal profile was selected for comparison because it would move the most it should be the easiest to measure. Each slab was collected in each run of data so a total of 26 profiles were extracted for each slab. This resulted in a data set of 26 quantitative curvature values for each of the slabs. Figure D.8 shows one of the longitudinal profiles for slab 1. The profile in the figure indicates that the slab is curled 2.79 mm (0.11 in).
The three slabs that were selected exhibited similar behavior so the first slab was selected to be described here. All of the curvature values were compared to see how the slab moved during the day. The curvature showed a parabolic trend which is what is expected but there were large variations between the individual points. Figure D.9 shows the curvature values that were calculated for slab 1 for each data collection run. It is unlikely that the slab curvature changes this drastically in such a short time period especially since the temperature changes is also gradual.
Figure D.9 Weigh Station Slab 1 Curvature

The slab curvature was further analyzed to see if there was any built in curvature or curvature caused by other factors, such as the moisture gradient, in the slabs and the effects that it has on the curvature results. To find the built in curvature the thermal data collected during the October data collection was analyzed to find the times that the top and bottom temperatures were the same this would indicate when there was no slab curvature due to the temperature gradient. The October thermal data was logged using a 1 minute interval and the 3D Line Laser data was collected at a 15 minute interval. The two times that the temperature difference were closest to zero were 11:45 A.M. and 12:00 P.M. The center profiles from these two runs were extracted. Then these profiles were averaged to form a new profile so that if there was some anomaly in a single run then it would not have as big of an impact. These profiles were then removed from the actual slab profiles and the quantitative curvature values were regenerated.
For slab 1 at the weigh station the results indicated that it had a negative built in curvature of approximately -5.58 mm (-0.22 in). After the built in curvature was removed from the original profiles the quantitative curvature values were recalculated using the same method. The plot of the quantitative curvature with the built in curvature removed followed the same path it was just shifted up by the built in curvature amount. These results show that the slab curvature caused by the temperature gradient can be isolated and evaluated.

The second method that was used to attempt to evaluate the longitudinal curvature was the corrected longitudinal profiles that were created from the 3D Line Laser data and the IMU data. Initially it was attempted to use the profiles that were created and used to calculate the IRI values, but there was drift in the data. Drift is random fluctuations that can occur in the IMU data (French, 2009). As the profile is created this drift accumulates and causes a continuous curve in the entire longitudinal profile. For the purpose of IRI analysis the drift does not have a significant impact on the results so it was not corrected for within the 3D Line Laser software. The drift can be filtered out of the corrected profile but the curvature of the slab is also removed by this filter. One method that was suggested to the manufacturer of the 3D Line Laser was to filter the IMU data then use it to correct the 3D Line Laser data to get a corrected profile that can be used for the purpose of curvature analysis.

An attempt was also made to reduce the effects of the drift on the slab curvature by generating short profiles. These profiles were for individual slabs. The problem with this method was that the software would create profiles that were shorter than the full length of the slab. Due to the incorrect profile length and the presence of the drift in the
data it was decided to forego using the corrected profiles until a more sophisticated method is developed to remove the drift and ensure that the curvature is not also eliminated.

\textit{D.5.2.3.2 Transverse Curvature}

The transverse curvature was also evaluated. The profiles were extracted, processed and analyzed in the same manner as the longitudinal profiles were from the raw 3D Line Laser data. The quantitative curvature values were found using the trend line function and subbing into the equation the same way as the longitudinal quantitative curvature values were found. The first, thirteenth, and twenty fifth slabs were used for this analysis also. The profile that passed through the center of the slab was used. This profile was not perfectly perpendicular to the travel direction but was at a 15° angle from the transverse direction.

For each slab there were 26 profiles, one from each data collection run. The curvature from only the temperature gradient was not isolated out, as it was in the longitudinal curvature analysis, because of an enormous amount of error in the left sensor during the October data collection. This error was random and was due to an issue that was encountered with the sensor and due to the sensors needing to be recalibrated. This was not an issue when evaluating the longitudinal curvature because the longitudinal profiles were taken from the right sensor which did not experience the same issues that the left sensor did.

