Technical Report Documentation Page

1. Report No. FHWA/TX-11/5-4322-01-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Validation and Implementation of the Structural Condition Index (SCI) for Network-level Pavement Evaluation		5. Report Date November 2010; Revised June 2011
		6. Performing Organization Code
7. Author(s) Sree Sravya Sruthi Peddibhotla Dr. Mike Murphy, P.E. Dr. Zhanmin Zhang, P.E.		8. Performing Organization Report No. 5-4322-01-1
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 1616 Guadalupe Street, Suite 4.202 Austin, TX 78701		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. 5-4322-01
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Technical Report May 2009–August 2010
		14. Sponsoring Agency Code

15. Supplementary Notes
Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

16. Abstract
The Texas Department of Transportation (TxDOT) uses the Pavement Management Information Systems (PMIS) to store and analyze pavement data, and to summarize information needed to support pavement-related decisions. The information on overall condition of the pavement is stored in PMIS, measured with various scores based on visual distress and ride quality surveys. However, a direct measure of the pavement structural condition is currently not in use. A network-level index that can distinguish pavements that require Preventive Maintenance (PM) from those that require Rehabilitation (Rhb) is required, as it is not cost-effective to apply PM treatments to pavements that are structurally inadequate. The need for an index to improve the pavement treatment selection process, especially under financial constraints, has motivated this research. The objective of this research is to validate the pavement Structural Condition Index (SCI) developed under a previous Research Project, 0-4322, and to develop guidelines for implementing the SCI at the network level.

17. Key Words	18. Distribution Statement
Structural Condition Index, SCI, Falling Weight Deflectometer, FWD, Network-level, pavement structural capacity, pavement structural condition, depth to bedrock, project segmentation	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161; www.ntis.gov.

19. Security Classif. (of report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	120	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Validation and Implementation of the Structural Condition Index (SCI) for Network-level Pavement Evaluation

Sree Sravya Sruthi Peddibhotla
Dr. Mike Murphy, P.E.
Dr. Zhanmin Zhang, P.E.

CTR Technical Report:	5-4322-01-1
Report Date:	November 2010; Revised June 2011
Project:	5-4322-01
Project Title:	Implementation of a Network -Level Pavement Structural Condition Index based on Falling Weight Deflectometer Data
Sponsoring Agency:	Texas Department of Transportation
Performing Agency:	Center for Transportation Research at The University of Texas at Austin

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

Center for Transportation Research
The University of Texas at Austin
1616 Guadalupe Street, Suite 4.202
Austin, TX 78701
www.utexas.edu/research/ctr

Disclaimers

Author's Disclaimer: The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation.

Patent Disclaimer: There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES.

Project Engineer: Dr. Mike Murphy, P.E.
Professional Engineer License State and Number: Texas No. 59874
P. E. Designation: Research Supervisor

Acknowledgments

The researchers would like to acknowledge the Project Director, Dr. Magdy Mikhail, and the Project Monitoring Committee Members, Mike Arellano, Miles Garrison, Patrick Downey, and RTI Research Engineer Dr. German Claros for their guidance and recommendations during this project. We would also like to acknowledge the contributions of Falling Weight Deflectometer data, maps and/or expert opinions contributed during the SCI Threshold Analysis task of John Bilyeu, Dr. Dar Hao Chen, Elias Rmeili, David Wagner, Darlene Goehl, Stacey Young, Joe Leidy, Ciro Baeza, Tracy House, and Thomas Reed.

Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

1.1 Background

Texas has the largest state-maintained highway system in the United States, with over 195,000 highway lane-miles. The Texas Department of Transportation (TxDOT) uses the Pavement Management Information Systems (PMIS) to store, retrieve, and analyze pavement data, and to prepare reports that summarize information needed to support pavement-related decisions [TxDOT 1994]. Pavement condition information is stored in PMIS, measured with various scores based on visual distress and ride quality surveys. These PMIS scores help identify the funding required for pavement Maintenance and Rehabilitation (M&R) activities.

The current funding for pavement infrastructure management is becoming increasingly limited due to factors such as construction cost inflation and reduced fuel tax revenue. The available funding will not be able to address all the pavement management needs, resulting in an impact at both economic (bad pavements increase fuel consumption and maintenance costs) and community (shift of business centers based on the pavement infrastructure condition) levels.

The current statewide goal for pavement condition, set by the Texas Transportation Commission in 2002, is to achieve 90% of the state-maintained lane miles in “good” or better condition by 2012. However, a recent study concluded that the current funding available for achieving and maintaining this goal is insufficient and that the pavement infrastructure condition will deteriorate to unacceptable levels [Zhang 2009]. In this study, the analysis was conducted based on the funding allocation for FY 2009 from the 4-year Pavement Management Plans, and funding projection for FY 2010–2035 developed by TxDOT. The predicted pavement performance trend for FY 2009–2030, from this analysis, is shown in Figure 1.1. Hence, under these financial constraints, a cost-effective pavement treatment selection process is a necessity.

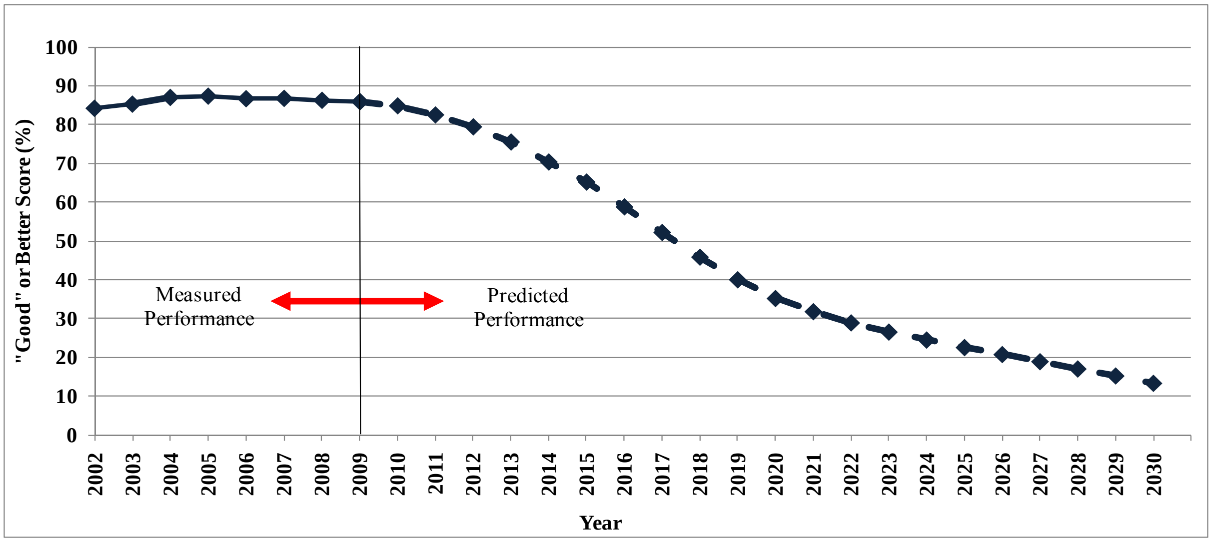


Figure 1.1: Predicted pavement performance trend for FY 2009–2030 [Zhang 2009]

The current PMIS scores provide a good indication of the overall pavement condition. However, a direct measure of the pavement structural condition is currently not in use. A network-level index that can distinguish pavements requiring Preventive Maintenance (PM) from those requiring Rehabilitation (Rhb) is necessary, given that applying PM treatments to pavements that are structurally inadequate is not cost-effective. Thus, the need for an index to improve the pavement treatment selection process under budget constraints has motivated this research. The objective of this research is to validate the pavement Structural Condition Index (SCI) developed under a previous research project conducted by CTR (Project 0-4322) [Zhang 2003], and to develop guidelines for implementing the SCI at the network level.

1.2 Research Objective

The main objective of this research is to validate the SCI with pavement sections representing a broad range of pavement conditions and climatic regions of the state, and to prepare the necessary materials to assist TxDOT with implementation of the SCI. During the course of the research, some districts were selected in coordination with the research Project Director, from which the necessary data was collected. More specifically, the objectives of this research are to:

- validate the SCI method;
- determine the effect of bedrock depth on the SCI values;
- determine the representative SCI value of a pavement section;
- develop guidelines about the M&R treatment category, based on the representative SCI value of a pavement section; and
- determine the ideal Falling Weight Deflectometer (FWD) testing spacing, for adequately characterizing the pavement structural condition using SCI, at the network level.

1.3 Research Scope

The Texas state highway system has 94% of its total mileage as flexible pavements and the other 6% as rigid pavements. This research focuses on evaluation of the SCI method for flexible pavements (asphalt concrete or thin surface-treated) in Texas. The SCI method has not yet been modified and evaluated for use on rigid pavements (portland cement concrete) in this research.

1.4 Research Organization

This technical report is organized into eight chapters. Chapter 1 presents the introduction, objectives, and organization. Chapter 2 focuses on the state of the art in network-level structural condition assessment. Chapter 3 discusses the data and data sources used for the research. Chapter 4 describes the SCI validation process and the effect of bedrock depth on SCI values. Chapter 5 discusses methods for determining the representative SCI value of a section. Chapter 6 summarizes the TxDOT survey results regarding SCI threshold analysis. Chapter 7 provides a recommendation for the necessary spacing of the FWD test points, in order to characterize pavement structural condition using SCI at the network level. Finally, Chapter 8 provides conclusions and recommendations for this research.

Chapter 2. An Overview of the State of the Art of Structural Indices for Network-Level Applications

2.1 Introduction to the Structural Condition Index

The structural condition of a pavement section can be assessed through non-destructive methods such as deflection testing using the FWD. The back-calculation of the subgrade and the pavement layer moduli is one of the procedures commonly used to characterize the structural condition of a pavement using the FWD data. However, at present, the TxDOT PMIS does not have the pavement layer thickness information required for the back-calculation procedure [TxDOT 2000]. The TxDOT PMIS stores a structural screening index called the Structural Strength Index (SSI) that is based on the FWD data [Scullion 1998]. Though the SSI does not require the pavement layer thickness information, TxDOT's internal studies indicated that the SSI was not sensitive enough to discriminate between pavements that need structural reinforcement and those that do not [TxDOT 2000].

This shortcoming of the SSI led to the development of a new methodology called the Structural Condition Index (SCI), using FWD data, under a previous research project (Project 0-4322) [Zhang 2003]. The SCI is the ratio of the "existing/effective" AASHTO (American Association of State Highway Transportation Officials) Structural Number (SN_{eff}) determined from both the FWD measurements and the total pavement thickness [AASHTO 1986], the "required" AASHTO Structural Number (SN_{req}) based on the estimated 20-year Equivalent Single Axle Loads (ESALs) for the route, and the subgrade modulus (M_R) [AASHTO 1993].

2.2 Objective of the Literature Review

The SCI methodology was developed more than 6 years ago [Zhang 2003]. Therefore, a review of the latest advancements in this area is important. A review of the structural indices for network-level applications was undertaken, seeking to evaluate any identified indices along with the SCI. Hence, in this research, the literature review focused on relevant material and previous research to identify structural indices that were developed to evaluate pavements at the network level.

2.3 Summary of the Network-Level Structural Indices

The review was not limited to the United States but also included methods developed internationally. Table 2.1 summarizes the methods developed by the different agencies, including each agency's objective, concept, approach, and conclusions.

Table 2.1: Agency Objective, Concept, Approach, and Conclusions

Agency	Objective	Concept	Approach	Conclusions
Oklahoma DOT [Williams 2006]	To determine the structural capacity of the primary arterial system.	FWD and Ground Penetrating Radar (GPR) profiles were used to identify the changes in the pavement structure.	GPR results were used to obtain the layer thickness estimates for use in FWD back-calculation of the layer moduli.	SN, M_R were used to determine the structural capacity. GPR was found to be effective only for certain pavement structures.
New Jersey DOT [Sameh 2004]	To develop Structural Adequacy Index (SAI) model so as to identify current and future structural needs and to prioritize the needs.	SAI = f (SNR) SNR (Structural Number Ratio) = $\left(\frac{SN_{eff}}{SN_{as\ built}}\right)30\% + \left(\frac{SN_{eff}}{SN_{req}}\right)70\%$	Layer thickness estimates were obtained from GPR or coring data. $SN_{eff} = f$ (FWD data) $SN_{req} = f$ (Future Traffic) $SN_{asbuilt} = f$ (AASHTO layer coefficients eq.)	Results obtained from SAI= f (SNR) were used to prioritize the needs. Proposed SAI model is based on judgment and local experience.
Kansas DOT [Mustaque 2000]	To determine the structural capacity of pavements at the network level.	Used regression for determining ΔSN (decrease in SN) ΔSN = f (time since pavement's last rehab, total pavement thickness).	SN was calculated using FWD data that was then correlated with factors like the total pavement thickness.	ΔSN gives the deterioration of the structural capacity at the network level. Study was limited only to 357 miles of non-interstate pavements.
Virginia DOT [Brian 2008]	To use the results from a FWD network-level survey to develop an index as a condition forecasting tool.	FWD data was analyzed by calculating M_R, SN_{eff}.	Analysis was done in accordance with the AASHTO design guide.	The index could not be developed in the study due to limitations in the traffic data.

Table 2.1 continued

Agency	Objective	Concept	Approach	Conclusions
Indiana DOT [Noureldin 2005]	To investigate employing FWD and GPR in pavement evaluation at the network level.	Layer modulus was determined through the FWD deflections. Layer thickness was estimated from the GPR readings.	Remaining Service Life (RSL) in terms of ESALs was estimated through the central FWD deflection (W_1).	Employing GPR at the network level is a cumbersome task.
European Cooperation in Science & Technology (COST) [Thierry 2008]	To identify badly performing sections at the network level by developing a Global Performance Indicator.	Global Performance Indicator was developed by grouping Single Performance Indices into Combined Indices such as Structural, Environmental, and Functional Performance.	Structural Index was determined by Surface Curvature Index (W_1-W_2 sensor deflections).	This index is measured from 0 (good condition) to 5 (poor condition). This model takes only the current pavement condition into account.
South Africa CSIR [Horak 2008]	To develop a benchmarking methodology using the deflection bowl parameters along with visual surveys.	Used deflection bowl parameters—Base Layer Index (BLI), Middle Layer Index (MLI), and Lower Layer Index (LLI)—and identified them as *sound*, *warning*, and *severe* based on the range of each parameter.	BLI= W_1-W_2 (sensor deflections) MLI= W_2-W_3 (sensor deflections) LLI= W_3-W_4 (sensor deflections)	Pavement layer thickness information is not required. However, information about base type is required.
Australia [Binod 2003]	To utilize Western Australia's experience in the usage of FWD at the network level survey.	Central FWD deflection data and Surface Curvature Index were used as the pavement strength indicators.	FWD deflections were used to compute the Surface Curvature Index (W_1-W_2).	This method considers only the current structural condition of the pavement.

Table 2.1 continued

Agency	Objective	Concept	Approach	Conclusions
Saudi Arabia [Abdullah 1999]	To collect and evaluate pavement data on the main street Riyadh network.	Central FWD deflection data was used as an indicator of pavement structural capacity.	The central FWD Deflection data was used in the analysis (W_1).	This method is simple. However, this method does not consider the future needs of the pavement structure.
Simple Model [Pradeep 2006]	To develop a simple and cost-effective model for structural evaluation of pavements at the network level.	This study's SCI was based on the cumulative damage principle of Miner. $SCI = \frac{n}{N}$	Used rutting and cracking data obtained from the LTPP database, to correlate with the SCI.	This model is based on the detailed project level visual distress survey results.
South Carolina DOT [Baus 2001]	To assess the feasibility of deflection-based SAI in the South Carolina DOT PMS.	SAI = *f* (ER) *ER*= *ESALs ratio* $ER = \frac{ESAL_c}{ESAL_f}$	SN, M_R = *f* (FWD data) $ESAL_c$ = Cumulative ESALs at the time of FWD testing $ESAL_f$=*f* (AASHTO design equation using SN and M_R)	Necessary changes to the SAI model can be made, but only after a pilot program implementation, which has not yet been conducted.
Ohio DOT [FHWA/OH 2007/05]	To improve decisions based on the structural adequacy of the pavement.	RSL was related based on the Strategic Highway Research Program test results.	-Report NA-	-Report NA-

2.4 Summary

The literature review suggested that most of the agencies adopted either the FWD or the Ground Penetrating Radar (GPR) (or in some cases, both pieces of equipment) for the structural evaluation of pavements at the network level. However, certain challenges are associated with using GPR and FWD at the network level. Considering the size of Texas, evaluating pavement structural conditions with GPR and/or FWD data at the network level requires personnel, traffic control, and other resources, resulting in high data collection costs. Moreover, Texas does not have an automated GPR data analysis software system, making GPR data interpretation completely dependent on human experts. As for the evaluation methods, although several methods developed and employed by some agencies were examined, neither new structural indices nor new information was obtained that could be used to improve the SCI method.

Chapter 3. Data and Data Sources

3.1 Introduction

This chapter describes the data collection activities undertaken for this research, including discussions on the collected data and supporting documents from TxDOT. More specifically, the following data was collected from TxDOT:

- FWD data along with Texas Reference Markers (TRM);
- Construction plan sheets showing both the project location and typical sections;
- GPR data (if available);
- Dynamic Cone Penetrometer (DCP) data (if available);
- Photographs of pavement conditions taken during data collection (if available);
- Core data with laboratory thickness measurement records (if available);
- Project-level pavement design documents (if available);
- Load Zone Removal Request forms R1084 (if available); and
- Project-level traffic data.

TxDOT provided the project-level FWD data for 350 pavement sections. All FWD data was collected using the standard 12 in. sensor spacing used in Texas for flexible pavement testing. However, obtaining the layer thickness information and other supporting data for all the sections was not feasible due to time constraints. Hence, a total of 180 pavement sections were used for this research. The researchers reviewed the obtained data and requested any additional data needed for the SCI analysis. The framework used for data collection and processing is illustrated in Figure 3.1. A separate Excel workbook stores the data for each pavement section. Table 3.1 presents the typical data stored for each pavement section.

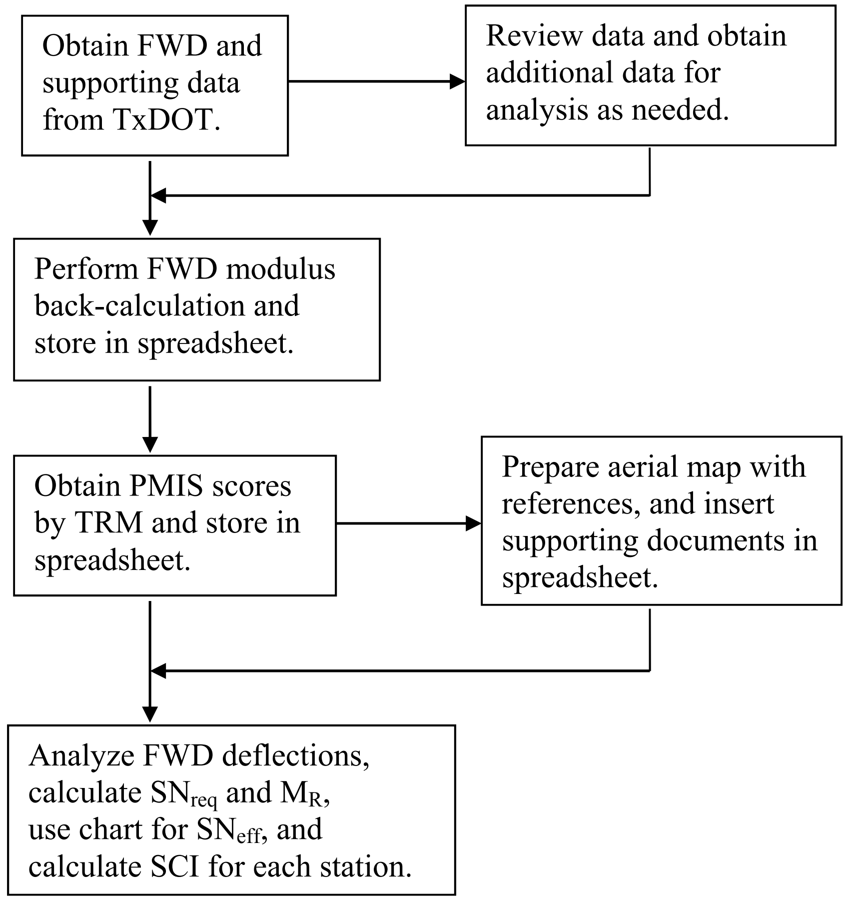


Figure 3.1: Framework used for data collection and processing

Table 3.1: Data Stored for Each Pavement Section in the Spreadsheet

<table>
<tr><th>Data Item</th><th>Example</th></tr>
<tr><td>District</td><td>Austin</td></tr>
<tr><td>County</td><td>Williamson</td></tr>
<tr><td>Environmental Zone</td><td>Mixed</td></tr>
<tr><td>Route</td><td>SH 195</td></tr>
<tr><td>Beginning and Ending TRM</td><td>TRM 416-0.921 to TRM 412+0.851</td></tr>
<tr><td>Section length (miles)</td><td>5.921</td></tr>
<tr><td>Average Daily Traffic (ADT)</td><td>10,500</td></tr>
<tr><td>Estimated 20-year ESALs</td><td>10,385,000</td></tr>
<tr><td>Pavement layer thickness (inches)</td><td>1.5” Asphalt Concrete (AC) surface; and
9” Flexible Base</td></tr>
<tr><td>Average bedrock depth (inches)</td><td>72”</td></tr>
<tr><td>FWD data</td><td>
<table>
<tr><th rowspan="3">TRM</th><th></th><th></th><th colspan="7">Deflection in Mils</th></tr>
<tr><th>Station</th><th>Load (lb)</th><th>0"</th><th>12"</th><th>24"</th><th>36"</th><th>48"</th><th>60"</th><th>72"</th></tr>
<tr><th></th><th></th><th>W1</th><th>W2</th><th>W3</th><th>W4</th><th>W5</th><th>W6</th><th>W7</th></tr>
<tr><td></td><td>0</td><td>10,550</td><td>3.8</td><td>3.22</td><td>2.69</td><td>2.15</td><td>1.66</td><td>1.28</td><td>0.91</td></tr>
<tr><td></td><td>0.198</td><td>10,538</td><td>3.22</td><td>2.56</td><td>2.15</td><td>1.78</td><td>1.37</td><td>1.07</td><td>0.79</td></tr>
<tr><td>416+0.50</td><td>0.394</td><td>10,264</td><td>3.54</td><td>3.15</td><td>2.42</td><td>1.77</td><td>1.39</td><td>1.04</td><td>0.72</td></tr>
<tr><td></td><td>0.558</td><td>10,308</td><td>4.43</td><td>3.83</td><td>3.05</td><td>2.43</td><td>1.88</td><td>1.47</td><td>1.09</td></tr>
<tr><td></td><td>0.811</td><td>10,387</td><td>3.69</td><td>3.05</td><td>2.56</td><td>2.06</td><td>1.61</td><td>1.19</td><td>0.81</td></tr>
<tr><td>416+00</td><td>0.921</td><td>10,435</td><td>4.67</td><td>4.27</td><td>3.95</td><td>1.84</td><td>1.46</td><td>1.19</td><td>0.94</td></tr>
<tr><td></td><td>1.213</td><td>10,479</td><td>2.97</td><td>2.3</td><td>1.82</td><td>1.39</td><td>1.07</td><td>0.8</td><td>0.6</td></tr>
<tr><td>414+1.5</td><td>1.433</td><td>10,486</td><td>2.66</td><td>2.09</td><td>1.55</td><td>1.2</td><td>0.88</td><td>0.65</td><td>0.44</td></tr>
</table>
</td></tr>
<tr><td>Back-calculated modulus (ksi)</td><td>
<table>
<tr><th colspan="4">BACK-CALCULATED MODULUS (ksi)</th></tr>
<tr><th>TRM</th><th>Surface</th><th>Base</th><th>Subgrade</th></tr>
<tr><td></td><td>372.3</td><td>41.7</td><td>9</td></tr>
<tr><td></td><td>140</td><td>10</td><td>4.4</td></tr>
<tr><td>TRM 416+0.50</td><td>554</td><td>75.6</td><td>7.5</td></tr>
</table>
</td></tr>
<tr><td>PMIS scores</td><td>Ride, Distress, and Condition scores</td></tr>
</table>

The total pavement thickness information, considered to be the “better material” placed and compacted above the natural or prepared subgrade, is used as an input in the SCI method. In this research, the pavement layers consisting of a bituminous surface (single or multiple layers), untreated flexible base, stabilized base, stabilized subgrade, recycled paving material, and scarified and re-compacted existing paving materials were considered to be part of the total pavement thickness.

The actual bedrock depth measurements, made using an auger or similar device, were not available in this research. Hence, the bedrock depth measurement was obtained from the calculated rigid layer depth estimate provided as a part of the MODULUS program output [Rohde 1990]. The average bedrock depth was thus based on an assessment of the calculated rigid layer depth values associated with each FWD test point.

3.2 Factors Considered in Data Preparation

The data preparation started with the categorization of factors such as pavement subgrade modulus (M_R), estimated 20-year ESALs, and environmental zones in order to develop a matrix chart.

3.2.1 Matrix Chart

One of the primary objectives of this research is to validate the SCI method. For the validation exercise, inputs that define a section, such as subgrade modulus, estimated 20-year ESALs, and environmental zones, play an important role. Texas is a large state and as such, pavement designs and materials vary significantly across the state, making the above three inputs more critical. As an example, all other factors being equal, a pavement in the wet-cold region of Texas would be expected to have higher seasonal deflections on average than a pavement in the dry-warm region of Texas, due to subgrade moisture conditions. Hence, a matrix chart, shown in Appendix A, was created to help ensure that all primary factors that could potentially affect SCI calculations have been taken into consideration during the validation, an important step for determining the effectiveness of SCI.