The results for slab one show that the curvature did not change during the data collection it remained constant at 8.64 mm (0.34 in). The results for slab 13 indicate that
the curvature remained constant at 10.80 mm (0.425 in) until 10:15 A.M. where it jumped to 12.97 mm (0.51 in). The curvature then returned to 10.80 mm (0.425 in) in the 10:30 A.M. run and jumped back to 12.97 mm (0.51 in) in the 12:45 P.M. to 1:45 P.M. runs. In the final data collection run, collected at 2:00 P.M., the curvature returned to 10.80 mm (0.425 in). The results for slab twenty five showed that the curvature jumped back and forth from 10.80 mm (0.425 in) to 12.97 mm (0.51 in) in the data collected between 5:45 A.M. to 10:30 A.M. In all of the runs collected from 12:45 P.M. to 2:00 P.M. the curvature remained constant at 12.97 mm (0.51 in). Figure D.10 shows the curvature values for the three slabs throughout the day.

![Figure D.10 Quantitative Transverse Curvatures](image)

**D.6 Summary**

This chapter described the procedures that were developed to collect thermal and 3D Line Laser data at a test site. After the weigh station was selected as a suitable test site a procedure was developed to install the thermocouples and to collect data with them.
in a way that the thermal information in the slab could be correlated to the 3D Line Laser data. The thermal data was used to determine when to collect the 3D Line Laser data. Once the 3D Line Laser data was collected it was processed and analyzed to see if the system were capable of detecting the changes in the concrete pavement characteristics caused by thermal variations in the slab. The characteristics that were evaluated included the faulting of the transverse joints, the smoothness, and the longitudinal and transverse curvature.

The faulting results indicated that the thermal effects on the faulting were either smaller than what could be detected by the sensors or it was within the accuracy range in the specification for automated detection. The smoothness was measured using the IRI and the results showed that the temperature did have a noticeable impact on the final results causing the IRI to increase as the curvature of the slabs increased.

The longitudinal curvature was assessed using two options the first being to use the raw 3D Line Laser range data and the second was to use the 3D Line Laser range data that was corrected by the IMU data. The results from the raw 3D Line Laser range data indicated that the slab curvature was changing although there were some improbable curvature values. These values displayed that the curvature in the slab jumped up and down in short time periods, but it was expected that the curvature would be a gradual change in the curvature. It was anticipated that the curvature would go from negative in the early morning to zero in the late morning then it would be positive and increase gradually with the temperature. Then as the temperature began to decrease in the late afternoon the curvature would also decrease until it reached zero and it would then become negative until sunrise the following day. The results from the corrected profiles
could not be accurately assessed due to the presence of the drift in data and the inability to remove it without affecting the curvature.

The transverse curvature was also considered and the results showed that the transverse curvature conditions can vary between the slabs at a single site. The results also showed jumps in the curvature values between data collection runs. Just as with the longitudinal curvature these jumps were surprising and inconsistent with what was expected. Due to the variability of the results, the lack of ground truth curvature values or slab profiles to compare to those estimated by the 3D Line Laser and the limited amount of time for this study it was decided to forego trying to quantify the curvature of the slab. In order to determine if the system is capable of measuring the curvature then the exact profiles that are to be extracted should be marked on the slabs and a dipstick profiler, or some other profiler, should be used to measure the slab profiles simultaneously with the sensing vehicle. Then these profiles should be compared to the ones collected by the sensing vehicle to see if the results are accurate or if there is some form of filtering or an index that needs to be created for the results to better represent the actual curvature of the slabs. For the remainder of this study it is assumed that the concrete pavement slabs are experiencing changes in curvature throughout the data collections.
REFERENCES


2D Laser Scanner LMS Q120. Riegl September 2007 Print.


Jung, Y. S., Freeman, T. J., and Zollinger, D. G. Guidelines for routine maintenance of concrete pavements, Texas Transportation Institute, College Station, TX. 2008. Print.


312