The matrix chart is developed based on these key factors: Texas environmental zones, average subgrade modulus, and estimated 20-year ESALs. These factors were chosen based on Texas' conditions that are known or expected to affect pavement structural condition and/or deflection values. Each factor was further subdivided into different categories and is discussed in the later part of the chapter. The matrix chart shows the data for the 180 pavement sections assigned to their respective cells, based on the factor level criteria, established for each of these categories. Thus, each cell in the chart represents a unique combination of factors that helps categorize a section.

3.2.1.1 Environmental Zones

Texas encompasses a broad range of climatic conditions. Figure 3.2 shows the environmental zones used in the study, which are defined by temperature and rainfall conditions. These zones were established based on the observation of similar seasonal deflection patterns under specific climatic conditions in each zone [Scullion 1988]. The information about Texas districts (district name abbreviations in Figure 3.2) are posted on the TxDOT website [http://www.dot.state.tx.us/local_information/, Accessed November 2010].

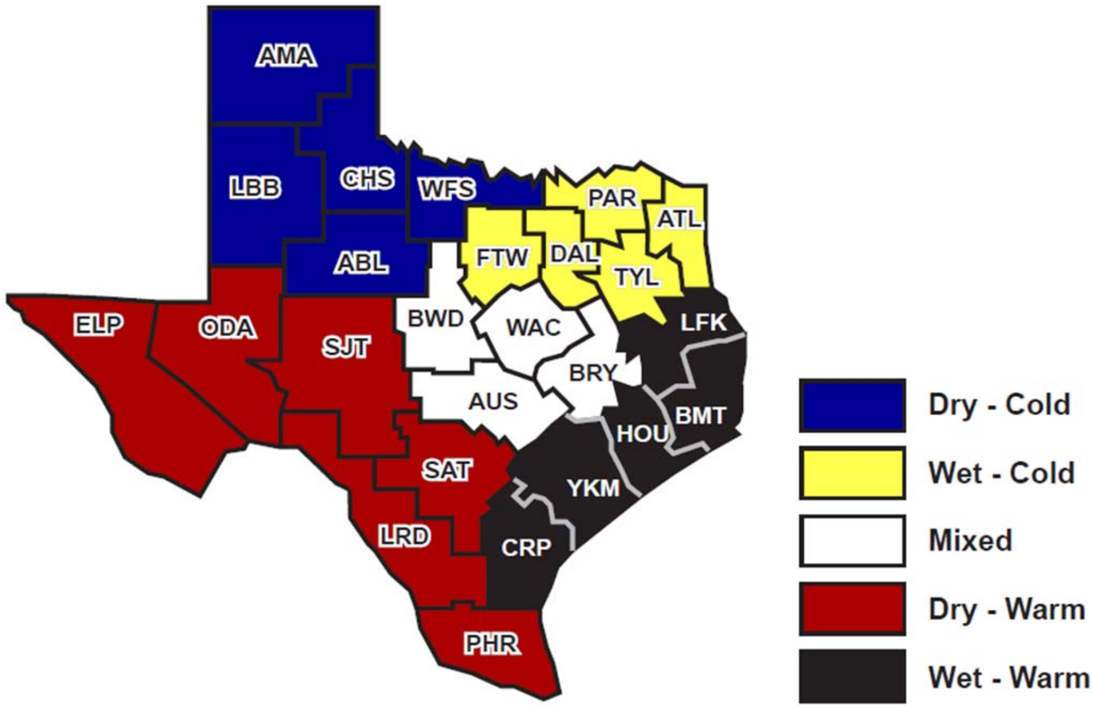


Figure 3.2: Texas environmental zones

3.2.1.2 Subgrade Categories

Pavement subgrade is a major factor in determining the pavement's performance. In the previous research (Project 0-4322), the subgrade modulus values, defined in psi, were assigned to three categories: low (1,000–5,400), medium (5,400–7,500) and high (7,500–40,000). However, during the implementation process, the subgrade limits were re-adjusted according to Texas' conditions. Discussions with the research Project Director resulted in a greater range of subgrade stiffness categories based on the back-calculated subgrade moduli values. The subgrade designations were assigned to the following five subgrade stiffness ranges as given in Table 3.2.

Table 3.2: Subgrade Categories

Category	Subgrade (psi)
Very Poor (VP)	< 6,000
Poor (P)	6,000–10,000
Fair (F)	10,001–14,000
Good (G)	14,001–18,000
Very Good (VG)	> 18,000

3.2.1.3 Traffic Categories

The estimated 20-year ESAL is one of the inputs in the SCI analysis. For this research, the estimated 20-year ESAL stratification included five categories as shown in Table 3.3. Based on Texas' conditions and engineering judgment, the "Very Low" category generally includes the low-volume Farm to Market (FM) roads with low Average Daily Traffic (ADT) and few trucks. The "Low" category includes the higher-volume FM roads and the lower-volume State Highway (SH) routes. The "Medium" category includes FM, SH, and US Highway (US) routes with high ADT and moderate truck volumes. The "High" and "Very High" categories include very high-volume routes with high truck traffic that usually exceeds 750 trucks per day [Murphy 2010].

Table 3.3: Traffic Categories

Category	Traffic (ESALs)
Very Low	< 1,000,000**
Low	1,000,000–3,000,000
Medium	3,000,000–10,000,000
High	10,000,000–30,000,000
Very High	> 30,000,000

** Note: The researchers note that evaluation of network-level FWD data on low-volume FM roads, after the completion of this project, has shown that additional traffic categories are needed below the 1,000,000 ESAL level. The researchers are evaluating additional traffic categories to be used in calculating SN_{req} of 50,000, 100,000, 250,000, 500,000, and 750,000 ESALs.

3.2.1.4 Bedrock Depth Categories

The SCI calculations are dependent on the FWD data. Large FWD deflections at the seventh sensor (W_7) location (72 in. from the load plate) are usually related to a weaker subgrade. However, based on experience with Texas conditions, low W_7 values may be due to either a strong subgrade or possibly a weak subgrade over relatively shallow bedrock. Although the matrix chart is not based on the bedrock depth categories, to find the effect of shallow bedrock on the SCI values with in-service pavements, the researchers decided to stratify bedrock depth categories as shown in Table 3.4. These categories were established based on engineering experience and other studies that have shown the effects of shallow bedrock on FWD deflections [Rohde 1994]. The "Variable" category was established for pavement sections that encompassed both shallow and deep bedrock along a route.

Table 3.4: Bedrock Depth Categories

Category	Bedrock Depth (inches)
Very Shallow	<60
Shallow	60–100
Moderate	100–140
Deep	140–180
Very Deep	>180
Variable	Shallow and Deep Sections

3.3 Data Sources and Data Utilization

The data was collected from TxDOT for the SCI analysis. The details of the aspects considered during the data collection along with the utilization of the data are summarized in this section.

3.3.1 FWD Data

The FWD data for the 180 sections was obtained from different projects, including forensic investigations, super-heavy load analyses, load zone roadway analyses, project-level pavement design projects, and data collected for other research projects. The number of pavement sections with available FWD data in each environmental zone is shown in Figure 3.3.

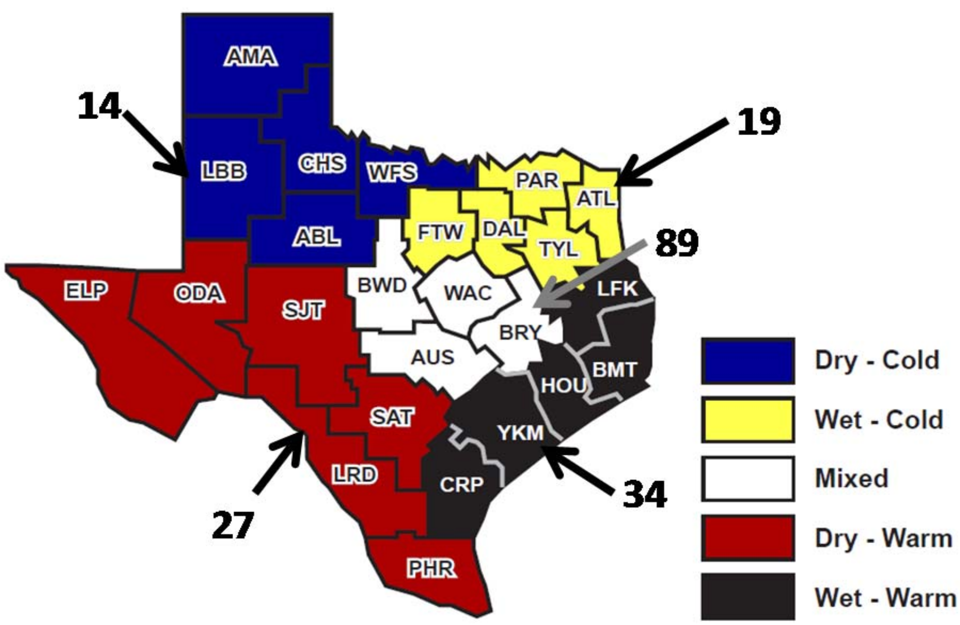


Figure 3.3: Number of pavement sections with available FWD data in each environmental zone

Most of the FWD data was collected between 1998 and 2009 during any given month of the year. The interval at which the FWD data was collected varied from section to section depending on the purpose of testing. For some projects, FWD measurements were recorded every 50 feet, whereas others were taken at 0.5-mile intervals. Texas suffered a drought between 2006 and 2009 and very stiff subgrade values have been observed, especially for pavements over desiccated clay soils. Very stiff subgrade due to drought conditions may result in an un-conservative estimate of the pavement structural capacity, compared to the worst case conditions. Hence, it was ensured that a representative sample of pavement sections obtained have FWD tests conducted prior to 2006.

FWD deflections (mils) along with the corresponding, actual applied loads (pounds) were recorded in the spreadsheet for each test station. In addition to the FWD data, the visual distress comments were also recorded based on the observations of the FWD crew during the data collection. Deflections were then normalized to a standard 9,000 lb load, which was used for subsequent calculations.

3.3.2 Back-calculation of Moduli Values

FWD deflection readings are obtained by applying a load to an 11.8 in. diameter load plate placed on the pavement during testing. These deflections are measured by seven sensors located at typical offsets of 12 inches from the load plate. The recorded pavement deflections in response to the applied load result in the FWD deflection basin. The FWD deflection basin is not unique and similar deflection basins can occur for different combinations of pavement structures.

The FWD data for each section was analyzed through the MODULUS back-calculation program. The MODULUS program output was stored in the spreadsheet, including layer moduli for each layer and the subgrade. Although the SCI analysis uses M_R values determined by the AASHTO method, the back-calculated moduli can be used along with the supporting information for later comparisons with the SCI, to determine whether the SCI provided a reasonable assessment of the pavement structural condition.

Figure 3.4 summarizes the distribution of pavement sections based on the average back-calculated subgrade modulus. The focus of this research is to validate the SCI method. This distribution shows that an illustrative sample of 180 pavement sections has been obtained, providing a balanced representation of the subgrade conditions in Texas.

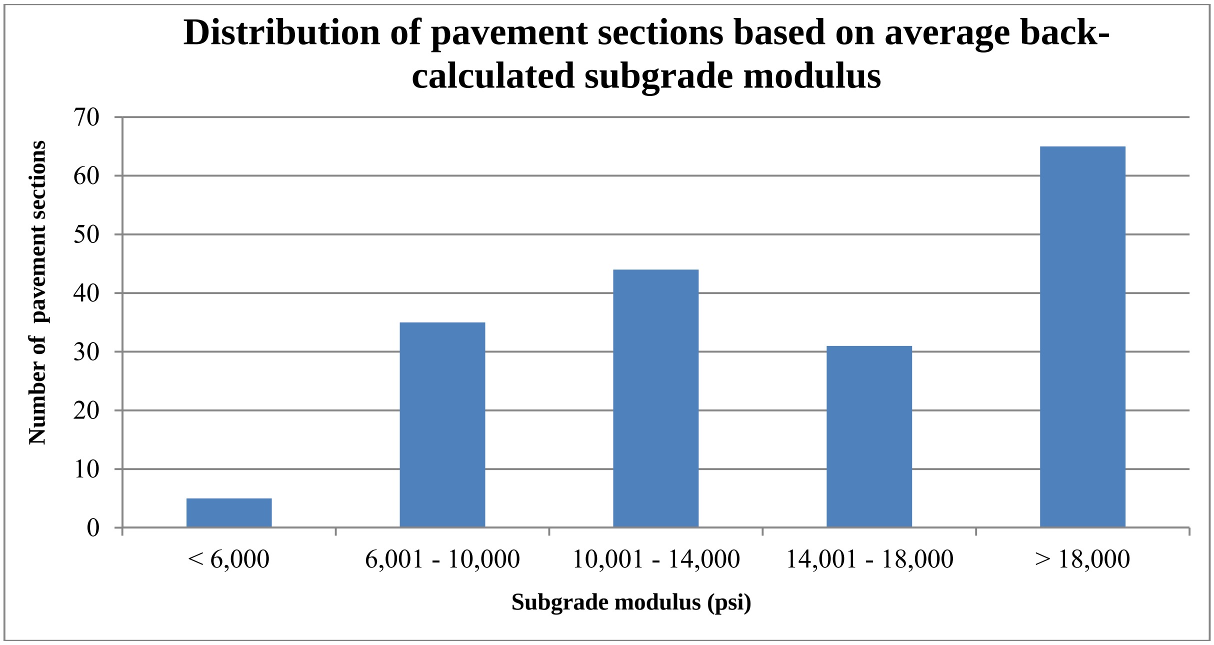


Figure 3.4: Distribution of pavement sections based on average back-calculated subgrade modulus

It should be noted that only a few pavement sections were observed with an average subgrade modulus at or below 6,000 psi. These very weak subgrades are primarily associated with pavements that are located in the wet climatic regions and have cracked unsealed surfaces and/or poor drainage conditions. Pavements in this condition are rare because the TxDOT maintenance forces are proactive in sealing pavements, and cleaning ditches and culverts.

3.3.3 Pavement Thickness Information

The advantage of the SCI methodology is the use of total pavement thickness information instead of the layer thickness information. However, at present, only surface layer type and thickness range information can be obtained from the TxDOT PMIS. Hence, for this research, the pavement thickness or material type information was usually obtained from the construction plan sheet, typical section details, pavement forensic reports, pavement designs, or Load Zone Analysis requests. However, on a few sections, GPR, core log information, or the DCP was used to obtain the pavement thickness information; records of these information sources were also stored in the spreadsheet. Table 3.5 summarizes the pavement layer and total thickness information for each of the route types in the 180 sections.

Route Type	Surface Type	Pavement Layer and Total Thickness			
FM	Surface Treated	1–5” Surface 5–24” Flexible base Total = 6–26”	2–6” Surface 5–24” Treated base Total = 7–30”	1–5” Surface 8–19” Flexible base 6–12” Treated subgrade Total = 32”	1–4” Surface 3–8” Treated base 6–15” Treated subgrade Total = 15–20”
	Asphalt Concrete	1.5–13” Surface 5–18” Flexible base Total = 7–23”	2–6” Surface 7–24” Treated base Total = 9–30”	7.5” Surface 14” Flexible base 6” Treated subgrade Total = 27.5”	1–8” Surface 4–9” Treated base 6–12” Treated subgrade Total = 14–31.5”
SH	Surface Treated	1–2” Surface 5–12” Flexible base Total = 6–13”	2” Surface 6” Treated base Total = 8”	1” Surface 12” Treated base 8” Treated subgrade Total = 21”	
	Asphalt Concrete	2–6” Surface 4–15” Flexible base Total = 6–21”	2–3” Surface 6–7” Treated base Total = 8–9”	2–7” Surface 8–10” Treated base 8–15” Treated subgrade Total = 18–29.5”	
US & IH	Asphalt Concrete	1.5–13” Surface 8–18” Flexible base Total = 11.5–28”	2” Surface 10” Treated base Total = 12”	3–18.5” Surface 6–12” Treated base 6–12” Treated subgrade Total = 26–38”	

Figure 3.5: Pavement layer and total thickness ranges for each route type

3.3.4 Traffic Information

The TxDOT PMIS database provided traffic information. As discussed earlier, the traffic information is divided into five categories. The 30 million ESAL limit is selected for the "Very High" traffic category based on an administrative policy, which requires at least this traffic level for consideration of a perpetual pavement. Figure 3.6 shows the number of pavement sections in each traffic category. It should be noted that the available data, 180 sections, did not include the"Very High" traffic category as there are only 10 in-service perpetual pavements in Texas [Lubinda 2010].

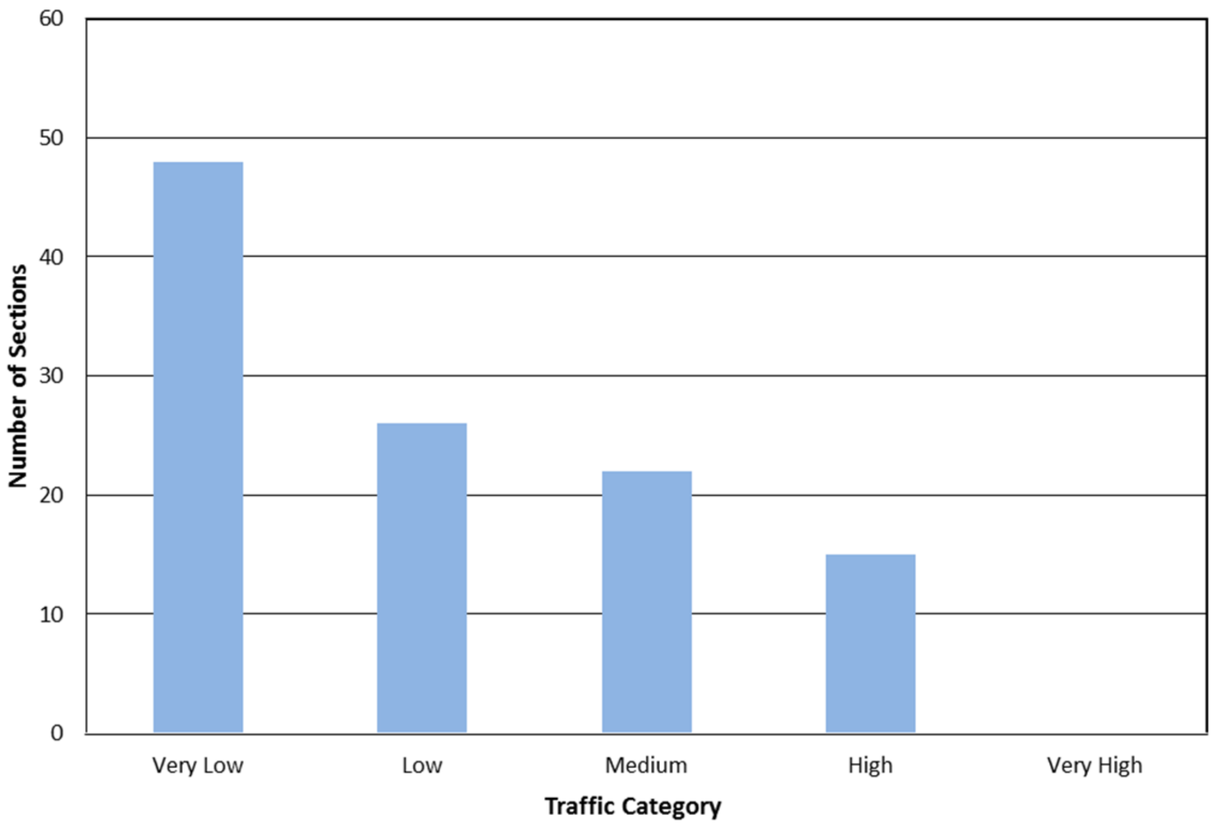


Figure 3.6: Number of pavement sections by traffic category

3.3.5 PMIS Scores

PMIS scores are not used in calculating the SCI, but were used in the SCI threshold analysis (Chapter 6). PMIS scores located by TRMs for all 180 sections were obtained from the web-based Pavement Performance & Maintenance Management (PPMM) system as shown in Figure 3.7. This system is maintained by the Transportation Infrastructure and Information Systems Lab of the Center for Transportation Research at The University of Texas at Austin. The PPMM system is composed of two groups of modules, the "Performance Monitoring" module and the "Maintenance Management" module, with each module having two corresponding tools [Tammy 2010]. Map-Zapper, a system that provides a user-friendly toolbox to use PMIS scores, was used to obtain TRM limits and offsets. Map-Zapper was also used for checking lane designations so as to ensure that the PMIS scores were from the same lane as the FWD data.

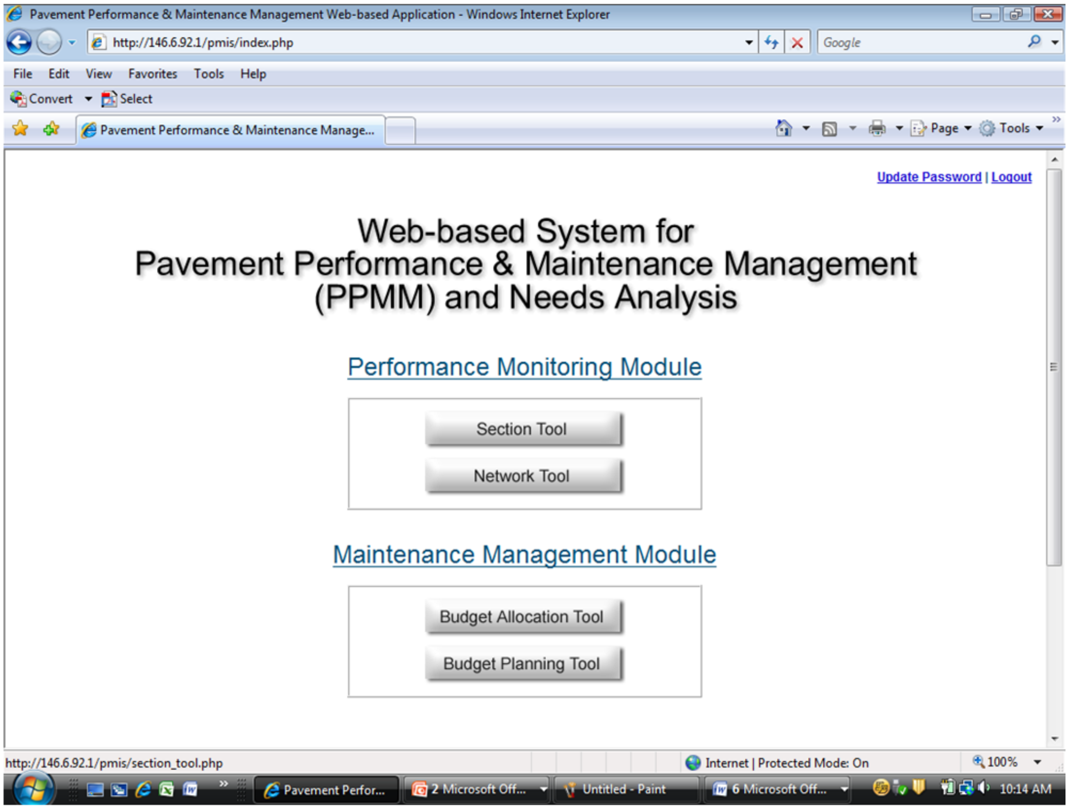
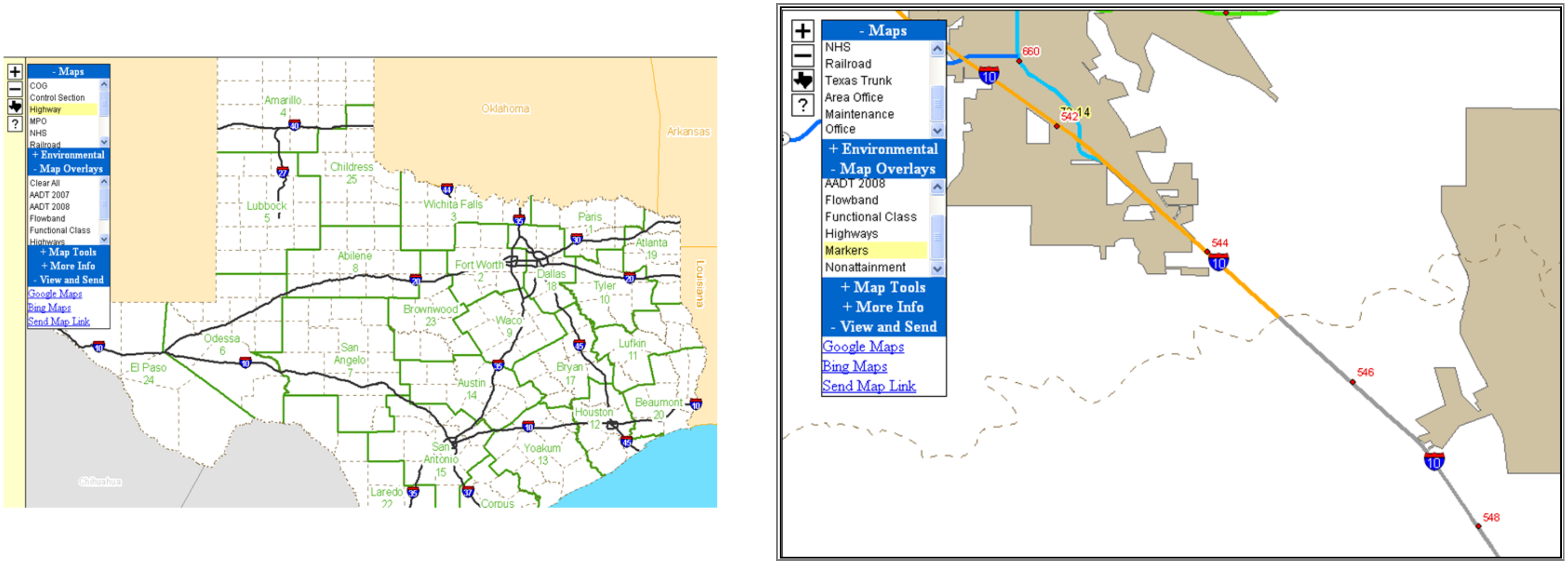


Figure 3.7: Pavement Performance & Maintenance Management menu screen

3.3.6 Aerial Maps and Other Information Sources

The Transportation Planning and Programming Division of TxDOT developed a web-based map similar to Google maps to display planning-related data. Users can pan and zoom, switch between multiple maps, overlay traffic counts, and search for and zoom to features [TxDOT 2008]. The TxDOT Statewide Planning Maps, as shown in Figure 3.8, were stored in the spreadsheet. Also, Google satellite aerial maps with the corresponding TRMs shown at the FWD test locations, as shown in Figure 3.9, were developed for each pavement section and stored in the spreadsheet.

Photos of the section or core data that depict the distressed areas were embedded in the spreadsheet when available, which helps users to understand the pavement condition along a route. Based on the availability, the other types of data used for some of the sections were construction plan sheets, Form 1084 R “Load Zoned Roadway Removal Request,” pavement design documents, GPR data, DCP data, trench data, and project-level pavement design traffic data from the Transportation Planning and Programming Division.



(a) Wide-angle view

(b) Close-up view

Figure 3.8: TxDOT statewide planning maps

[http://www.txdot.gov/apps/statewide_mapping/StatewidePlanningMap.html, Accessed November 2010]

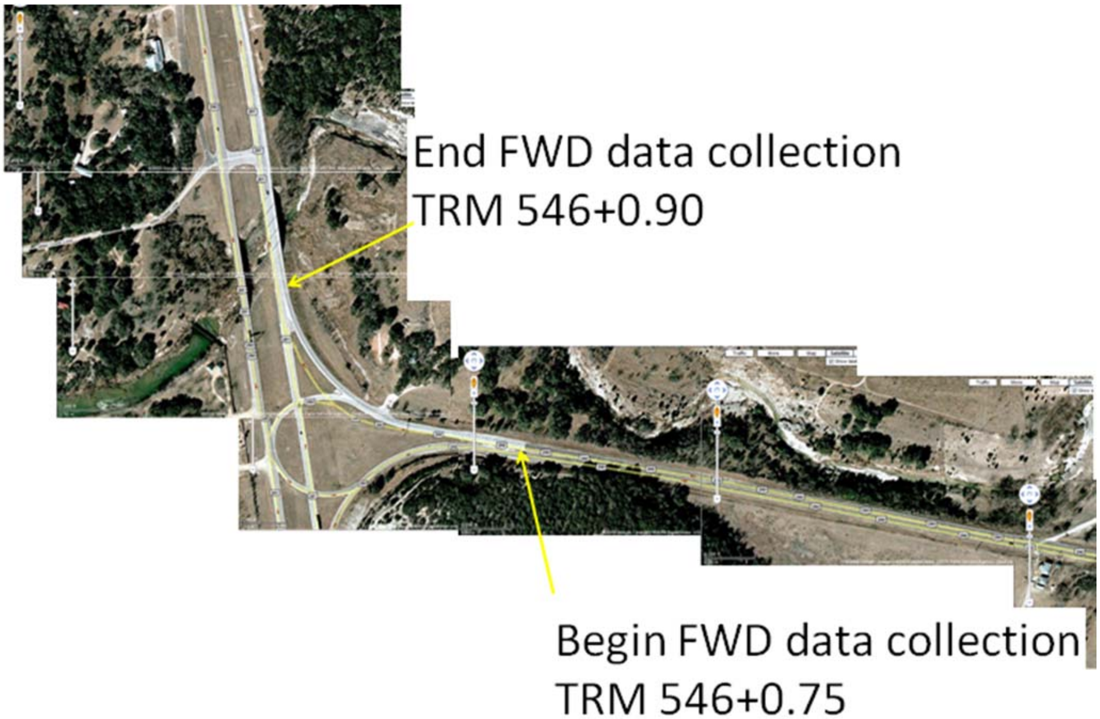


Figure 3.9: Google aerial online maps showing terrain and street system [Google 2010]

3.4 Summary

This chapter presented the data-related activities undertaken for this research. The process for data collection is discussed in this chapter. FWD data along with the supporting data for 180 pavement sections were collected from TxDOT, and summarized in a matrix chart. This chart summarizes the comprehensive sample of data, which is comprised of principle factors that could potentially affect the SCI values. The discussion of the SCI validation process, performed on the collected data, is presented in Chapter 4.

Chapter 4. Evaluation of the Structural Condition Index

4.1 Data Analysis

The SCI is a ratio of the existing/effective AASHTO Structural Number (SN_{eff}) and the required AASHTO Structural Number (SN_{req}). In order to assess the validation of the SCI, the FWD data along with the supporting data for 180 sections, as shown in Appendix B, was analyzed with an Excel workbook, where the SCI for each of the sections was calculated following the procedures defined under Project 0-4322 [Zhang 2003]. The only change is that a different SN_{req} lookup table, as shown in Table 4.1, was used in this research. This lookup table has more categories for the subgrade modulus and the estimated 20-year ESALs than the table used in the previous research. The analysis results were summarized for each pavement section and graphically presented with plots of the SCI values over the length of the pavement section, along with the cumulative frequency distributions of the SCI values as illustrated in Figure 4.1.

Table 4.1: SN_{req} Lookup Table Used in the SCI Analysis

SNreq for varying Traffic and M_r		**20 -Year Accumulated Traffic in ESALs**						
		Category		**Very Low**	**Low**	**Moderate**	**High**	**Very High**
			Range	< 1,000,000	1,000,000–3,000,000	3,000,000–10,000,000	10,000,000–30,000,000	> 30,000,000
M_r (psi)	**Subgrade Category**	**Range**	**Average**	**500,000**	**1,500,000**	**6,500,000**	**20,000,000**	**40,000,000**
	Very Poor	< 6000	**3,000**	4.4	4.9	5.9	6.9	7.5
	Poor	6,000–10,000	**8,000**	3	3.5	4.4	5.1	5.6
	Fair	10,001–14,000	**12,000**	2.5	3	3.8	4.5	5
	Good	14,001–18,000	**16,000**	2.3	2.7	3.4	4	4.5
	Very Good	> 18,000	**24,000**	2	2.3	3	3.5	4

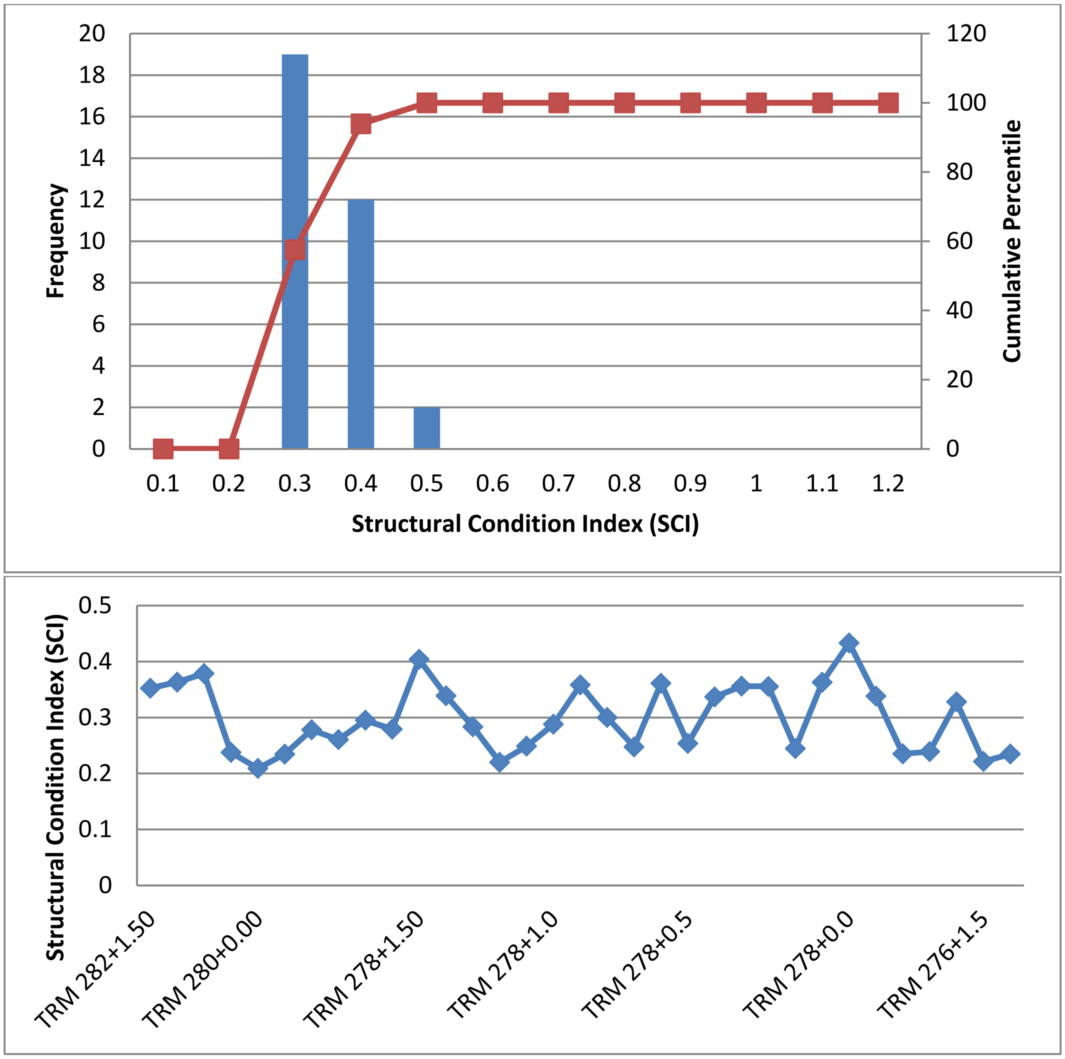


Figure 4.1: Graphical summary of the SCI results for a pavement section

To facilitate the implementation of the SCI methodology by TxDOT, an SCI algorithm tool was also developed in a macro-enabled Excel workbook using Visual Basic for Applications as shown in Appendix C. The tool acts as an interface between the SCI methodology and the users. The user can input the required data, run the SCI algorithm, and view the SCI analysis results. A user manual was also developed to aid the user in the understanding of the SCI algorithm and is attached as Appendix D.

4.2 Validation of the SCI

One of the primary objectives of this research is to validate the SCI method. As part of the validation process, the calculated SCI values were compared with those values obtained from the mechanistic analysis of the same pavement section. More detailed discussions of the mechanistic analysis are presented in this section.

The mechanistic analysis was conducted using WESLEA, a linear elastic layered theory program [Van Cauwelaert 1989]. The pavement mechanistic responses such as the stress, strain, and deflection were determined using the WESLEA program. Seven pavement sections, with 380 data points, were used in the analysis as listed in Table 4.2.

Table 4.2: Data Used in the SCI Validation Process

Route	Environmental Zone	Subgrade Soil Category	Estimated 20-year ESALs	Total Pavement Thickness (inches)
US 259 NB	Wet-Cold	Very Good	3,500,000	15.5
US 259 SB	Wet-Cold	Very Good	2,438,000	16.1
FM 486	Mixed	Poor	1,082,000	7
FM 2199	Wet-Cold	Poor	1,404,000	9
US 69 NB	Wet-Warm	Poor	10,719,000	17.5
SL 375 L2	Dry-Warm	Poor	2,798,000	13
SH 195	Mixed	Fair	10,385,000	16

4.2.1 Mechanistic Analysis

The vertical compressive strain at the top of the subgrade and the horizontal tensile strain at the bottom of the surface layer were determined at each FWD test point for the seven sections, using the WESLEA program. Based on the estimated strain values from the Asphalt Institute (AI) rutting and fatigue equations [TAI 1982], ESALs to failure was computed. It should be noted that ESALS to failure can also be computed from other models such as the Shell rutting and fatigue models. TxDOT currently uses the AI rutting and fatigue models to conduct mechanistic checks of the FPS-19W flexible pavement design solutions. Therefore, the AI rutting and fatigue models were used in this research, which are presented as Equations 4.1 and 4.2:

$$N_d = 1.365 * 10^{-9}.(\varepsilon_c)^{-4.477} \qquad (4.1)$$

Where:

N_d = Number of ESALs to rutting failure

ε_c = Vertical compressive strain at the top of the subgrade

$$N_f = 0.0796 * 10^{-9}.(\varepsilon_t)^{-3.291}.(E)^{-0.854} \qquad (4.2)$$

Where:

N_f = Number of ESALs to fatigue failure

ε_t = Horizontal tensile strain at the bottom of asphalt concrete (AC) layer

E = Surface layer modulus

Factors that represent the percentage of remaining life, analogous to the SCI, have been derived by calculating the ratio of ESALs to failure (from the AI rutting and fatigue models), and the estimated 20-year ESALs. These factors were referred to as the *rutting remaining life ratio* and the *fatigue remaining life ratio* respectively in the analysis as shown in Equations 4.3 and 4.4.

$$\textit{Rutting Remaining Life Ratio} = \frac{\textit{Number of ESALs to rutting failure}}{\textit{Estimated 20-year ESALs}} \tag{4.3}$$

$$\textit{Fatigue Remaining Life Ratio} = \frac{\textit{Number of ESALs to fatigue failure}}{\textit{Estimated 20-year ESALs}} \tag{4.4}$$

4.2.2 Validation Analysis Results

The SCI validation was conducted using the seven pavement sections listed in Table 4.2. However, for the discussions in this section, the focus is on four particular cases that broadly represent the pavement types expected to affect the SCI values. The four pavement types considered in the discussion are as follows: (a) thick asphalt concrete surface—US 69 NB, (b) thin asphalt concrete surface—FM 486, (c) thick surface-treated—US 259 NB, and (d) thin surface-treated—FM 2199. For the purposes of this validation, a pavement structure having a total pavement thickness greater than 10 inches was considered "thick," and the one having a total pavement thickness less than 10 inches was considered "thin."

A non-linear regression was performed for each of the cases to determine the correlation between the rutting/fatigue remaining life ratio and the SCI values. The rutting/fatigue remaining life ratios were computed for each of the FWD test points and then compared to the SCI value for the same point. The coefficient of determination (R^2) was used for comparison. The regression graphs for the thick and thin pavement structures were plotted separately as shown in Figure 4.2 and Figure 4.3. The initial observations made from the regression graphs were that the SCI values are more correlated to the rutting and fatigue remaining life ratios for the thick pavement structures than for the thin pavement structures. The values of R^2 for the thick pavement structures were in the range of 0.8–0.9 whereas the R^2 values for the thin pavement structures were in the range of 0.6–0.7. Given that the validity of the SCI methodology cannot be simply judged from the R^2 values, hypothesis testing was conducted for the four pavement types to further support the validation process.

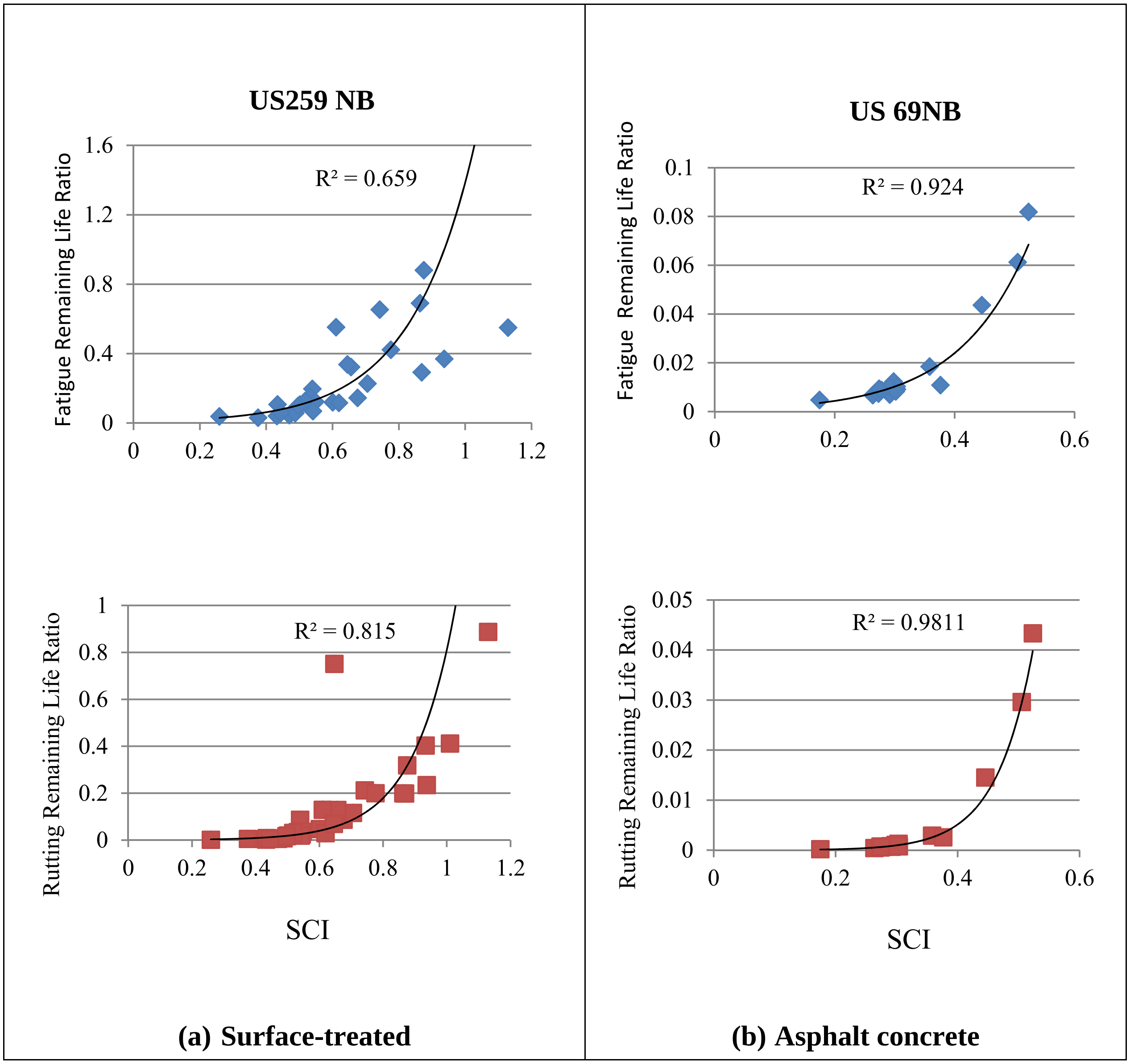


Figure 4.2: Correlation between the fatigue/rutting remaining life ratios and the SCI values for a thick pavement structure

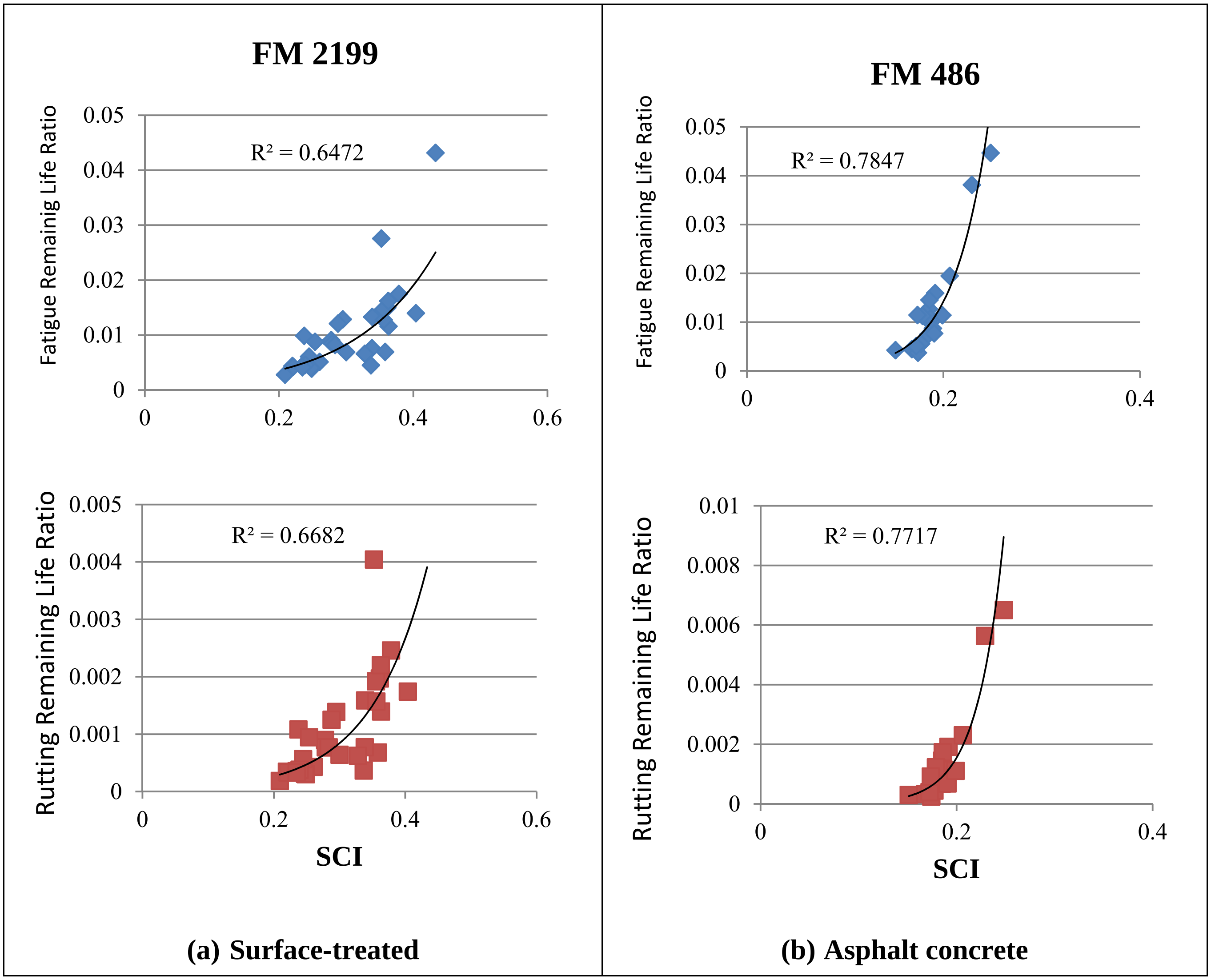


Figure 4.3: Correlation between the fatigue/rutting remaining life ratios and the SCI values for a thin pavement structure

For purposes of determining the statistical significance of the coefficient of determination (R^2), a t-test was conducted for each of the four pavement types using Equation 4.5. The null hypothesis used in the analysis was that there is no correlation between the SCI values and the fatigue/rutting ratios. The results from the t-test showed that this null hypothesis was rejected with a 99% confidence level using a two-tailed t-distribution in all cases as shown in Table 4.3. Therefore, it was concluded that the SCI values and the fatigue/rutting ratios are correlated, thereby validating the SCI methodology.

$$t = \frac{R\sqrt{n-2}}{\sqrt{1-R^2}} \qquad (4.5)$$

Where:

t = t-test statistic

R^2 = coefficient of determination

n = sample size

Table 4.3: Hypothesis Testing Results for the Four Pavement Types

Section	Pavement Type	R^2		Sample Size (n)	Null Hypothesis Result
		SCI vs. Fatigue Remaining Life Ratio	SCI vs. Rutting Remaining Life Ratio		
US 259 NB	Thick surface-treated	0.659	0.815	34	Reject
US 69NB	Thick AC	0.924	0.9811	33	Reject
FM 2199	Thin surface-treated	0.6472	0.6682	20	Reject
FM 486	Thin AC	0.7847	0.7717	19	Reject

The validation procedure until this point looked at the four pavement types separately: thick surface-treated, thick asphalt concrete, thin surface-treated, and thin asphalt concrete. To verify whether the SCI validation results hold even when all the four pavement types are grouped together as one, another regression was carried between the fatigue/rutting ratios and the SCI values. The coefficient of determination (R^2) was computed for the four pavement types grouped together, as shown in Figure 4.4. The results indicated that a high correlation exists between the SCI values and the fatigue/rutting ratios. Based on the relationship between the structural condition from the mechanistic analysis method and the SCI values for the entire group of pavements, the SCI can be further confirmed as a reliable index.

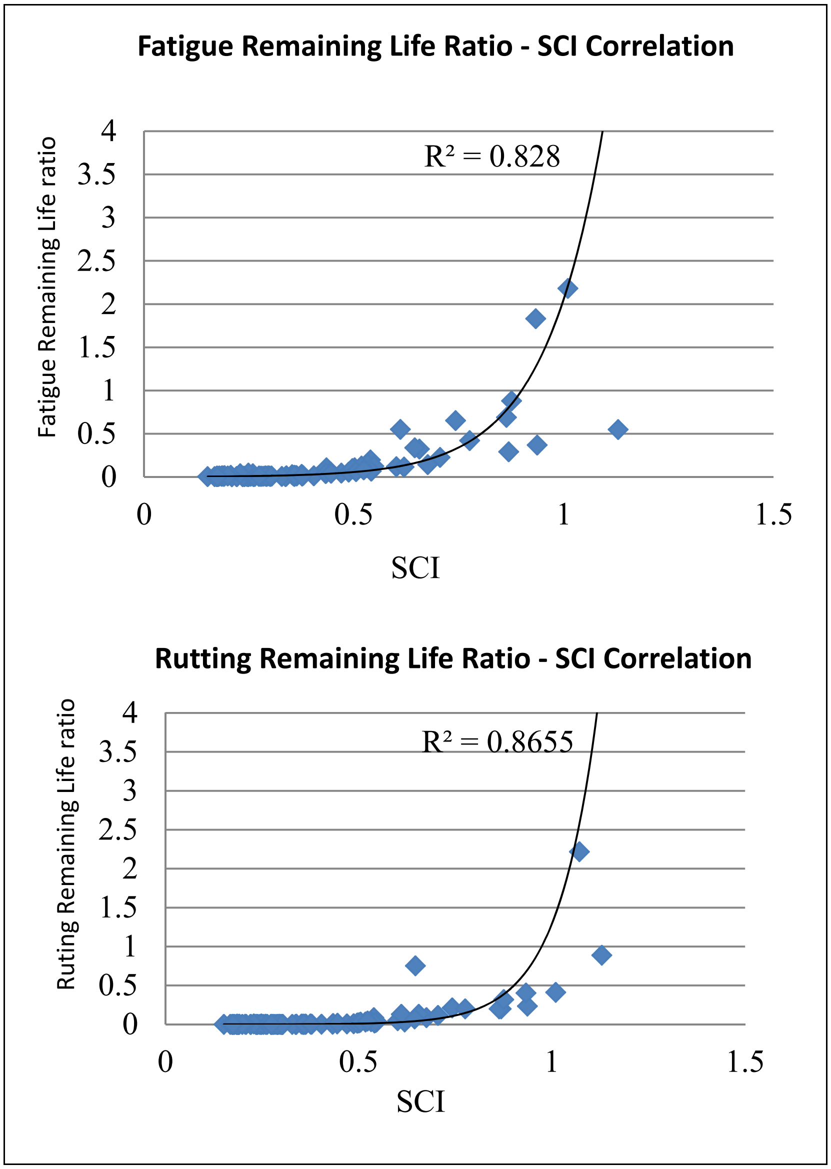
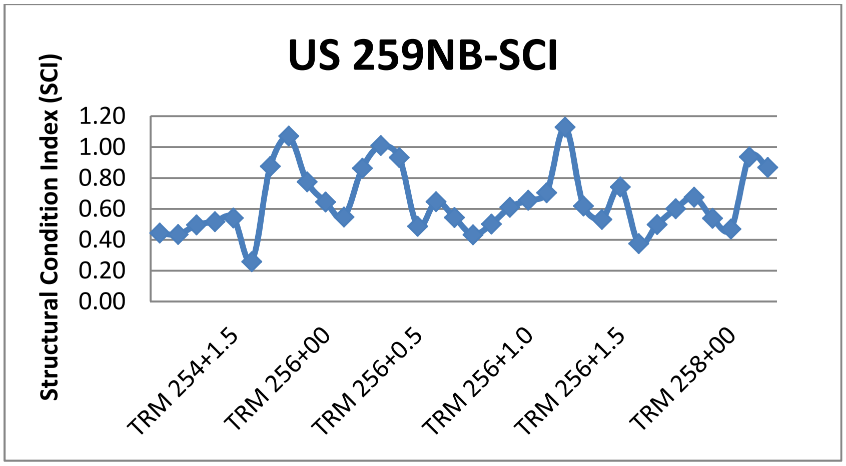
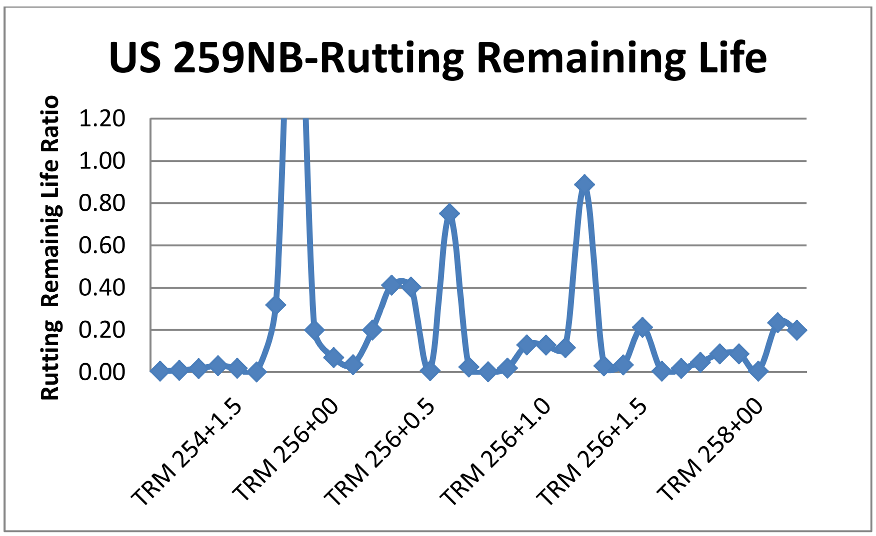


Figure 4.4: Correlation between the SCI values and the fatigue/rutting remaining life ratios for the grouped pavements

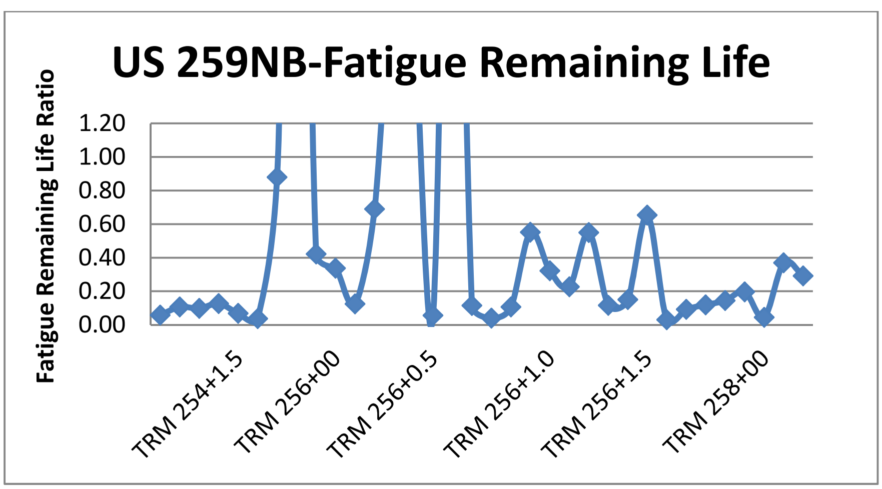
The trends observed for the SCI values, the fatigue remaining life ratio, and the rutting ratio for the thick and thin pavement structures are plotted in Figure 4.5 and Figure 4.6 respectively. It was found that the trend of the SCI values is the same as the trends for fatigue remaining life ratio and rutting ratio, along the same pavement section. Also, the peaks in the SCI graph correspond to the peaks in the mechanistic graphs. Generally, a change in the thickness of a pavement structure or a patch at the FWD test point results in unusual performance in comparison to the neighboring data of a pavement section. As an example, the total pavement thickness was found to vary along the US 259 NB section, which resulted in the peak points as seen in Figure 4.5a. Similar observations were made about the pavement structural condition using both the SCI method and the mechanistic method. These observations are further a positive confirmation about the rational results obtained from the SCI methodology.


US 259NB-SCI
Structural Condition Index (SCI)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
TRM 254+1.5
TRM 256+00
TRM 256+0.5
TRM 256+1.0
TRM 256+1.5
TRM 258+00

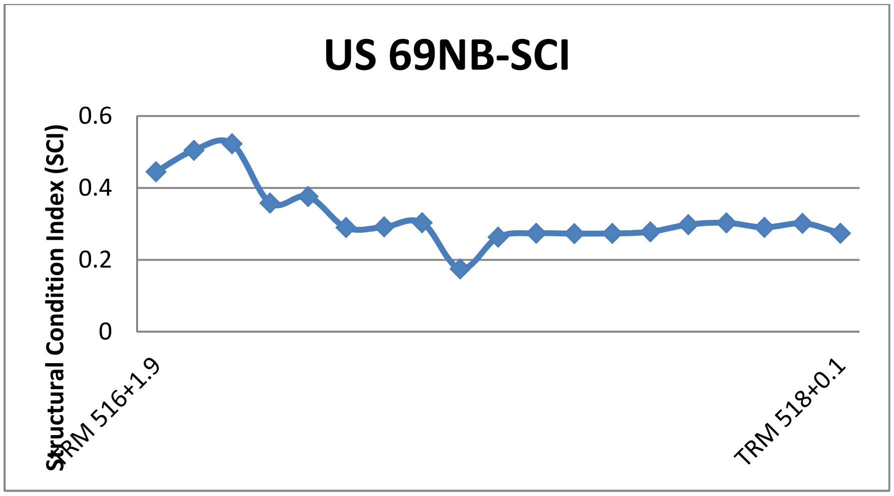
(a)


US 259NB-Rutting Remaining Life
Rutting Remainig Life Ratio
1.20
1.00
0.80
0.60
0.40
0.20
0.00
TRM 254+1.5
TRM 256+00
TRM 256+0.5
TRM 256+1.0
TRM 256+1.5
TRM 258+00

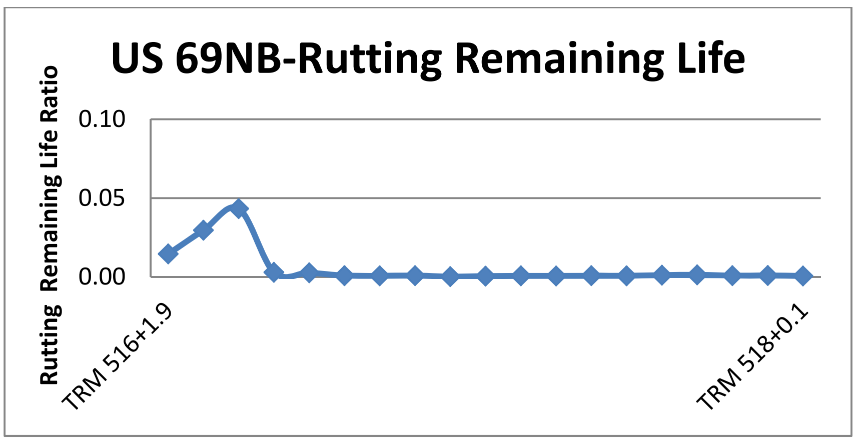
(b)


US 259NB-Fatigue Remaining Life
Fatigue Remaining Life Ratio
1.20
1.00
0.80
0.60
0.40
0.20
0.00
TRM 254+1.5
TRM 256+00
TRM 256+0.5
TRM 256+1.0
TRM 256+1.5
TRM 258+00

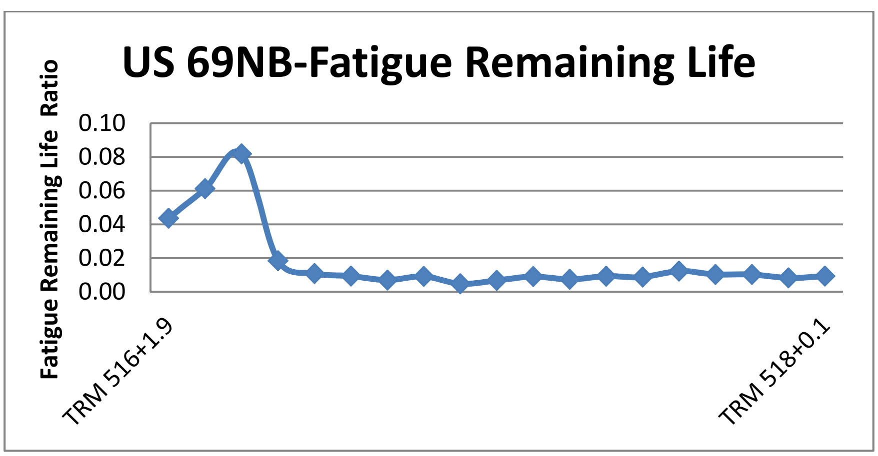
(c)



(d)

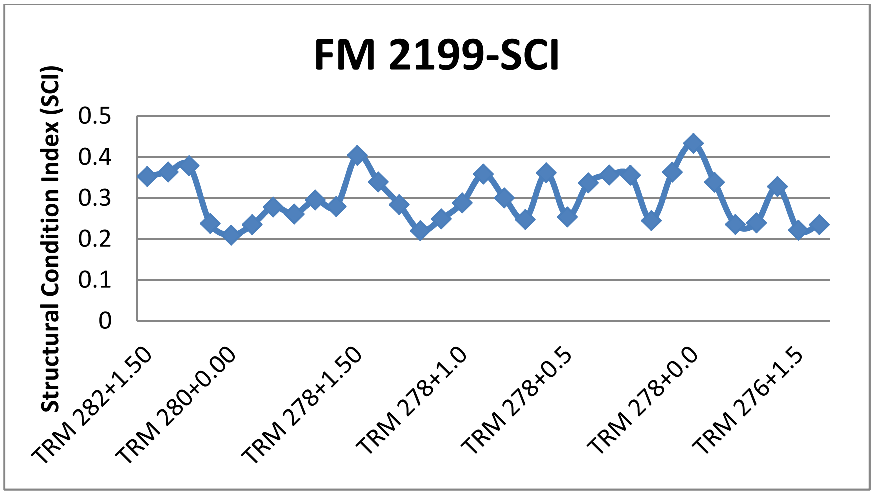


(e)

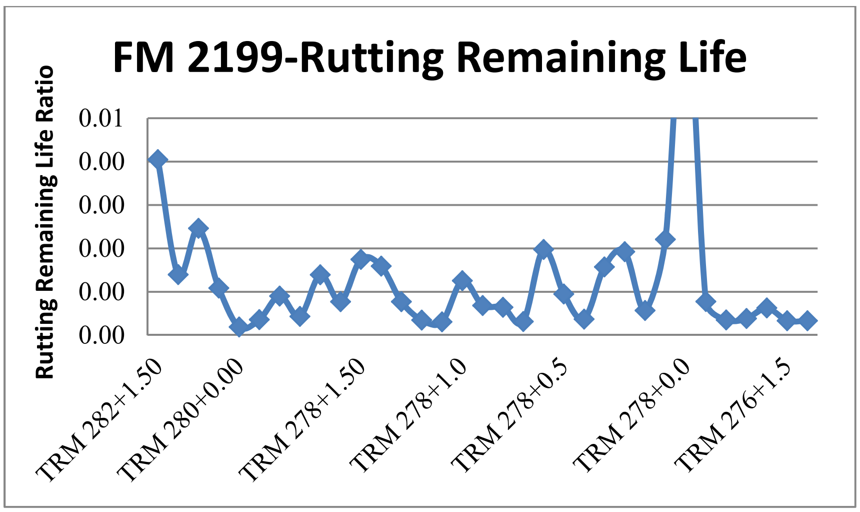


(f)

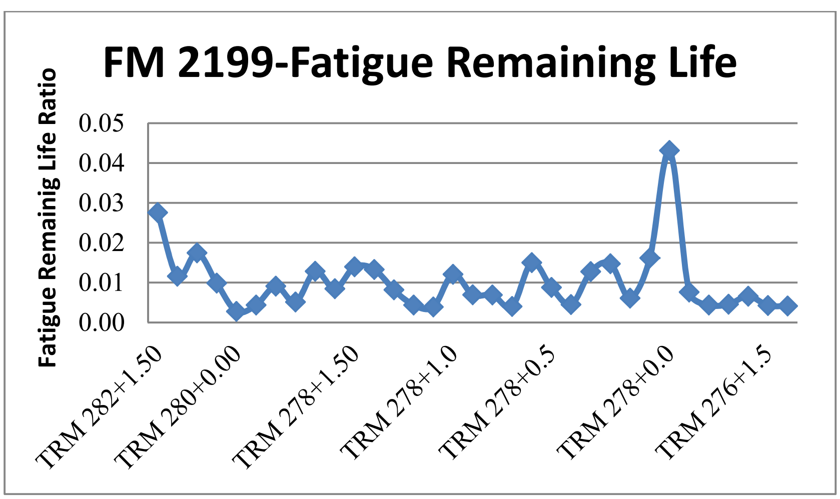
Figure 4.5: Comparison of trends between the fatigue/rutting remaining life ratios and the SCI values for two thick pavement structures (US 259NB and US 69NB)


FM 2199-SCI
Structural Condition Index (SCI)
0.5
0.4
0.3
0.2
0.1
0
TRM 282+1.50
TRM 280+0.00
TRM 278+1.50
TRM 278+1.0
TRM 278+0.5
TRM 278+0.0
TRM 276+1.5

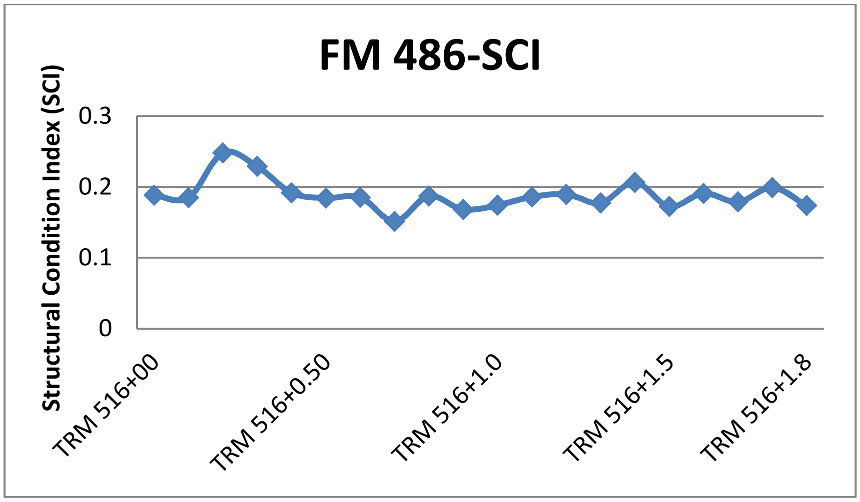
(a)


FM 2199-Rutting Remaining Life
Rutting Remaining Life Ratio
0.01
0.00
0.00
0.00
0.00
0.00
TRM 282+1.50
TRM 280+0.00
TRM 278+1.50
TRM 278+1.0
TRM 278+0.5
TRM 278+0.0
TRM 276+1.5

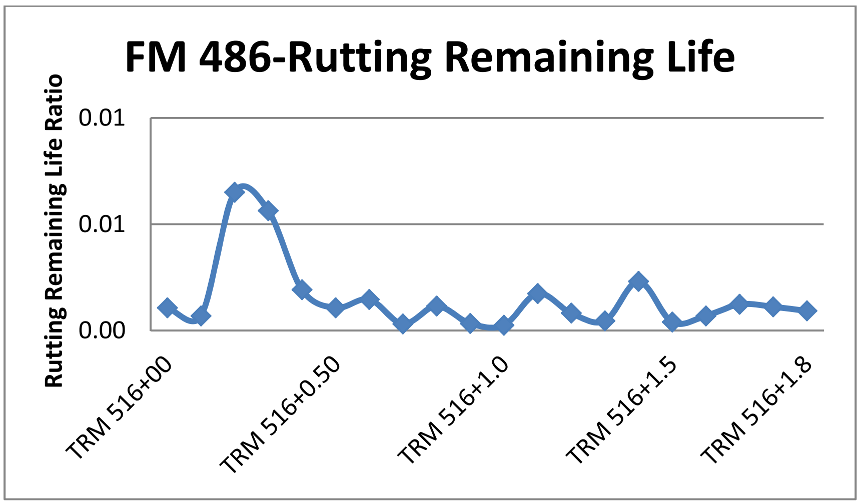
(b)


FM 2199-Fatigue Remaining Life
Fatigue Remainig Life Ratio
0.05
0.04
0.03
0.02
0.01
0.00
TRM 282+1.50
TRM 280+0.00
TRM 278+1.50
TRM 278+1.0
TRM 278+0.5
TRM 278+0.0
TRM 276+1.5

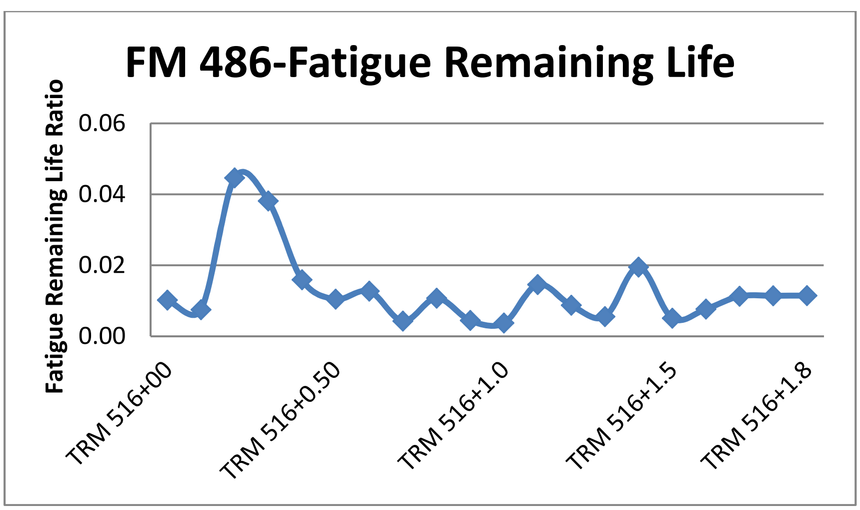
(c)



(d)



(e)



(f)

Figure 4.6: Comparison of trends between the fatigue/rutting remaining life ratios and the SCI values for two thin pavement structures (FM 2199 and FM 486)

4.3 Sensitivity of SCI to Total Pavement Thickness

The total pavement thickness information is used as an input in the SCI method and is obtained from multiple sources such as the GPR or coring. However, it is very probable that the pavement thickness estimates are not accurate because of factors such as construction practices, among others. Hence, an analysis was undertaken to estimate the expected error in the SCI values due to error in the total pavement thickness estimates.

The SCI is a ratio of the effective SN (SN_{eff}) to the required SN; the SN_{eff} is dependent on the total pavement thickness information. Using these relationships, the change in the SCI estimate due to the change in the total pavement thickness was determined via the sensitivity analysis using Equations 4.6a to 4.6e. SN_{eff} is also dependent on the pavement surface type: surface-treated or asphalt concrete. Thus, the SCI error estimates will vary according to the pavement surface type. Based on the Equation 4.6e, a generalized trend showing the sensitivity of the SCI error estimates for different pavement surface type is plotted in Figure 4.7.

$$SCI = \frac{SN_{eff}}{SN_{req}} \qquad (4.6a)$$

$$SN_{eff} = f(H_p) = k_1 \times SIP^{k_2} \times H_p^{k_3} \qquad (4.6b)$$

Where:

k₁, k₂, and k₃ → k_1, k_2, and k_3	=	Regression coefficients [Rohde 1994]
SIP	=	Structural index of pavement [Rohde 1994]
H_p	=	Total pavement thickness

$$SCI = c \times H_p^{k_3} \qquad (4.6c)$$

Where:

$$c = \frac{k_1 \times SIP^{k_2}}{SN_{req}}$$

$$\ln(SCI) = \ln(c) + k_3 \times \ln(H_p) \qquad (4.6d)$$

$$\frac{\Delta SCI}{SCI} = k_3 \times \frac{\Delta H_p}{H_p} \qquad (4.6e)$$

Where:

k_3 = 0.7581 and 0.8241 for surface-treated and asphalt concrete pavement surface respectively

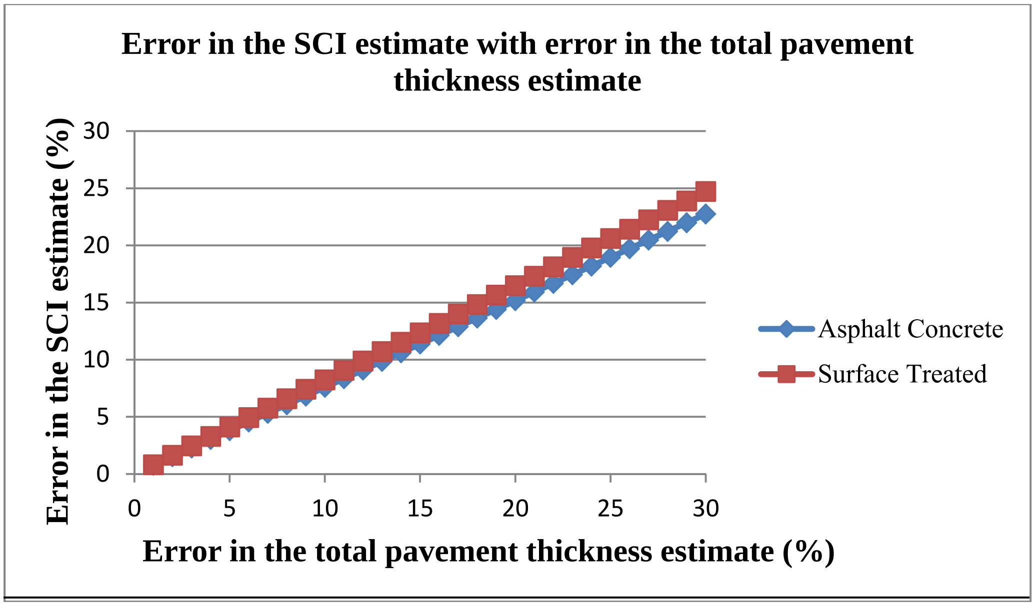


Figure 4.7: Sensitivity of the SCI estimate to the total pavement thickness estimate

To quantify the error for the SCI estimate using Figure 4.7, field data on the expected pavement thickness error is required. Certain assumptions on the total pavement thickness variability were made using an engineering judgment. Table 4.4 summarizes the assumed variability in the total pavement thickness and the corresponding expected error in the SCI estimates. The results indicated that there is a significant impact on the SCI estimate with variability in the total pavement thickness estimate.

Table 4.4: Sensitivity of the SCI Estimate to the Total Pavement Thickness Estimate

Pavement type	Assumed total pavement thickness variability (%) $\left(\frac{\Delta H_p}{H_p} * 100\right)$	Expected error in the SCI estimate (%) $\left(\frac{\Delta SCI}{SCI} * 100\right)$	
		Surface-treated	Asphalt Concrete
Surface-treated	10–15	7.58–11.37	7.58–12.36
Asphalt concrete pavement	10–15	7.58–12.36	7.58–12.36

4.4 Effect of Shallow Bedrock on Structural Condition Index

The SCI calculations are dependent on the FWD deflection data. Large FWD deflections at the seventh sensor (W_7) location (72 in. from the load plate) are usually related to a weaker subgrade. However, based on experience with Texas' conditions, low W_7 values may be due to either a strong subgrade or a weak subgrade over relatively shallow bedrock. Hence, this analysis was undertaken to determine whether the calculated SCI values for a pavement structure with shallow bedrock allow for a different interpretation of the same pavement structure with deep bedrock.

The subgrade modulus, the total pavement thickness, and the bedrock depth are the three important factors used for the analysis. Based on the literature review and discussions with the Project Director, these factors were broadly categorized as shown in Table 4.5.

Table 4.5: Factors Considered in the Bedrock Depth Analysis

Subgrade Modulus (ksi)	Total Pavement Thickness (inches)	Bedrock Depth (inches)
Weak (<8 ksi)	Thin (<10”)	Shallow (<60”)
Strong (>14 ksi)	Intermediate (10–16”)	Intermediate (60–180”)
	Thick (>16”)	Deep (>180”)

4.4.1 Data Source

The researchers initially planned to conduct the analysis with bedrock depth measurement data (e.g., using auger or DCP measurements) collected on in-service pavement sections. However, due to the lack of pavement sections with actual bedrock depth measurements, the analysis was conducted using a comprehensive set of FWD deflection data calculated with the BISAR program [de Jong 1973]. BISAR is a linear elastic layered theory program that computes mechanistic responses such as deflections, stresses, and strains within a pavement structure. This program was used to analyze over 7 million hypothetical pavement structures in a previous research [Murphy 1998]. These pavement structures were modeled based on the survey information from the TxDOT District and Division personnel about the layer thicknesses and the material types used in Texas. The resulting data was stored in a SYBASE SQL database named NETFWD [Murphy 1998].

An example of the NETFWD database output is shown in Figure 4.8, which lists the pavement layer thicknesses, the moduli values, depth to rigid layer, and the FWD deflections for over 400,000 pavement structures with a surface modulus of 450 ksi. As Figure 4.8 shows, with all other factors held constant, the FWD deflections increase as the depth to rigid layer decreases. The SCI index is directly related to the FWD deflections. Therefore, it is important to determine whether these changes in FWD deflections due to changes in the bedrock depth would affect the conclusions about the pavement structural condition.

K31 fx 7.99

	Surf Thickness	Base Modulus	Base Thickness	Subgrade Modulus	Subgrade Thickness	Total Pavt Thk	w1	w2	w3	w4	w5
2	2.5	15	6	4	30	8.5	53.7	28.2	10.3	3.21	0.61
3	2.5	15	6	4	40	8.5	57.1	31.4	12.9	5.01	1.69
4	2.5	15	6	4	50	8.5	59.5	33.7	14.9	6.53	2.75
5	2.5	15	6	4	60	8.5	61.2	35.4	16.4	7.78	3.72
6	2.5	15	6	4	70	8.5	62.6	36.6	17.5	8.81	4.56
7	2.5	15	6	4	80	8.5	63.6	37.7	18.5	9.66	5.29
8	2.5	15	6	4	90	8.5	64.4	38.5	19.3	10.4	5.91
9	2.5	15	6	4	100	8.5	65.1	39.2	19.9	11	6.46
10	2.5	15	6	4	110	8.5	65.7	39.7	20.5	11.5	6.93
11	2.5	15	6	4	120	8.5	66.2	40.2	20.9	11.9	7.34
12	2.5	15	6	4	130	8.5	66.6	40.6	21.3	12.3	7.7
13	2.5	15	6	4	140	8.5	67	41	21.7	12.7	8.02
14	2.5	15	6	4	150	8.5	67.3	41.3	22	13	8.31
15	2.5	15	6	4	180	8.5	68.1	42.1	22.8	13.7	9

Figure 4.8: NETFWD database

4.4.2 Experiment

In order to make the analysis practical, a total of 104 pavement sections were selected from the initial 400,000 pavement sections obtained from the NETFWD database. These 104 pavement sections included a range of bedrock depths from 40 in. to 720 in. The existing/effective SN_{eff} was calculated using the AASHTO material stiffness coefficient and thickness equation as shown in Equation 4.7. Table 4.6 shows the assumptions about the material stiffness coefficients for asphalt concrete pavement (ACP) surface and base, which were made using the AASHTO guide for the design of Pavement Structures [AASHTO 1986].

$$SN = a_1 d_1 + \sum_{i=1}^{n} a_i d_i m_i \tag{4.7}$$

Where:

SN = Structural Number

a_i = Structural layer coefficients

d_i = Layer thickness

m_i = Moisture coefficients (assumed to be 1.0 for this analysis)

Table 4.6: AASHTO Material Stiffness Coefficients

Material type	Modulus(ksi)	AASHTO coefficient
ACP	450	0.44
Flexible base	<90	0.14
Lime-stabilized base	120–240	0.20
Cement-stabilized base	500–1,000	0.30

4.4.3 Assumptions about the Traffic Information

The required AASHTO SN_{req} is calculated from the M_R and the traffic information [AASHTO 1993]. The TxDOT PMIS database has traffic information for in-service pavements. However, this analysis was based on modeled pavement structures from the NETFWD, and thus the traffic information cannot be obtained from the TxDOT PMIS. Hence, based on an engineering judgment, the traffic assumptions were made using the available thickness information as shown in Table 4.7.

Table 4.7: Assumptions of Traffic Information Based on the Total Pavement Thickness

Total Pavement Thickness (inches)	Traffic Category	Range of Traffic (20-year ESALs)
Thin pavements (<10”)	Low traffic	1,000,000–3,000,000
Intermediate pavements (10–16”)	Medium traffic	3,000,000–10,000,000
Thick pavements (>16”)	High traffic	10,000,000–30,000,000

The SCI values were thus computed as a ratio of SN_{eff} and SN_{req}. The SN_{eff} was calculated from the AASHTO’s material stiffness and thickness equation and the SN_{req} was calculated using the subgrade modulus (determined by the AASHTO method) and the assumed traffic, which was linked to the total pavement thickness.

4.4.4 Observations Made from the Analysis

The following observations were made from the analysis:

- The SCI values tend to decrease as the bedrock depth increases with other factors, such as the subgrade modulus and the total pavement thickness, held constant, as shown in Figure 4.9. Also, the SCI values tend to stabilize at relatively lower bedrock depths for a pavement structure on a weak subgrade than for the same pavement structure on strong subgrade.

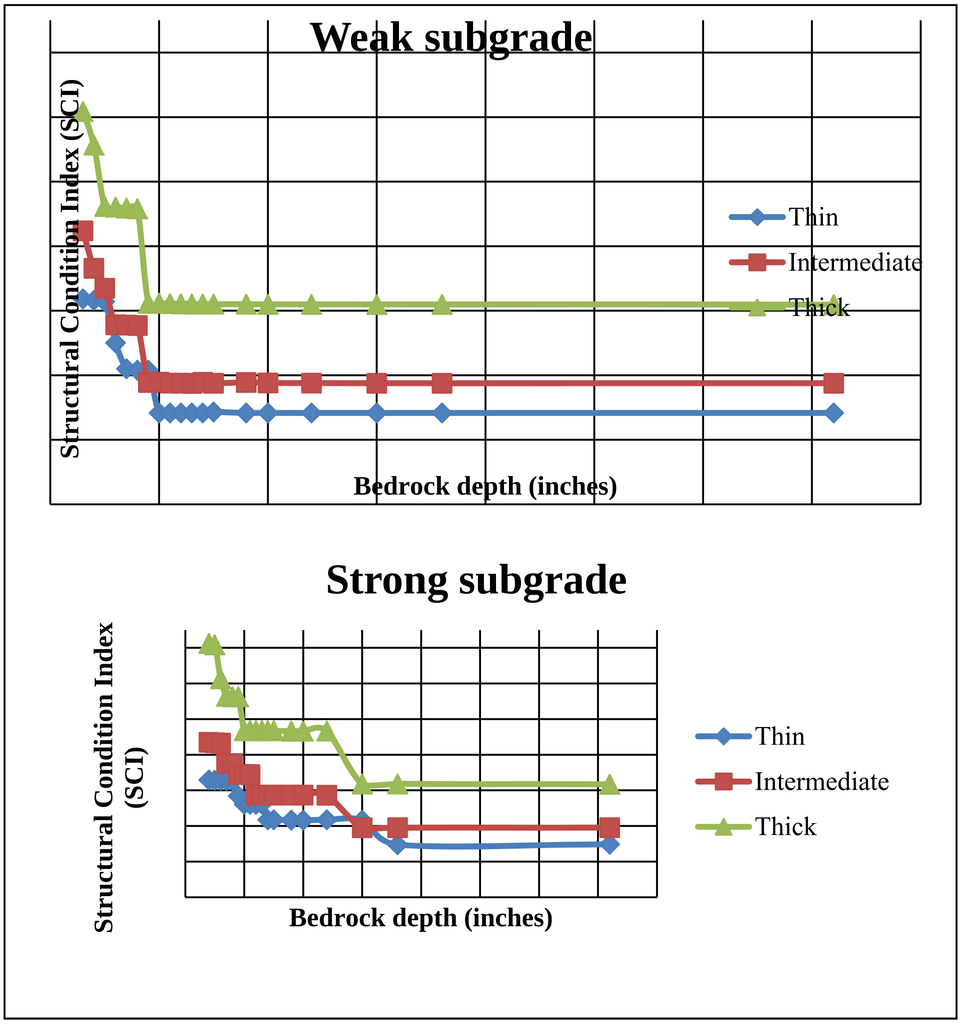


Figure 4.9: Effect of the bedrock depth on the SCI values

- *Thin/intermediate pavement structures on a weak/strong subgrade:* The effect of the bedrock depth on the SCI values was found to have a significant impact on intermediate and thin pavement structures, which are over either a weak or strong subgrade. From Figure 4.9, it can be observed that the SCI values are greater than 1 at shallow bedrock depths for both types of subgrade, indicating that thin and intermediate pavement structures are structurally adequate at shallow bedrock depths. However, the interpretation changes as the bedrock depth increases beyond 100 in. In this scenario, the SCI values for the thin and intermediate pavement structures are below the threshold value of 1, indicating that the pavement structures are structurally inadequate. Thus, the structural interpretations of the same thin/intermediate pavement structures on both types of subgrade over shallow and deep bedrock depths are very different.
- *Thick pavement structures on a weak/strong subgrade*: On the other hand, the thick pavement structure is structurally sound at both shallow and deep bedrock depths on either a weak or a strong subgrade. At shallow bedrock depths, the SCI values

for a thick pavement structure are around 2, which indicates that the pavement structure is substantially over-designed from an engineering point of view. However, at larger bedrock depths, the same thick pavement structure is structurally sound and only slightly over-designed.

- The sensitivity of the SCI to the bedrock depth with varying subgrade modulus and total pavement thickness is summarized in Table 4.8, where “Yes” is stated when there is a change in the SCI value with bedrock depth; otherwise, “No” is stated.

Table 4.8: Effect of the Bedrock Depth on the SCI Values

Thin Pavements (<10”)										
Bedrock Depth (inches)	40	50	60	70	80	90	100	120	240	300
Weak Subgrade (<8ksi)	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No
Strong Subgrade (>14 ksi)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Intermediate Pavements (10–16”)										
Bedrock Depth (inches)	40	50	60	70	80	90	100	120	240	300
Weak Subgrade (<8ksi)	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No
Strong Subgrade (>14 ksi)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Thick Pavements (>16”)										
Bedrock Depth (inches)	40	50	60	70	80	90	100	120	240	300
Weak Subgrade (<8ksi)	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No
Strong Subgrade (>14 ksi)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes

4.5 Conclusions

This chapter discussed the SCI validation process carried out using the mechanistic analysis. The percent-remaining-life factors, called the fatigue remaining life ratio and the rutting ratio, were derived using the AI fatigue and rutting equations respectively. A non-linear regression analysis wasconducted with these ratios and the SCI values on the four pavement types: thick asphalt concrete, thick surface-treated, thin asphalt concrete, and thin surface-treated; and the grouped pavements (four pavement types together). This analysis shows that a correlation exists, indicating that the SCI method provides rational results. The results for hypothesis testing on the statistical significance of the correlation further validate the SCI method.

Given that the total pavement thickness changes with factors such as the age of the pavement, construction practices, etc., a significant error can be associated with the total pavement thickness estimates. The total pavement thickness is used as an input in the SCI methodology and hence, the expected error in the SCI estimate was discovered using the sensitivity analysis.

An analysis to determine the effect of the shallow bedrock depth on the SCI analysis was also undertaken using the NETFWD-modeled pavement structures. The results show that the SCI values tend to decrease as the bedrock depth increases with other factors, such as the subgrade modulus and the total pavement thickness, held constant. The results indicate that the thin and intermediate pavement structures on a weak/strong subgrade over shallow bedrock depths are structurally sound; however, the same pavement structures are found to be structurally inadequate at higher bedrock depths. At shallow bedrock depths, the thick pavement structure is identified as an over-designed pavement structure from an engineering point of view. However, at larger bedrock depths, the same thick pavement structure is structurally sound and slightly over-designed. These results thus conclude that the shallow bedrock depth plays a significant role in affecting the SCI values.

Chapter 5. Characterizing the Representative SCI Value of a Section

5.1 Introduction

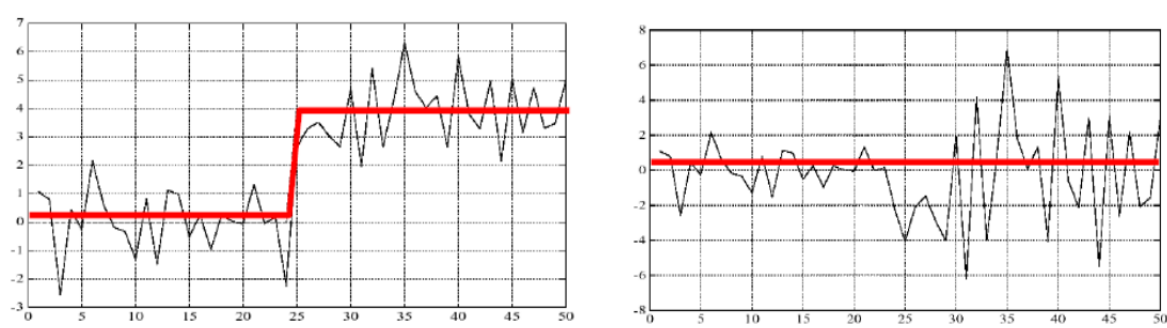
The SCI values are not uniform along a pavement section because of the variations in both the pavement structure and the subgrade soil condition. An average SCI score for a one-mile-long pavement section based on individual SCI values obtained at multiple stations may not adequately capture the condition variability within the section, and could result in an incorrect assessment of the structural capacity of the pavement. A methodology characterizing the representative value of a section should account for these variations. The need to quantify such variability has led to the use of the segmentation techniques in this research.

Homogeneous segments can be determined by identifying points at which a change in the mean or variance of the dataset occurs [Sergio 2009]. The objective of this chapter is to propose a segmentation technique to characterize the representative SCI value of a pavement section. This chapter includes a brief discussion of the three segmentation methodologies to be considered. They are as follows:

- Cumulative Sums (CUMSUM);
- Absolute difference in sliding mean values; and
- Cumulative Difference Approach (CDA).

5.2 Segmentation Methods

The main principle of a segmentation technique is to identify a homogeneous segment by analyzing changes in the mean or variance of the data series. Following are the two basic scenarios that can be observed in a data series: change in mean under a constant variance or change in variance under a constant mean. The borders of a homogeneous segment are usually identified by considering either one of two scenarios as shown in Figure 5.1.



(a) Mean changes and constant variance

(b) Variance changes and constant mean

Figure 5.1: Type of changes in a data series [Sergio 2009]

5.2.1 Method I—Cumulative Sums (CUMSUM)

The CUMSUM method is based upon the comparison of the measured data with a target value. The user has the flexibility to choose the target value, which can be an arithmetic mean of the dataset, threshold value, etc. Break points are created when the trend of the CUMSUM value changes. The following formula is used in this method:

$$CUMSUM_i = (CUMSUM_{i-1} - X_t) + X_i \tag{5.1}$$

Where:
X_t = Target value
X_i = Measured value of a data point

5.2.2 Method II—Absolute Difference in Sliding Mean Values

This method as illustrated in Figure 5.2 involves the smoothing of the data series, which is followed by the data series analysis [Rubensam 1996]. The smoothing function is given as follows:

$$y_i = \frac{1}{2q+1} \sum_{i=i-q}^{i+q} x_i \tag{5.2}$$

Where:
y_i = Smoothed data
x_i = Measured data value
q = Number of neighboring elements to be weighted

The absolute differences are then calculated between the *"d"* neighbors contained in the smoothed function. It should be noted that this method does not give any guidelines about the *"d"* window.

$$z_i = |y_i - y_{i+d}| \tag{5.3}$$

Where:
z_i = Series of absolute difference
d = Number of elements between y_i and y_{i+d}

A threshold value ($z_{threshold}$) is then selected by the user, playing the role of a target value for the absolute difference series (z_i). The position of maxima in z_i above $z_{threshold}$ indicate the borders of the homogeneous segments.

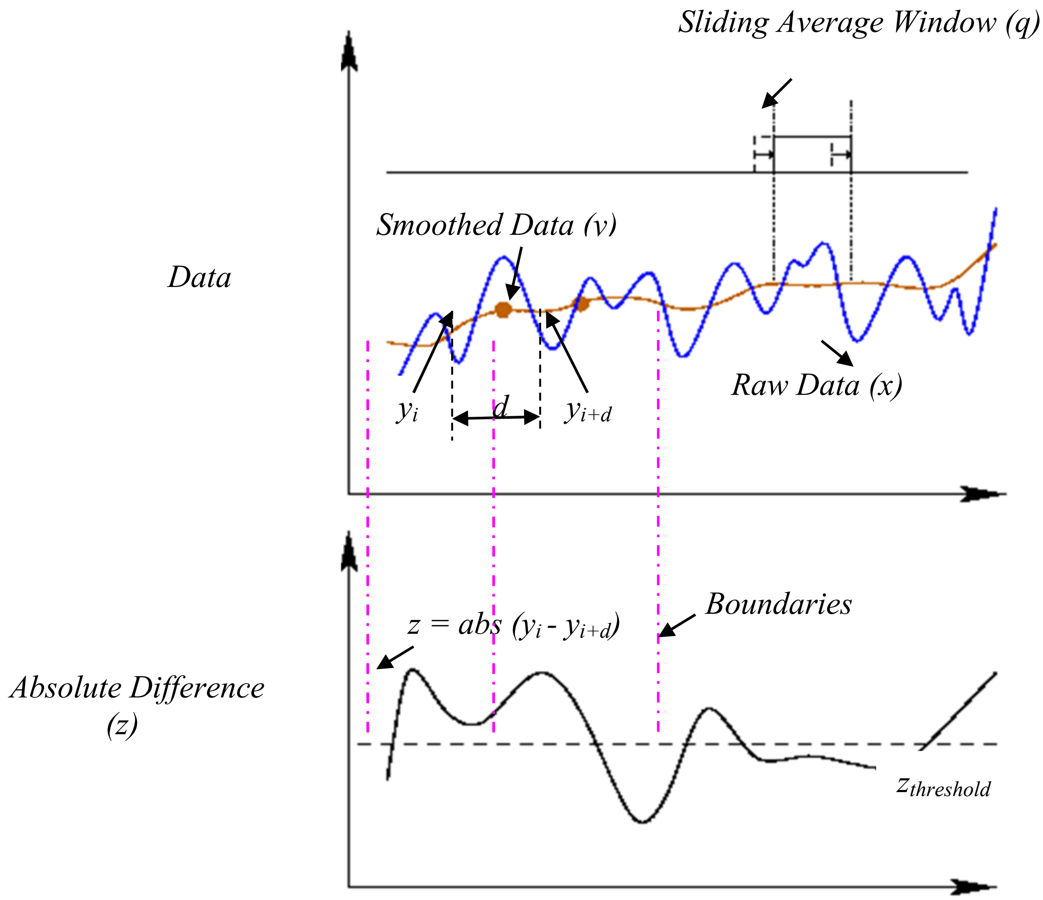


Figure 5.2: Graphical representation of the absolute difference in sliding mean values method

5.2.3 Method III—Cumulative Difference Approach (CDA)

The CDA, as illustrated in Figure 5.3, is a graphical method that helps detect the homogeneous segments [AASHTO 1986]. From the statistic Z_x, the difference between the cumulative area under the curve of a data series and the cumulative mean area is calculated, using Equation 5.4. The homogeneous segment borders are defined by the points where the slope of Z_x changes its sign.

$$Z_X = \sum_{i=1}^{n} a_i - \left[\frac{\sum_{i=1}^{n} a_i}{L_p} \right] \sum_{i=1}^{n} x_i ; a_i = \left[\frac{r_{i-1} + r_i}{2} \right] x_i . \tag{5.4}$$

Where:

x_i = Distance between an i^{th} data point and the first data point
n = n^{th} pavement response measurement
n_t = Total number of pavement response measurements
r_i = Value of the segmented characteristic of the pavement section
L_p = Total length of the pavement section

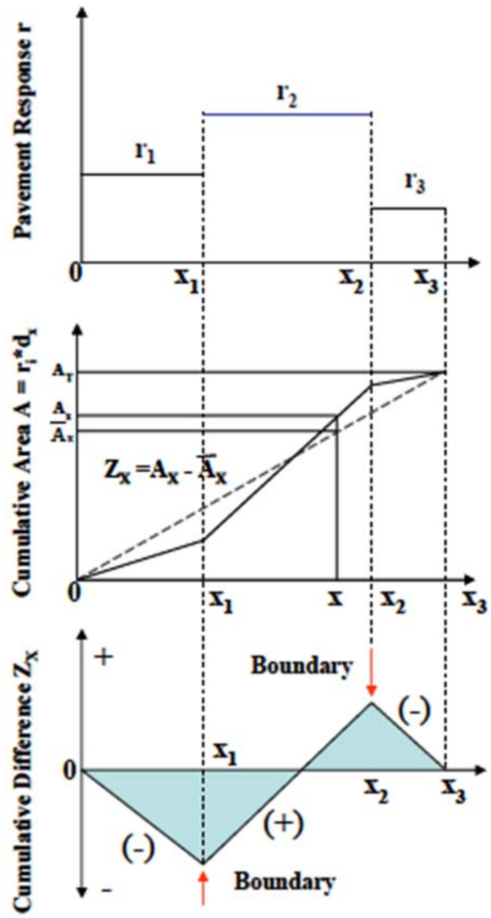


Figure 5.3: Graphical representation of the CDA method [AASHTO 1986]

5.3 Analysis and Results

The focus of this chapter is to recommend a method to characterize the representative SCI value of a pavement section. As part of this process, the segmentation results obtained using the reviewed three methods were compared for the same pavement section. More detailed discussion of the segmentation analysis is presented in the following section.

5.3.1 Assumptions Made in the Segmentation Analysis

In order to assist the segmentation analysis, assumptions about certain parameters used in the three segmentation methods are shown in Table 5.1.

Table 5.1: Assumptions of Parameters Used in the Segmentation Methods

Method	Parameter	Assumptions
CUMSUM	Target value	SCI threshold value of 1
Absolute difference in sliding mean values	Smoothing window (*q*)	3
	Neighboring elements for absolute difference (*d*)	3
	Threshold value	0.1
CDA	-NA-	-NA-

5.3.2 Comparison of the Segmentation Methods

A total of seven pavement sections were analyzed to compare the segmentation methods as listed in Table 5.2. The main principle of a segmentation technique is to identify a homogeneous segment by analyzing changes in the mean or deviation of the data series, and thus the seven sections were chosen in such a way that different ranges of SCI average and standard deviation were included. This selection helped to ensure that the recommended segmentation method would perform well under all possible scenarios.

Table 5.2: Data Used in the Segmentation Analysis

Route	Environmental Zone	Subgrade Soil Category	Estimated 20-year ESALs	Total Pavement Thickness (inches)	SCI	
					Mean	Standard Deviation
US 259 NB	Wet-Cold	Very Good	3,500,000	15.5	0.65	0.21
US 259 SB	Wet-Cold	Very Good	2,438,000	16.1	0.84	0.26
FM 486	Mixed	Poor	1,082,000	7	0.19	0.02
FM 2199	Wet-Cold	Poor	1,404,000	9	0.3	0.06
SL 375 L1	Dry-Warm	Poor	2,798,000	13	0.52	0.14
US 69 NB	Wet-Warm	Poor	10,719,000	17.5	0.32	0.08
SH 195	Mixed	Fair	10,385,000	16	1.73	0.36

Using the assumptions from Table 5.1, the homogeneous segments for each pavement section were determined using the three segmentation methods. Figure 5.4 shows the segmentation results obtained for one of the seven pavement sections, where the homogeneous segments are labeled as AB, BC, CD, and so on.

The average of a segment's SCI values was used to summarize the data of a homogeneous segment. To determine the effectiveness of each method, Standard Square Error (SSE) of the pavement section was computed using Equation 5.5. The results show that the CDA method gave the lowest error among all the three methods, indicating it is a reasonable method. Also, the CDA method requires no assumptions on any parameters required for the segmentation analysis, unlike the other two methods. Hence, it is recommended that the CDA method be used to characterize the representative SCI value of a pavement section in this research.

$$SSE = \sum_{j=1}^{m} \sum_{i=1}^{n} \left(\overline{X_j} - X_{ij} \right)^2 \tag{5.5}$$

Where:

$\overline{X}_j$ = Average SCI for a segment j

X_{ij} = SCI value for each i^{th} station in j^{th} segment

m = Number of homogeneous segments obtained by a segmentation method

n = Number of stations in a homogeneous segment

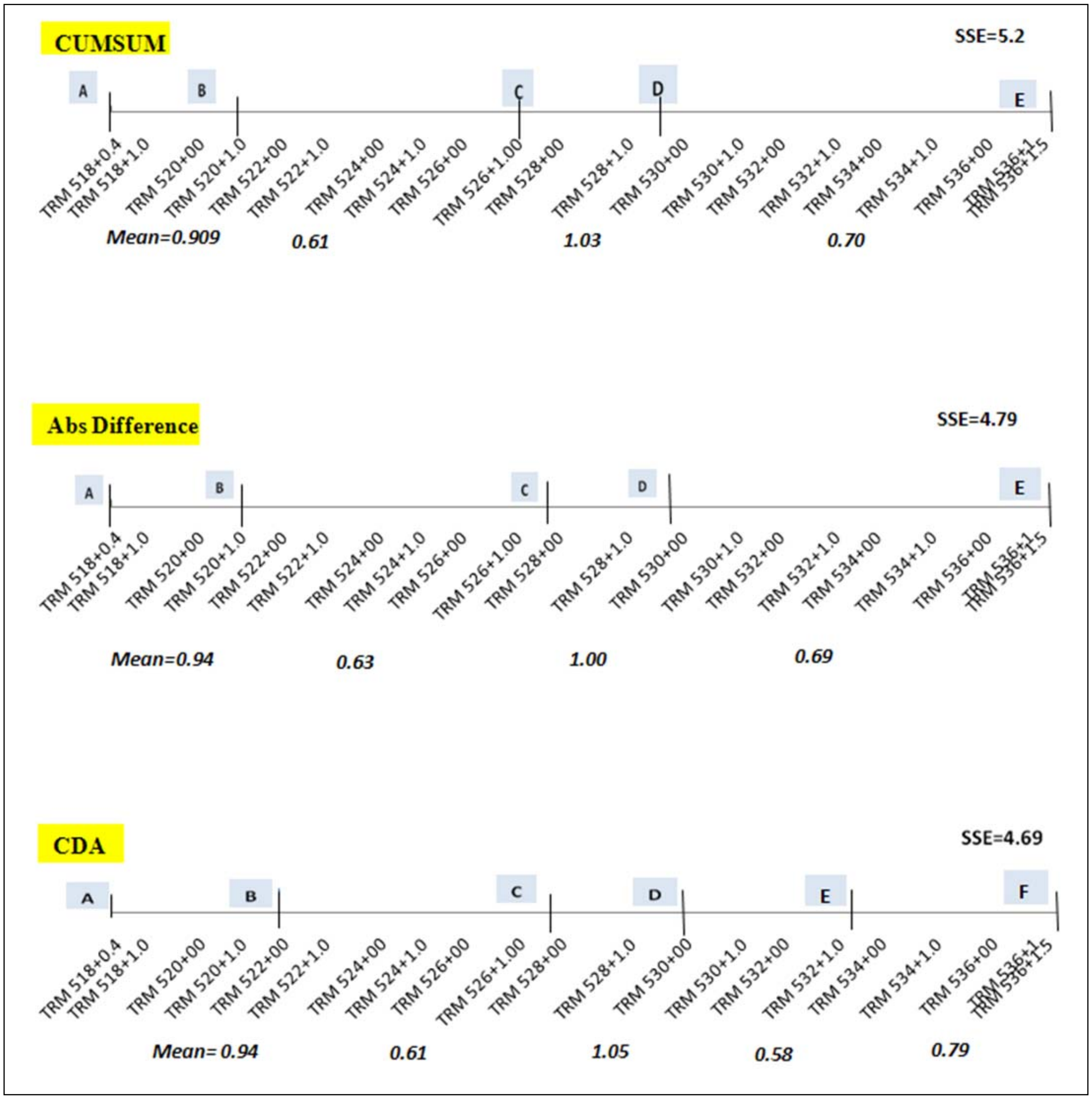


Figure 5.4: Comparison of the three segmentation methods

5.4 Conclusions

This chapter discussed the three reviewed segmentation methods for characterizing the representative value of a pavement section. The SSE of mean was adopted to determine the effectiveness of each method, and the results showed that the CDA method has the least SSE among the three methods. Moreover, the demerit of the CUMSUM method and the absolute difference in sliding mean value method is that these methods require assumptions regarding certain parameters due to the lack of guidelines. The CDA method, on the other hand, requires no such assumptions. Hence, in this research, it is recommended that the CDA method be used to characterize the representative SCI value of a pavement section.

The researchers realize that the methods previously discussed were evaluated using project-level data collected based on FWD stationing that might or might not coincide with TRM locations or the beginning/end of a PMIS section. As will be discussed in Chapter 6, the researchers recommend a network-level FWD data collection protocol that includes three tests on each PMIS Rating Section on 0.25-mile intervals. This protocol will result in one test at the beginning of the PMIS Section, one at approximately mid-point, and one at the end. FWD test locations might not occur exactly on these points due to variations in actual TRM locations in the field, small errors that might occur in Distance Measurement Instrument readings and variation in actual PMIS section lengths.

In any case, the CDA method can be used to evaluate network-level FWD data and to establish uniform (homogeneous) structural condition sections that may or may not exactly coincide with the limits of a PMIS section. The analysis may show that an SCI uniform section breakpoint, based on CDA analysis, occurs at some intermediate point within a PMIS section. Therefore, the homogeneous SCI segment may be more accurately characterized in conjunction with other characteristics such as traffic volumes, distress, and ride quality using the PMIS 0.10-mile summary intervals. For this reason, it is recommended that PMIS distress, ride quality and condition data, summarized on 0.10-mile increments, is evaluated in conjunction with the SCI CDA breakpoints.

Chapter 6. SCI Threshold Analysis

6.1 Introduction

This chapter describes the SCI threshold analysis. The SCI threshold analysis was undertaken to develop guidance for the Maintenance and Rehabilitation (M&R) treatment category selection based on the corresponding SCI threshold values. In this chapter, the SCI values and other types of project-related data were evaluated by selected TxDOT pavement experts to determine which M&R treatment option or categories should be selected. The M&R treatment options include seal coat, thin overlay, etc., while M&R treatment categories include Preventive Maintenance (PM), Light Rehabilitation (LRhb), Medium Rehabilitation (MRhb) and Heavy Rehabilitation (HRhb).

6.2 Threshold Analysis Approach

As part of the SCI threshold analysis, expert opinions were used to evaluate the M&R treatment categories based on the corresponding SCI values and other project-related data. In this process, 8 experts (knowledgeable and experienced in selecting M&R treatments based on an assessment of various types of project-level data) evaluated 16 pavement sections that included approximately 153 half-mile PMIS sections. The experts selected M&R treatments given an unlimited budget in order to assess the type of treatment that was *actually* needed rather than the treatment that might be selected due to inadequate funding.

6.2.1 Analysis Sheet

Sixteen pavement sections along with their typical section information were stored in four separate spreadsheets, and transmitted to the selected experts electronically for evaluation. For each pavement section, the SCI values were summarized and graphically represented along with the homogeneous segments based on the CDA method, as discussed in Chapter 5. The homogenous segments for a pavement section were labeled as AB, BC, CD, DE, and EF, as shown in Figure 6.1.

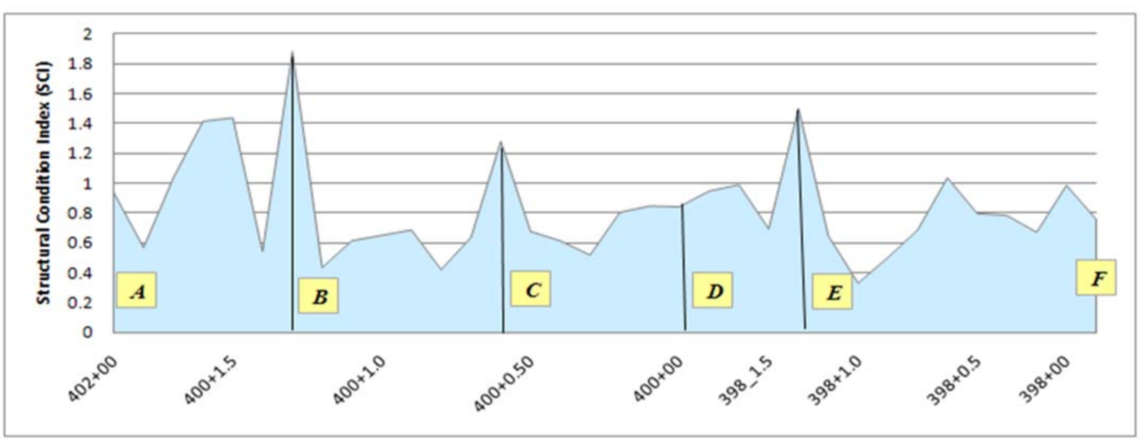


Figure 6.1: Homogeneous segments for a pavement section obtained from the CDA method

The spreadsheets, as shown in Table 6.1, included the pavement section information such as homogeneous segments obtained from the CDA method, section location, typical section, traffic data, FWD data, PMIS scores, soil type, soil modulus, Plasticity Index, and the SCI. Additionally, the spreadsheets contained embedded documents such as maps showing the FWD locations and any other details of the section potentially useful to the pavement experts in their analysis.

The experts were asked to select an M&R treatment option (PM, LRhb, MRhb, or HRhb) from a dropdown box provided in the spreadsheet, as shown in Table 6.1, by evaluating the data associated with each homogenous segment, with the assumption that the budget is not constrained. In addition, a “comment box” was included in the spreadsheet so that the experts could recommend a specific M&R treatment option for each segment.

Table 6.1: SCI Threshold Analysis Evaluation Spreadsheets

Segment	AB	AB	BC	CD	CD	DE	EF	EF	EF
TRM	402+00	400+1.5	400+1.0	400+0.50	400+00	398+1.5	398+1.0	398+0.5	398+00
Segment Average SCI	1.12		0.58	0.80		1.04	0.72		
Distress Score	67	61	47	29	54	41	46	37	76
Ride Score	0.8	2.2	2.6	2.9	2.6	2.4	2.7	3.0	3.3
Condition Score	6	43	45	29	52	35	46	37	76
Current ADT	710	710	710	710	710	710	710	710	710
Future ADT	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
20 Year ESALs	607000	607000	607000	607000	607000	607000	607000	607000	607000
% Trucks	23.9%	23.9%	28.1%	28.1%	28.1%	28.1%	28.1%	28.1%	28.1%
Trucks per Day	170	170	200	200	200	200	200	200	200
ATHWLD	10700	10700	10700	10700	10700	10700	10700	10700	10700
Speed Limit	70	70	70	70	70	70	70	70	70
ROW Width	100	100	100	100	100	100	100	100	100
Nr Thru Lanes / Dir	1	1	1	1	1	1	1	1	1
Right Shldr Width	4	4	4	4	4	4	4	4	4
Functional Class	Major Collector	Major Collector	Major Collector	Major Collector	Major Collector	Major Collector	Major Collector	Major Collector	Major Collector
Soil Type Unified	CL	CL	CL	CL	CL	CL	CL	CL	CL
Soil Type AASHTO	A-6	A-6	A-6	A-6	A-6	A-4	A-4	A-6	A-6
Soil Description	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam
Plasticity Index	11 - 25	11 - 25	11 - 25	11 - 25	11 - 25	9 - 23	9 - 23	11 - 25	11 - 25
Liquid Limit	23 - 40	23 - 40	23 - 40	23 - 40	23 - 40	24 - 43	24 -43	23 - 40	23 - 40
Distress observed									
M& R Options		Do Nothing PM LRhb MRhb HRhb							
Comment Box (eg. Description of your pavement repair recommendation)									

6.3 Analysis and Results

The 8 experts, after completing the M&R treatment category selections and documenting the M&R treatment options for the 16 pavement sections, returned the completed spreadsheets. The survey results obtained from the experts were analyzed, and used as the basis for the SCI threshold recommendations.

6.3.1 Anomalies in M&R Treatment Options

The results showed that for the same homogenous segment, the selection of M&R treatment categories varied significantly from expert to expert. Sometimes the same M&R treatment option is described for different M&R treatment categories. Table 6.2 displays some of the examples of the anomalies in M&R treatment options.

Table 6.2: Anomalies in M&R Treatment Options

M&R Treatment Categories	PM	LRhb	MRhb	HRhb
2” ACP overlay	X	X		
Repair failures, level up, and seal		X	X	
Mill existing ACP and place minimum 3” overlay	X			
Mill existing ACP and place minimum 2” overlay		X		

6.3.2 Assumptions in the SCI Threshold Analysis

The focus of this chapter is to develop guidelines about the M&R treatment categories based on the SCI thresholds. To assist the analysis process, M&R treatment categories (PM, LRhb, MRhb, and HRhb) were converted from linguistic terms to numerical scores as shown in Table 6.3, so that the average of all expert opinions could be used to determine the “average M&R treatment category” for a homogeneous segment.

Table 6.3: Assumptions Regarding the M&R Treatment Categories for the SCI Threshold Analysis

M&R Treatment Categories	Treatment Score
Do Nothing	0
PM	1
LRhb	2
MRhb	3
HRhb	4

For example, if one expert selected "Do Nothing" as the treatment for a homogeneous segment, and the other seven experts selected "PM" as the treatment, then the "average treatment score" in terms of the treatment options for the pavement segment is (0+1+1+1+1+1+1+1)/8 = 0.875. Table 6.4 shows the calculation of average treatment score for the rest of the segments.

Table 6.4: The SCI Threshold Analysis Spreadsheet

H3 =(0+0+0+2+0+1+0+0)/8

	A	B	C	D	E	H	I	J
1							Stacey Young	Darlene Goehl
2	District	County	Route	TRM	SCI	Average Score (PMIS Treatment Level Score)	PMIS Treatment Level	PMIS Treatment Level
3	Lubbock	Hockley	FM 303	236+1.5	100	0.38	Do Nothing	Do Nothing
4	Lubbock	Hockley	FM 303	238+00	100	0.25	Do Nothing	Do Nothing
5	Atlanta	Harrison	FM 2199	278+0.5	28	3.50	MRhb	HRhb
6	Atlanta	Harrison	FM 2199	278+1.0	28	3.50	MRhb	HRhb
7	Atlanta	Harrison	FM 2199	278+1.50	34	3.63	MRhb	HRhb
8	El Paso	El Paso	SL 375	55+0.5	55	3.63	MRhb	MRhb
9	El Paso	El Paso	SL 375	56+0.9	55	3.50	LRhb	MRhb
10	El Paso	El Paso	SL 375	56+00	55	3.63	MRhb	MRhb
11	Laredo	Duval	SH 359	530+0.0	60	3.50	HRhb	MRhb
12	Wichita Falls	Wichita	US 82 Foam	510+0.2	113	3.63	HRhb	HRhb
13	Bryan	Brazos	FM 50 NB	416+00	27	1.88	LRhb	PM
14	Bryan	Washington	FM 50 SB	436+0.75	27	2.00	LRhb	Do Nothing
15	Bryan	Washington	FM 50 SB	436+00	27	2.00	LRhb	Do Nothing
16	Bryan	Brazos	FM 50 NB	414+0.0	28	2.38	LRhb	PM
17	Bryan	Brazos	FM 50 NB	414+0.5	28	2.13	LRhb	PM
18	Bryan	Brazos	FM 50 NB	414+1.0	28	2.38	LRhb	PM
19	Bryan	Brazos	FM 50 NB	414+1.50	28	1.88	LRhb	PM
20	Bryan	Brazos	FM 50 NB		28	2.38	LRhb	PM
21	Bryan	Washington	FM 50 SB	436+0.826 (RR)	28	2.00	LRhb	Do Nothing
22	Bryan	Washington	FM 50 SB	436+1.04	28	2.00	LRhb	Do Nothing
23	Bryan	Washington	FM 50 SB	436+1.14	33	2.00	LRhb	Do Nothing

In addition, assumptions regarding the average M&R treatment categories for the corresponding average treatment scores were made as shown in Table 6.5.

Table 6.5: Assumptions of Average M&R Treatment Categories

Average Treatment Score	Average M&R Treatment Category
0.0–0.5	Do Nothing
0.5–1.5	PM
1.5–2.5	LRhb
2.5–3.5	MRhb
3.5–4.0	HRhb

6.3.3 Discussion of the Two Alternative Methods for the SCI Threshold Analysis

The average treatment scores and the SCI scores (multiplied by a factor of 100) for each pavement segment were plotted as shown in Figure 6.2. The average SCI value shown as the red dots in Figure 6.2, corresponding to each average M&R treatment category, was calculated. These averages were then joined using a straight line. The LRhb average based on the analysis results was 51. However, a large number of SCI values sat around 41 within this LRhb range. Therefore, a straight line was drawn through the other SCI averages to arrive at the proposed SCI for an LRhb of 65. Once the SCI average for each of the treatment designations was determined, two approaches were taken to determine the SCI thresholds.

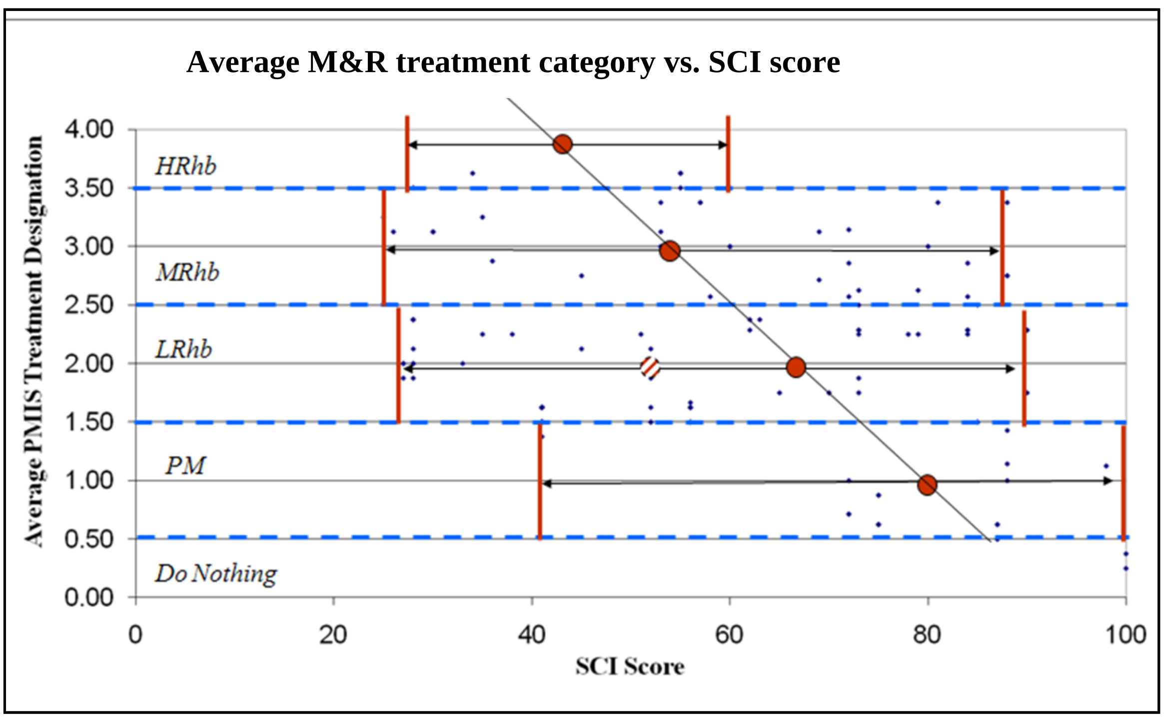


Figure 6.2: Average M&R treatment category vs. SCI score

Alternative Method 1:

The SCI averages, shown as the red dots in Figure 6.3, represent the boundaries for average M&R treatment category. Considering the SCI score of 80 as the threshold value for "Do Nothing," the SCI thresholds can be established as follows: 80–100 as "Do Nothing," 65–79 as "PM," 55–64 as "LRhb," 45–54 as "MRhb," and 44 or lower as "HRhb." Using this categorization, an SCI score of 64 is assigned LRhb treatment level. However, using an engineering judgment, a pavement section that has a performance score of 64 indicates that it has lost more than half of its life, which suggests that the section requires a PMIS treatment level of MRhb or higher. This shortcoming of the developed SCI thresholds led to Alternative Method 2.

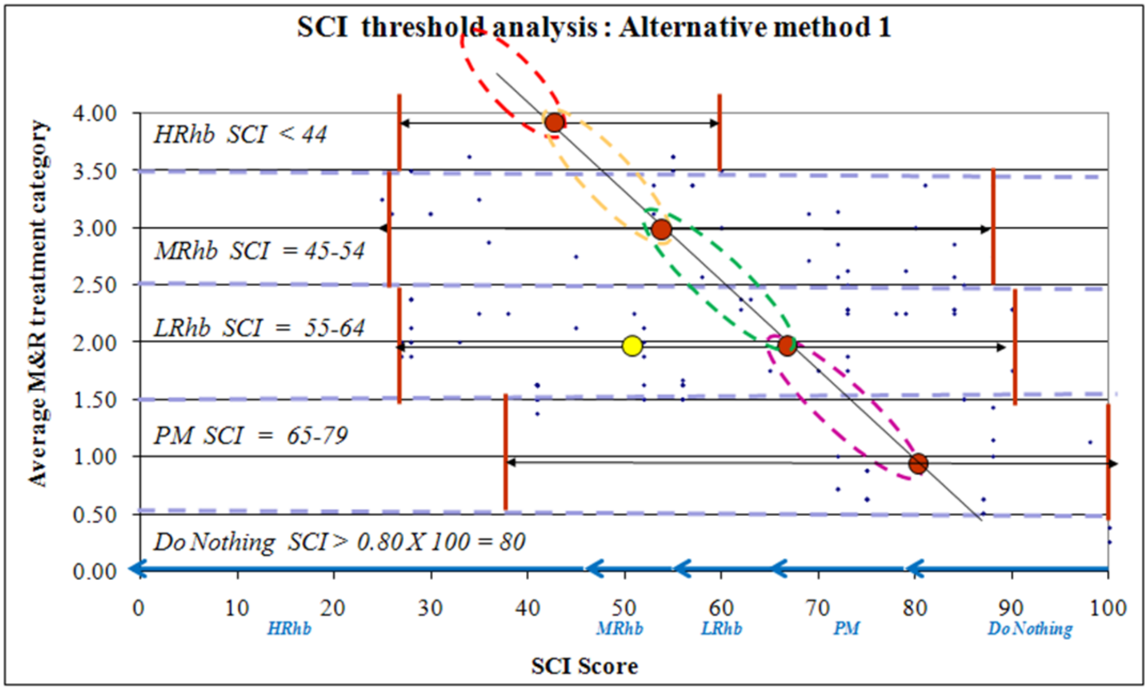


Figure 6.3: SCI threshold analysis using alternative method 1

Alternative Method 2:

In this case, the line formed by the four average values was extrapolated until it intersected the SCI score axis. This point of intersection gave the lower threshold value for the "Do Nothing" alternative. The SCI thresholds can be established as follows: 90–100 as "Do Nothing," 80–89 as "PM," 65–79 as "LRhb," 50–64 as "MRhb," and 49 or lower as "HRhb." Using this categorization, an SCI score of 64 is assigned MRhb treatment level, which is reasonable from an engineering point of view. Hence, results from Alternative Method 2 are recommended for the determination of the SCI thresholds in this research and are summarized in Table 6.6.

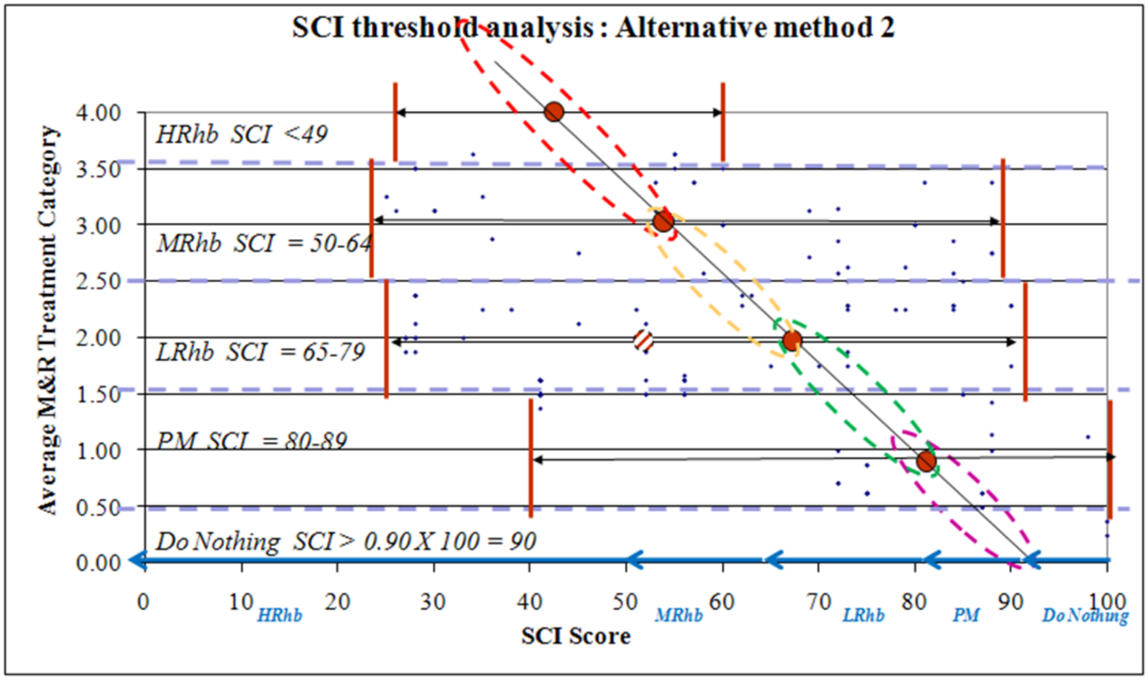


Figure 6.4: SCI threshold analysis using alternative method 2

Table 6.6: Recommended SCI Thresholds

SCI Scores (SCI*100)	M&R Category
90–100	Do Nothing
80–89	PM
65–79	LRhb
50–64	MRhb
0–49	HRhb

6.4 Conclusions

This chapter discussed the process to develop the SCI threshold values for a particular M&R treatment category. The SCI threshold analysis results showed that the eight experts gave a wide range of specific M&R treatment options and categories for the identical pavement section information. The two alternatives for determining the SCI threshold values were also discussed. It should be noted that the SCI scores cannot be correlated with the detailed M&R options, because the SCI is a network-level index and is not suitable for identifying specific M&R treatment options for a particular SCI. The SCI can only help select the M&R treatment categories at the project level, and should be used along with detailed distress data and additional field tests such as coring, GPR, etc., to determine the specific M&R treatments.

Chapter 7. Determination of FWD Testing Spacing

7.1 Introduction

One of the major issues in the pavement management is the high cost of FWD data collection for determining the structural condition of a pavement at the network level. These expenses include operational costs associated with the FWD and the traffic control. In addition, safety is another concern, especially on high-speed highways, due to the “stop-and go” nature of the FWD deflection testing. Extensive research has been conducted to determine the ideal FWD testing spacing for adequately characterizing the pavement strength, while minimizing the cost and safety concerns. FWD pavement deflections are used by a number of agencies to evaluate pavement strength for project-level applications while a few agencies use the FWD pavement deflections for network-level applications. TxDOT currently has no specific policy on the collection of pavement deflection data for network-level applications [TxDOT 2002]. Hence, this chapter discusses the ideal FWD test spacing required to characterize the structural condition of a pavement section using the SCI.

7.2 Analysis Approach

In the previous Project 0-4322 [Zhang 2003], the recommended frequency of FWD tests was two tests per half-mile section, using a risk-based method that controls the Type I error. In the current research, an analysis was conducted with the network-level SCI values to determine the FWD testing spacing by increasing the FWD testing spacing until it reaches a level at which the SCI value no longer provides a reasonably accurate assessment of the pavement section when compared to a complete set of project-level data. The analysis was accomplished by creating new datasets in two ways:

- randomly removing test points from the original project-level data; and
- removing test points based on predetermined spacing that would result in approximately equally spaced test points.

7.2.1 Data Used in the Analysis

The SCI analysis is primarily based on the FWD deflections. In this research, the SCI analysis was conducted using FWD data collected on pavement sections for the project-level applications, such as pavement design support, load zone posting analysis, and super-heavy load route evaluation. The FWD readings for these sections were collected at different test spacings to accommodate the project needs and local conditions. Some pavement sections were tested using equally spaced FWD measurement stations at 0.2 miles, 0.1 miles, or smaller spacing, while in other cases FWD measurement stations were randomly spaced.

A subset of pavement sections containing SCI values, computed using the FWD data collected at approximately 0.1-mile spacing, was first selected, providing a dataset that could be modified by increasing the FWD test spacing to 0.2, 0.25, 0.3, 0.4, or 0.5 miles as shown in Figure 7.1. This approach was used to obtain a total of seven project-level pavement sections for the analysis. The random removal of test points was achieved using a random number generator to avoid any potential bias.

As an example, if there are a total of 40 data points in a pavement section with FWD data collected at 0.1-mile equal spacing, then the dataset with FWD data at equal spacing of 0.2-mile has 20 points. The average spacing (0.2 miles in this example) for the equal and random spacing datasets is the same; therefore, the number of data points (20 in this example) in both the datasets should be the same. Hence, the dataset for random spacing is obtained by randomly choosing 20 points from the 0.1-mile dataset.

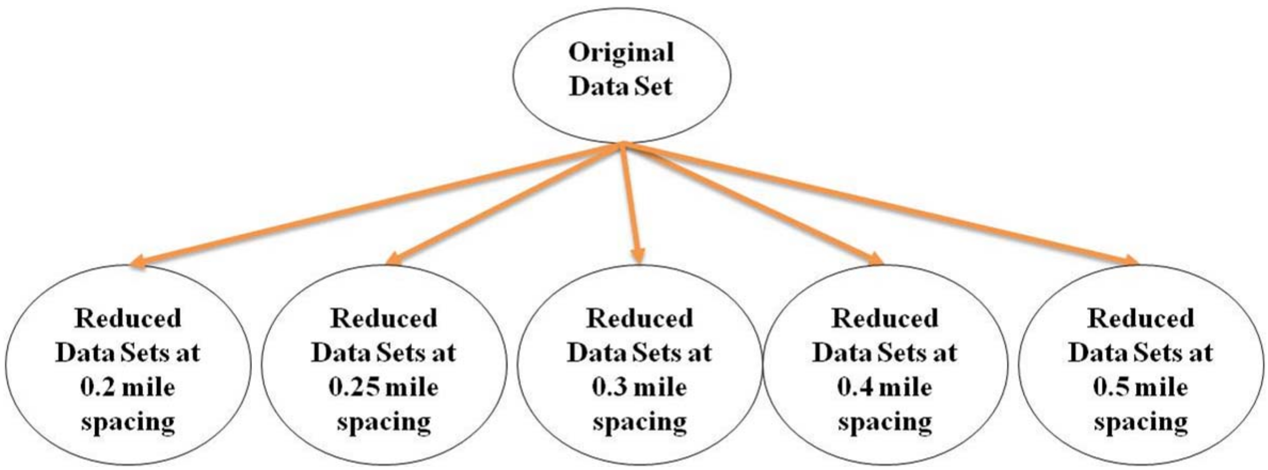


Figure 7.1: Data used in the analysis

7.3 Discussion of the Results

The original dataset was modified by removing data points randomly or systematically to create a series of new datasets with reduced data points at different test spacing. The results obtained using the CDA method (Chapter 5) for the original dataset were used as a reference to compare the results from the reduced datasets. The cumulative difference (z) trends and segmentation results, for the original and reduced datasets, are discussed in this section.

7.3.1 Trend Analysis

The intention of the trend analysis was to visually compare the cumulative difference (z) trends between the original and the reduced datasets. Break points are created from the change in cumulative difference (z) trends; this visual comparison helps in anticipating whether the segmentation from the reduced dataset is similar to that of the original dataset.

Figures 7.2 and 7.3 show the results obtained for one of the seven sections used in the analysis. With larger station spacing of 0.4 miles, the trend of cumulative difference (z) curve hardly follows the original dataset. The results indicated that 0.2-mile spacing and 0.25-mile spacing give a representation close to the original data.

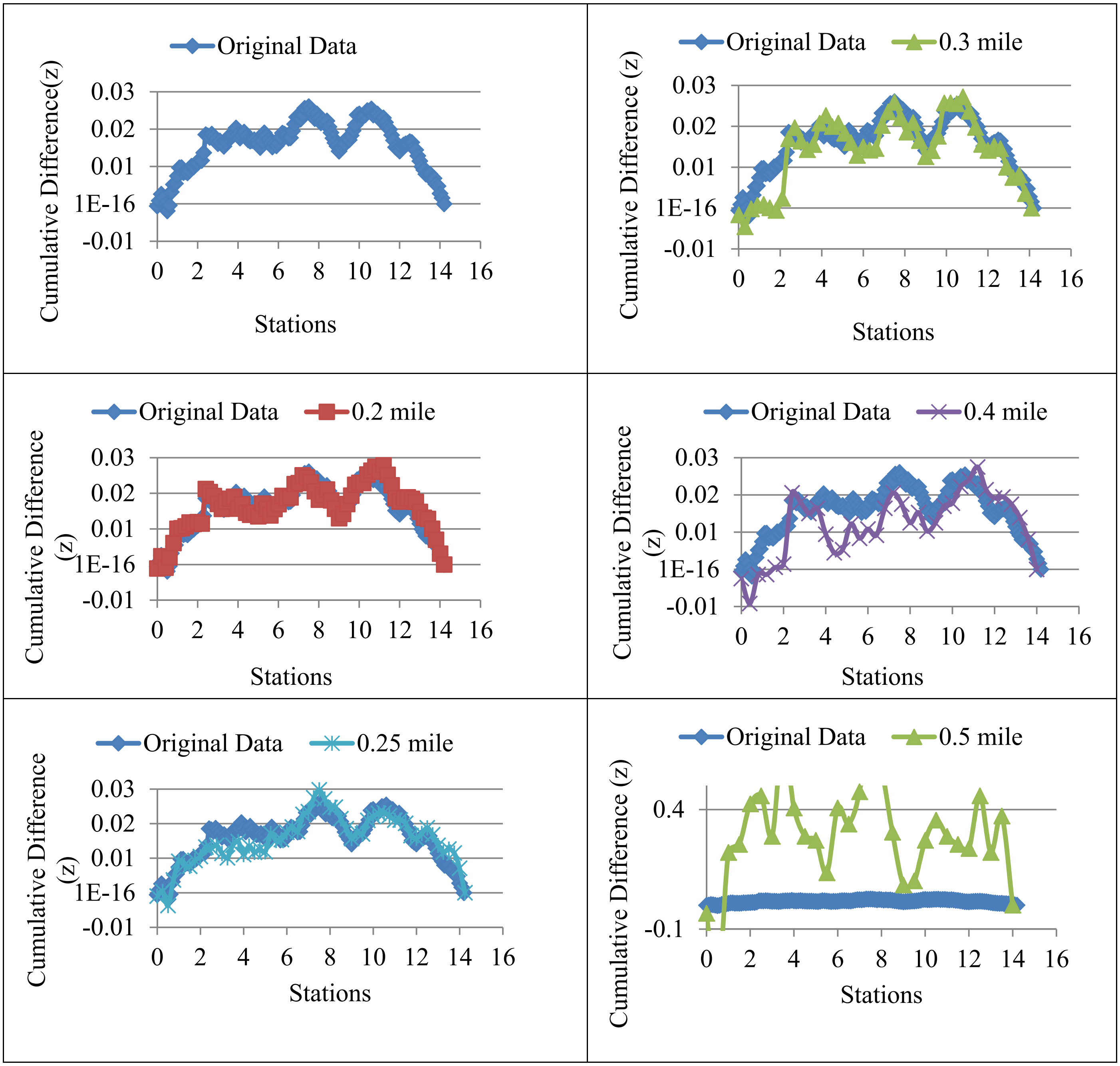


Figure 7.2: Comparison of cumulative difference (z) trends of original and reduced datasets with FWD data at equal spacing

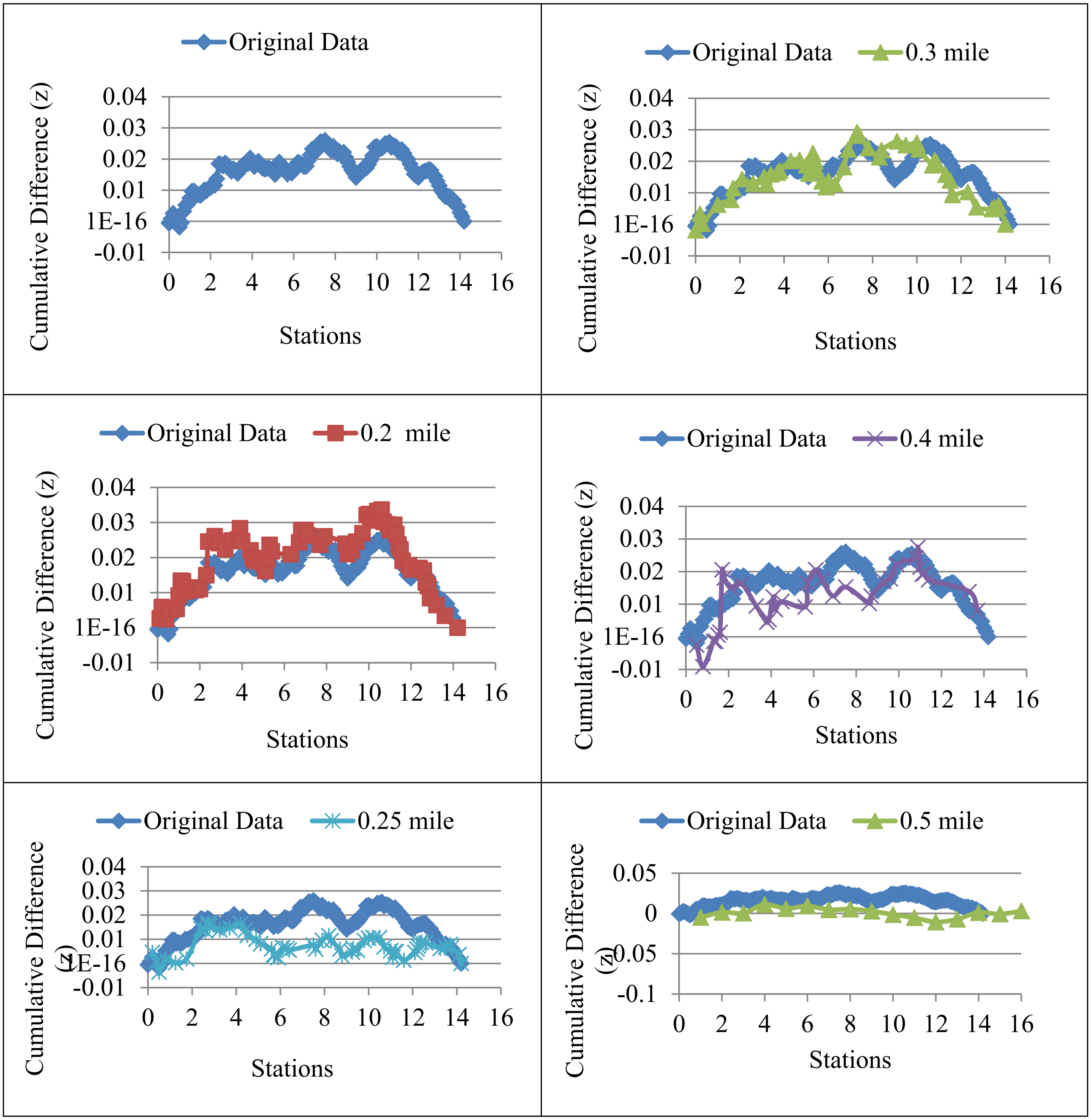


Figure 7.3: Comparison of cumulative difference (z) trends of original & reduced datasets with FWD data at random spacing

7.3.2 Segmentation Results

The new datasets created with FWD data at 0.2-mile spacing and 0.25-mile spacing were considered for comparison of the segmentation results as shown in Figure 7.4. A comparison of the number of homogenous segments between the original dataset and new datasets was used in determining the optimal FWD testing spacing.

Figure 7.4 shows that eight homogeneous segments (labeled as AB, BC, and so on to HI) were obtained from the CDA method for the original dataset. FWD data with 0.2-mile equal spacing was the closest dataset with seven homogeneous segments. On the other hand, datasets with 0.2-mile random spacing, 0.25-mile random spacing, and 0.25-mile equal spacing were divided into six homogenous segments. The segmentation results for the original dataset are closest to the dataset with 0.2-mile equal spacing. Therefore, a 0.2-mile equal spacing is recommended as the ideal FWD testing spacing for the SCI analysis.

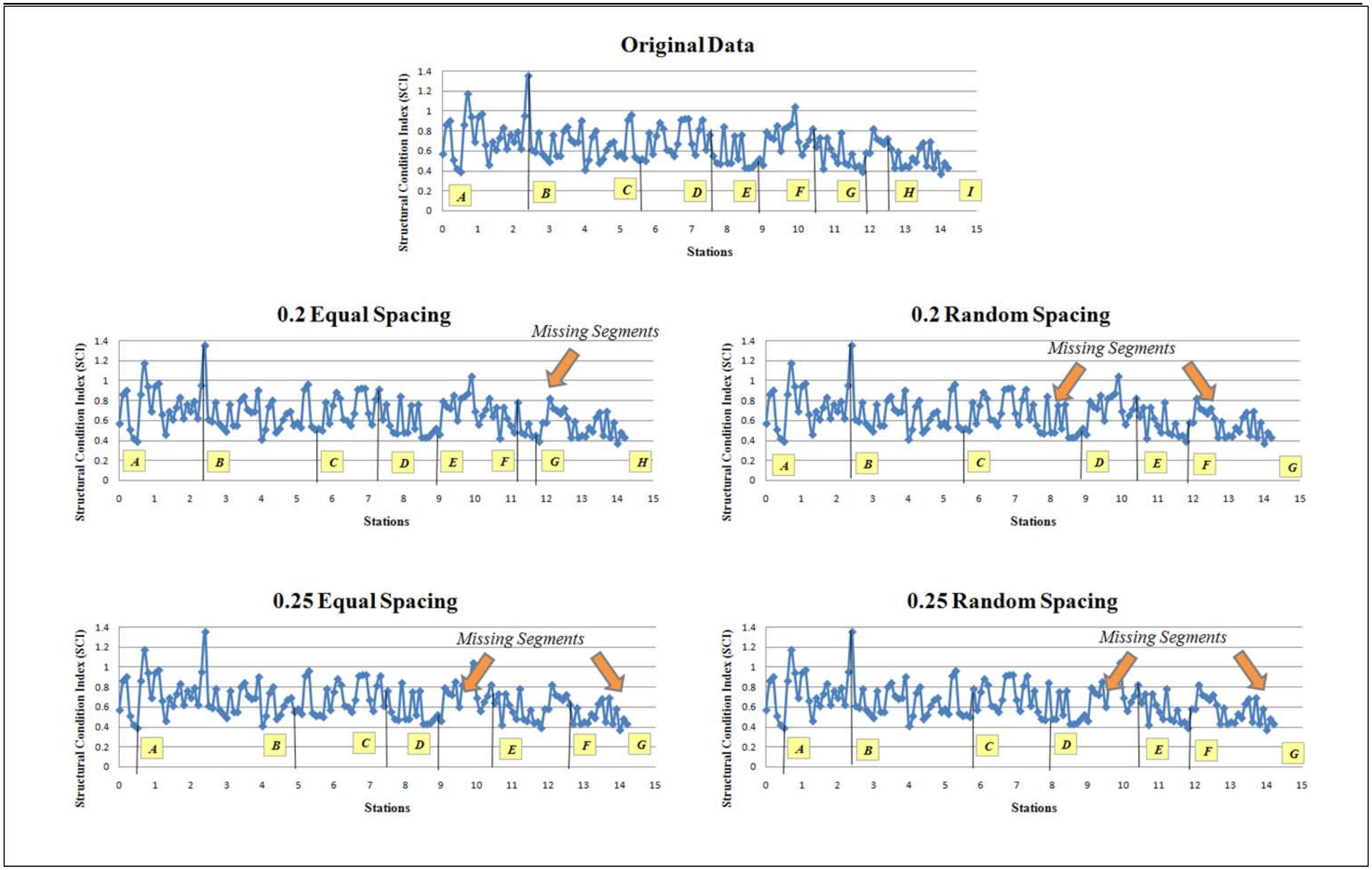


Figure 7.4: Comparison of segmentation results for the original and the reduced datasets

7.4 Recommendations on Testing Spacing

The analysis results indicated that the dataset obtained from 0.2-mile equal spacing compares well with the original dataset. Hence, the FWD data collected at test spacing of 0.2 miles is recommended for the SCI analysis. The FWD testing at 0.25-mile spacing can be recommended as a second alternative for the SCI analysis. The FWD testing at 0.2-mile spacing will not coincide well with the PMIS section lengths of 0.5 miles. However, the FWD testing at 0.25-mile spacing will achieve a standard test pattern in relation to the PMIS section (beginning, middle, end) as shown in Figure 7.5.

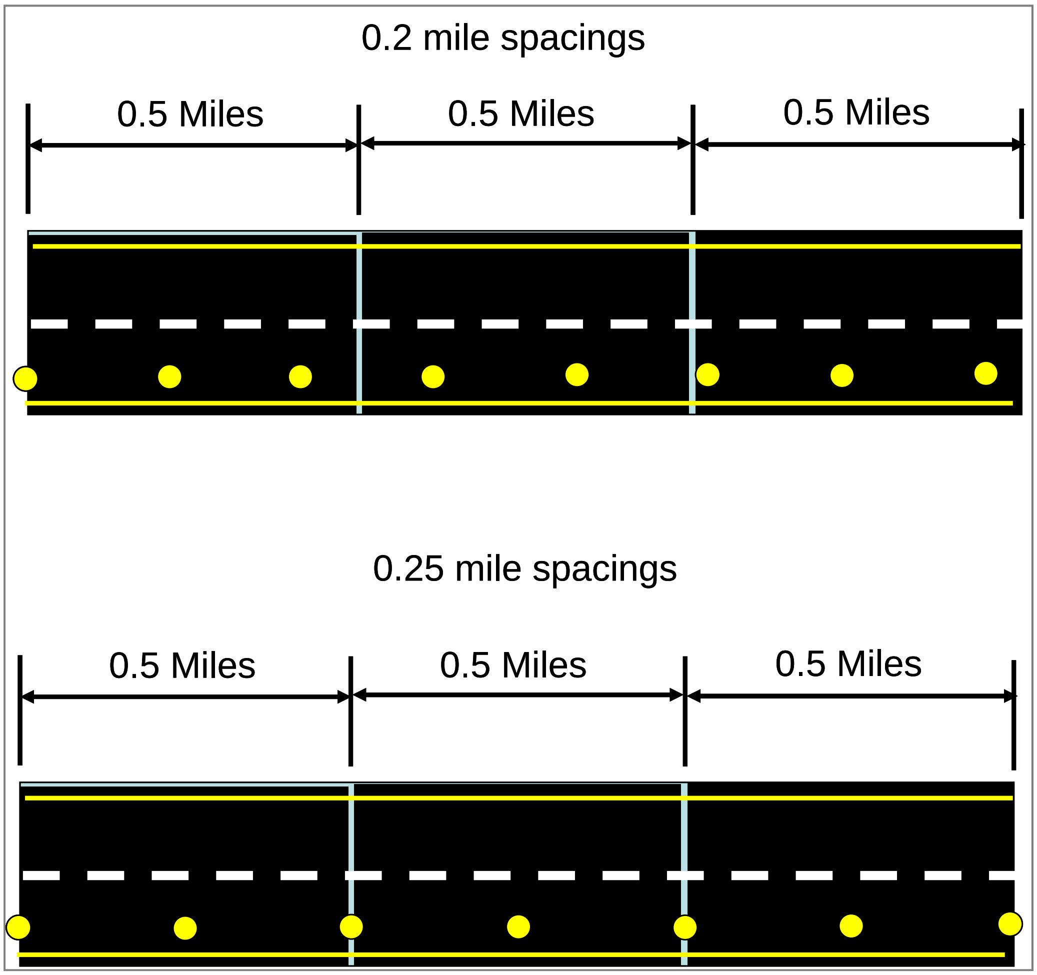


Figure 7.5: Comparison of FWD testing spacing at 0.2 miles and 0.25 miles

Chapter 8. Conclusions and Recommendations

The primary goal of this research is to validate the Structural Condition Index (SCI) method, and to develop guidelines for implementing the SCI at the network level. The scope of the research covered only flexible pavements in Texas. This chapter presents the conclusions drawn from this research and the recommendations for future work.

8.1 Conclusions

Conclusions drawn from this research are as follow:

- A literature review was undertaken to identify research on the state of the art for structural indices at the network level. It was found that most of the agencies adopted either the Falling Weight Deflectometer (FWD) or the Ground Penetrating Radar for structural evaluation of pavements at the network level. The FWD data collection requires traffic control and both methods require data collection and analysis personnel as well as other resources, resulting in high data collection costs. The evaluation methods, on the other hand, did not uncover any new structural indices or new information that could help improve the SCI method.
- The pavement mechanistic analysis responses such as the stress, strain, and deflections, estimated from the WESLEA program, were used in the SCI validation process. These responses were used to derive the percent-remaining-life factors, analogous to the SCI, from the Asphalt Institute fatigue and rutting equations. The percent-remaining-life factors were called *fatigue remaining life ratio* and *rutting remaining life ratio*, respectively, in this research. A non-linear regression analysis conducted with these ratios and the SCI values show that a correlation exists, indicating that the SCI method provides rational results.
- In addition to the SCI evaluation, an analysis was conducted to determine the effect of shallow bedrock depth on the SCI values, as the SCI calculations are based on the FWD deflection data without considering the bedrock depth. Due to the lack of data collected on in-service pavement sections with different bedrock depths, the NETFWD database was used in this analysis. The NETFWD database was developed as part of a previous research project and has information on modeled pavement structures with bedrock depths ranging from 40 in. to 720 in. The analysis results show that the SCI values tend to decrease as bedrock depth increases, with all other factors remaining constant. As an example, the results indicate that the thin and intermediate pavement structures on a weak subgrade over shallow bedrock depths are structurally sound; however, the same pavement structures are found to be structurally inadequate at higher bedrock depths.
- This research recommends the use of a segmentation technique called the Cumulative Difference Approach (CDA) method to characterize the representative SCI value of a pavement section. The CDA method employs changes in the mean of a data series to identify the homogenous segments in a pavement section.
- A survey was conducted with eight TxDOT pavement experts to determine the SCI threshold values for M&R treatment categories. The experts were asked to select an

M&R treatment category by evaluating the SCI values and other types of project-related data. These data were provided for each homogeneous segment in a pavement section, and the experts were asked to select the M&R treatment category with the assumption that the budget was not constrained. The survey results were analyzed and used as the basis for the SCI threshold recommendations. The recommended SCI threshold values for each M&R treatment category in this research are as follow: SCI scores between 0.9–1.0 as “Do Nothing,” 0.80–0.89 as “PM,” 0.65–0.79 as “LRhb,” 0.50–0.64 as “MRhb,” and 0.49 or lower as “HRhb.”

- An analysis was conducted using the CDA method to determine the ideal FWD testing spacing for the SCI analysis. An ideal FWD testing spacing will help minimize data collection costs without reducing the accuracy of the pavement structural condition assessment. From the analysis results, this research recommends that the FWD data should be collected at a test spacing of 0.2 miles for the SCI analysis.
- An SCI algorithm tool was developed to assist TxDOT with the implementation of the SCI for network-level applications. This tool was developed using Visual Basic Applications in a macro-enabled Excel workbook, providing an interface between the SCI methodology and the users. The tool allows the user to input the required data, run the algorithm, and view the SCI analysis results for a pavement section.
- The SCI analysis is based on the SN_{req} table created from discussions with the Project Director. To allow more flexibility, the SCI algorithm tool incorporates the ability to create custom SN_{req} tables, which allows TxDOT districts to customize according to their needs.
- A user manual was also developed to explain the SCI algorithm tool, specifically addressing and giving necessary guidelines on using the SCI analysis results to evaluate the structural condition of a pavement section.

8.2 Recommendations

Recommendations for further research are as follow:

- The SCI analysis uses total pavement thickness information. Hence, a pavement layer thickness and material type database should be developed for the Texas PMIS in order to fully implement and automate SCI at the network level. Also, a methodology for incorporating pavement treatment history information in the PMIS database should be developed to ensure that the pavement layer thickness and material type database is kept current.
- Given that the SCI values are affected by the shallow bedrock depths, an algorithm that considers the effects of shallow bedrock depth on the SCI values should be developed and incorporated in the SCI analysis.
- Further work is needed to supplement the SCI with the development of a “Deep Distress” index that uses the PMIS data. The SCI values can be estimated by a regression on the Deep Distress index when the FWD deflections for pavement sections are not available. Collecting a 100% FWD data sample of the TxDOT roadway network may be impractical due to cost and time considerations.

Therefore, the Deep Distress index could serve as a surrogate estimate of pavement structural condition for pavement sections without FWD data. This approach would provide a 100% sample of pavement structural condition assessment that can support statewide implementation of the SCI method.

- Further work is needed to evaluate inclusion of the SCI method in the pavement preventive maintenance and rehabilitation ranking procedure, specifically for the development of a program of projects in a district's 4-year pavement management plan.
- Further work is needed to modify and evaluate the SCI method for use on rigid pavements as this research focuses on evaluation of the SCI method for flexible pavements only.
- The efficiency of the SCI algorithm can be improved by developing temperature correction factors for the SCI values. The current SCI algorithm tool facilitates this improvement by allowing the user to input variables such as the FWD deflection testing time and the pavement, air, and surface temperature data.
- An automated segmentation procedure using the CDA method should be developed in the SCI algorithm tool for determination of the representative SCI value of a pavement section.
- Further automation can be achieved by incorporating an FWD parsing code in the SCI algorithm tool that will directly read the values from a raw FWD file, eliminating the need for the user to manually input the FWD data.
- Upon development of the layer thickness database and bedrock depth algorithm, further enhancements can be achieved by developing a master algorithm that automates the SCI analysis process for an entire county, district, or statewide network without the need for further human interaction.

Appendix A: Matrix Chart

	ENVIRONMENTAL ZONE																																				
	MIXED									WET-WARM							WET-COLD							DRY-WARM								DRY-COLD					
SUBGRADE / TRAFFIC	VP	P		F		G	VG			VP	P		F	G		VG	VP	P	F	G	VG			VP	P		F	G	VG			VP	P	F	G		VG
VERY LOW		127		28,21,178	125,169,177	22, 44, 45,134, 143,179, 180	64,131	18, 41, 42, 46,128, 133, 135, 136	176	114	43, 47	2	4		16,110,138,139	65, 66, 67, 68,142	108	38	69	70						91	73, 75, 76, 77, 78	74, 79	80	87, 93	94		95, 96, 97	48	37	20	3
				117,132		124	144	145, 146, 147		5	113		115, 116			141		107, 109		106							100							103	156		
LOW			120	167,175	122	123,151	126	171	172				101, 102		140						111, 112	105															
			19,121	25,152	24, 33 & 34	130	31,129,137,166	29, 30, 118, 119	173, 174,				12			14		6					10 & 11		81, 82	49, 50	89	98					62, 63				
MEDIUM			39	40		170	148,149,150					17						51		104	72	52, 53	32		88		84, 85							35 & 36			32, 71
							181,182																														
HIGH						154	168	1,8,9,153, 155			54	15	55, 56, 59, 61	57, 60	13	58										83		86			7						
VERY HIGH		157,158, 159,160		163,164		162	165	161																													

SECTION NO.

Appendix B: List of 180 Sections

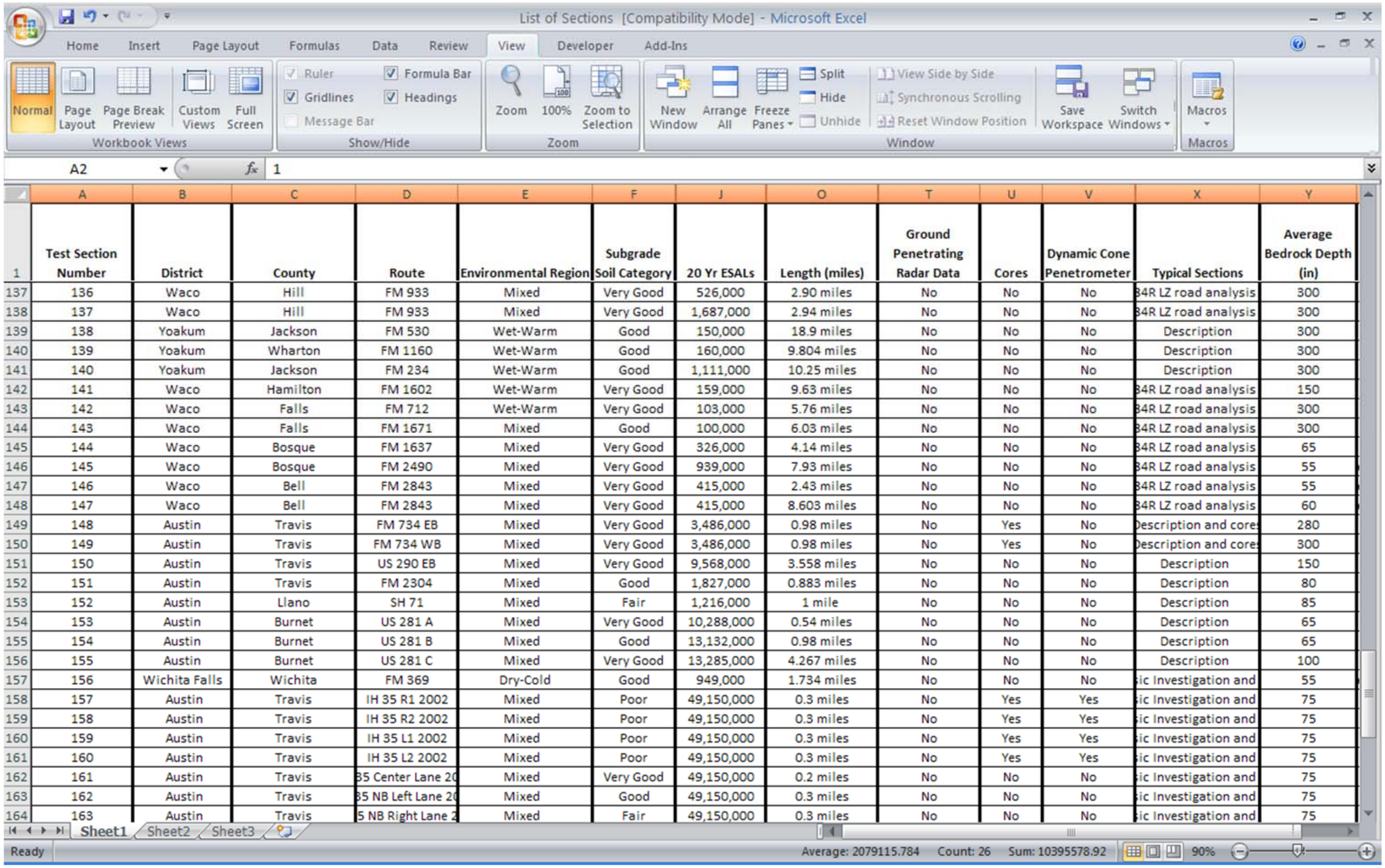
Test Section Number	District	County	Route	Environmental Region	Subgrade Soil Category	20 Yr ESALs	Length (miles)	Ground Penetrating Radar Data	Cores	Dynamic Cone Penetrometer	Typical Sections	Average Bedrock Depth (in)
1	Austin	Williamson	SH 195	Mixed	Fair	10,385,000	5.921	Yes	No	No	Yes & GPR	72
2	Houston	Galveston	FM 3436	Wet - Warm	Very Poor	467,000	1.568	No	No	No	Description	140
3	Abilene	Taylor	FM 89	Dry - Cold	Very Good	607,000	4	No	No	Yes	From DCP Data	60
4	Beaumont	Hardin	FM 1293	Wet - Warm	Fair	531,000	0.5	No	Yes	No	Description & Cores	140
5	Corpus Christi	Nueces	FM 1694	Wet - Warm	Very Poor	577,000	3.7 (3 pads)	No	No	Yes	From DCP Data	110
6	Atlanta	Harrison	FM 2199	Wet - Cold	Poor	1,404,000	4	No	No	No	Plans	140
7	Odessa	Ward	IH 20	Dry - Warm	Very Good	22,625,000	10.9 (gaps in data)	No	Yes	No	scription, cores and S	120
8	Austin	Travis	SH 71 EB	Mixed	Very Good	10,438,000	4.31	No	No	No	Plans	170
9	Austin	Travis	SH 71 WB	Mixed	Very Good	11,247,000	5.75	No	No	No	Plans	148
10	Atlanta	Upshur	US 259 NB (A)	Wet - Cold	Very Good	3,500,000	3.2	No	Yes	No	Plans and cores	140
11	Atlanta	Upshur	US 259 SB (B)	Wet - Cold	Very Good	2,438,000	4	No	Yes	No	Plans and cores	140
12	Beaumont	Orange	FM 1442	Wet - Warm	Fair	1,396,000	2.8	No	No	No	Description	125
13	Beaumont	Hardin	US 69 Lumberton	Wet - Warm	Good		30 feet	No	No	Shoulder only	Description	140
14	Beaumont	Tyler	US 69 Woodville	Wet - Warm	Very Good	8,033,000	6.6	No	Yes	Yes	cription, cores and D	140
15	Beaumont	Jefferson	US 69 NB ML near District Office	Wet - Warm	Poor	10,719,000	1000 feet	Yes	No	Yes	scription, GPR and D	140
16	Beaumont	Newton	SH 87 NB	Wet - Warm	Good	839,000	6.6	Yes	No	No	Description, GPR	240
17	Beaumont	Jefferson	SH 82 SB	Wet - Warm	Poor	3,814,000	2	Yes	Yes	No	Description, GPR	300+
18	Bryan	Brazos	SH 47 EB	Mixed	Very Good	993,000	6.6	No	No	No	Description	200
19	Bryan	Milam	FM 486	Mixed	Poor	1,082,000	1.75	No	No	No	Description	180+
20	Lubbock	Floyd	FM 97	Dry - Cold	Good	99,000	18	No	No	No	Description	70
21	Austin	Williamson	FM 112	Mixed	Fair	874,000	15	No	No	No	Description	300+
22	Austin	Williamson	FM 619	Mixed	Good	577,000	2.5	No	No	No	Description	250+
23	Austin	Travis & Williamson	FM 973 NB	Mixed	Fair	2,650,000	16.1	No	No	No	Plans	150+
24	Austin	Williamson	FM 1660	Mixed	Fair	1,336,000	10.7	No	No	No	Description	200+

1	Test Section Number	District	County	Route	Environmental Region	Subgrade Soil Category	20 Yr ESALs	Length (miles)	Ground Penetrating Radar Data	Cores	Dynamic Cone Penetrometer	Typical Sections	Average Bedrock Depth (in)
26	25	Austin	Williamson	FM 3349	Mixed	Fair	175,000	4	No	No	No	Description	170
27	26	Bryan	Washington	FM 50 SB	Mixed	Poor	669,000	1.14	No	No	No	Description	145
28	27	Bryan	Brazos & Burleson	FM 50 NB	Mixed	Poor	575,000	3	No	No	No	Description	140
29	28	Bryan	Brazos	FM 1687 EB	Mixed	Fair	202,000	2.9	No	No	No	Plans	300
30	29	Brownwood	Brown	US 67 NEB	Mixed	Very Good	5,000,000	2.9	No	Yes	No	Description & Cores	65
31	30	Brownwood	Brown	US 67 SWB	Mixed	Very Good	5,000,000	2.9	No	Yes	No	Description & Cores	100
32	31	Waco	Hill	FM 66	Mixed	Very Good	2,167,000	2	Yes	Yes	No	Description & GPR	200+
33	32	Atlanta	Titus & Morris	SH 49	Wet - Cold	Very Good	3,889,000	7.4	No	No	No	Description	40+
34	33	Austin	Travis	FM 1625 N	Mixed	Fair	1,405,000	4.6	No	No	No	Description	300+
35	34	Austin	Travis	FM 1625 S	Mixed	Fair	1,405,000	4.6	No	No	No	Plans	300+
36	35	Amarillo	Hartley	US 87 K1	Dry - Cold	Fair	4,318,000	14.2	No	No	No	Description	130
37	36	Amarillo	Hartley	US 87 K2	Dry - Cold	Fair	4,318,000	14.1	No	No	No	Description	130
38	37	Lubbock	Hockley	FM 303	Dry - Cold	Good	502,000	5.2	No	No	No	Description	60+
39	38	Dallas	Navarro	FM 1126	Wet - Cold	Poor	219,000	22.6	No	No	No	Description	140+
40	39	Bryan	Burleson	21 WB pads 22 23	Mixed	Poor	3,682,000	.9 miles	No	No	No	Plans	120 +
41	40	Bryan	Brazos	21 WB pads 28 29	Mixed	Fair	3,841,000	.9 miles	No	No	No	Plans	230+
42	41	Brownwood	Comanche	FM 1702 NB	Mixed	Very Good	350,000	2.8 miles	No	No	No	Description	300+
43	42	Brownwood	Comanche	FM 1702 SB	Mixed	Very Good	350,000	2.8 miles	No	No	No	Description	300+
44	43	Corpus Christi	Nueces	FM 2826	Wet - Warm	Poor	127,000	3.2 miles	No	No	No	Description	300+
45	44	Bryan	Brazos	SH 47 EB pad 5	Mixed	Good	993,000	500 feet	No	No	No	Description	200
46	45	Bryan	Brazos	SH 47 EB pad 6	Mixed	Good	993,000	500 feet	No	No	No	Description	200
47	46	Bryan	Brazos	H 47 EB pads 1, 2,	Mixed	Very Good	993,000	500 feet each pad	No	No	No	Description	300
48	47	Corpus Christi	Nueces	FM 1694 SB	Wet - Warm	Poor	408,000	6.6 miles	No	No	No	Plans	300
49	48	Amarillo	Randall	FM 2219	Dry - Cold	Fair	748,000	5.9 miles	No	No	No	Description	120
50	49	El Paso	El Paso	375 EB outside la	Dry - Warm	Poor	2,798,000	5.3 miles	No	No	No	Description	60+
51	50	El Paso	El Paso	375 EB inside la	Dry - Warm	Poor	2,798,000	12.4 miles	No	No	No	Description	60+
52	51	Ft. Worth	Johnson	M 917 WB 6-200	Wet - Cold	Poor	4,553,000	9.13 miles	No	No	No	Plans	100+

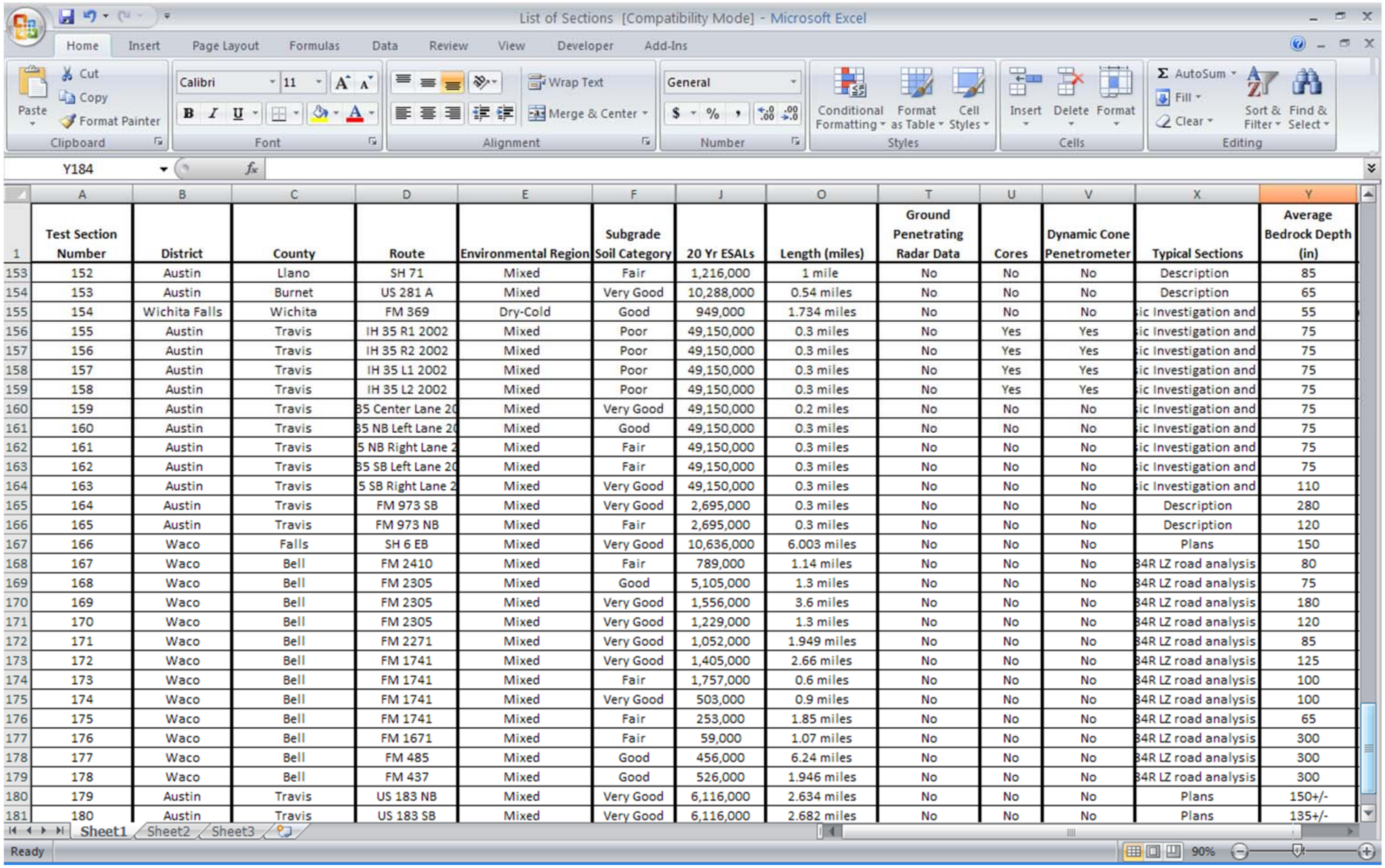
	Test Section Number	District	County	Route	Environmental Region	Subgrade Soil Category	20 Yr ESALs	Length (miles)	Ground Penetrating Radar Data	Cores	Dynamic Cone Penetrometer	Typical Sections	Average Bedrock Depth (in)
53	52	Ft. Worth	Johnson	M 917 WB 7-200	Wet - Cold	Very Good	4,553,000	9.13 miles	No	No	No	Plans	170
54	53	Ft. Worth	Johnson	FM 916	Wet - Cold	Fair	332,000	0.60 miles	No	No	No	Plans	200+
55	54	Lufkin	Polk	US 59 F1	Wet - Warm	Poor	14,362,000	0.2 mile	No	Yes	No	Research Report 98	90+
56	55	Lufkin	Polk	US 59 F2	Wet - Warm	Fair	14,362,000	0.2 mile	No	Yes	No	Research Report 98	90+
57	56	Lufkin	Polk	US 59 F3	Wet - Warm	Fair	14,362,000	0.2 mile	No	Yes	No	Research Report 98	90+
58	57	Lufkin	Polk	US 59 F4	Wet - Warm	Good	14,362,000	0.2 mile	No	Yes	No	Research Report 98	90+
59	58	Lufkin	Polk	US 59 F5	Wet - Warm	Very Good	14,362,000	0.2 mile	No	Yes	No	Research Report 98	200+
60	59	Lufkin	Polk	US 59 F6	Wet - Warm	Fair	14,362,000	0.2 mile	No	Yes	No	Research Report 98	90+
61	60	Lufkin	Polk	59 F0 1-1/2" surf	Wet - Warm	Good	14,362,000	0.1 mile	No	Yes	No	Research Report 98	90+
62	61	Lufkin	Polk	S 59 F0 3" surfa	Wet - Warm	Fair	14,362,000	0.1 mile	No	Yes	No	Research Report 98	120+
63	62	Wichita Falls	Archer	82 Foamed Asph	Dry - Cold	Poor	2,739,000	3 miles	Yes	Yes	Yes	ernal and ASCE repo	70+
64	63	Wichita Falls	Wichita	S 82 Lime Treate	Dry - Cold	Poor	2,739,000	1 mile	No	No	No	ernal and ASCE repo	120+
65	64	Austin	Blanco	US 290 WB	Mixed	Very Good	1,340,000	0.15 miles	No	No	Yes	Description	90+
66	65	Houston	Harris	US 290 FR good	Wet - Warm	Very Good	2,404,000	0.3 miles	Yes	Yes	Yes	GPR, cores and Desig	280+
67	66	Houston	Harris	US 290 FR bad	Wet - Warm	Very Good	2,404,000	0.4 miles	Yes	Yes	Yes	GPR, cores and Desig	280+
68	67	Houston	Harris	90 FR Bad Inside	Wet - Warm	Very Good	2,404,000	0.4 miles	Yes	Yes	Yes	GPR, cores and Desig	280+
69	68	Houston	Harris	0 FR Bad Outside	Wet - Warm	Very Good	2,404,000	0.4 miles	Yes	Yes	Yes	GPR, cores and Desig	280+
70	69	Ft. Worth	Jack	US 281 SB	Wet - Cold	Fair	2,404,000	0.29 miles	Yes	Yes	Yes	Research Report 18	55
71	70	Ft. Worth	Jack	US 281 NB	Wet - Cold	Good	2,404,000	0.29 miles	Yes	Yes	Yes	Research Report 18	55
72	71	Childress	Motley	US 70 / US 62 WE	Dry - Cold	Very Good	685,000	5.4 miles	No	No	No	Description	75
73	72	Ft. Worth	Hood	FM 51	Wet - Cold	Very Good	7,952,000	1.1 miles	No	No	No	Plans	300+
74	73	Pharr	Cameron	1479 test sectio	Dry - Warm	Fair	1,037,000	0.1 mile	No	No	No	Pavement Design	300+
75	74	Pharr	Cameron	1479 test sectio	Dry - Warm	Good	1,037,000	0.05 mile	No	No	No	Plans	300+
76	75	Pharr	Cameron	1479 test sectio	Dry - Warm	Fair	1,037,000	0.1 mile	No	No	No	Plans	300+
77	76	Pharr	Cameron	1 800 test sectio	Dry - Warm	Fair	1,220,000	0.1 mile	Yes	Yes	Yes	ic Investigation and	300+
78	77	Pharr	Cameron	1 800 test sectio	Dry - Warm	Fair	1,220,000	1.4 mile	Yes	Yes	Yes	ic Investigation and	300+
79	78	Pharr	Cameron	1 800 test sectio	Dry - Warm	Fair	1,220,000	0.1 mile	Yes	Yes	Yes	ic Investigation and	300+
80	79	Pharr	Cameron	FM 1419	Dry - Warm	Good	1,195,000	5.7 miles	No	No	No	ent Design & Forensi	300+

	Test Section Number	District	County	Route	Environmental Region	Subgrade Soil Category	20 Yr ESALs	Length (miles)	Ground Penetrating Radar Data	Cores	Dynamic Cone Penetrometer	Typical Sections	Average Bedrock Depth (in)
81	80	Laredo	Duval	FM 1329	Dry - Warm	Very Good	473,000	8.5 miles	No	No	No	Plans	140+
82	81	Laredo	Webb	Loop 20 NB	Dry - Warm	Poor	5,117,000	1.9 miles	No	No	No	Plans	110+
83	82	Laredo	Webb	Loop 20 SB	Dry - Warm	Poor	5,117,000	1.8 miles	No	No	No	Plans	110+
84	83	Laredo	Webb	SH 359 EB	Dry - Warm	Poor	13,119,000	4.7 miles	No	No	No	Plans	75+
85	84	Laredo	Duval	59 NB @ San Dieg	Dry - Warm	Fair	3,633,000	1.5 miles	No	No	No	Plans	110+
86	85	Laredo	Duval	59 NB @ San Dieg	Dry - Warm	Fair	3,633,000	1.4 miles	No	No	No	Plans	110+
87	86	El Paso	El Paso	FM 1281 NB	Dry - Warm	Good	14,824,000	2.5 miles	No	Yes	No	and Core log spreads	80+
88	87	El Paso	Hudspeth	FM 1437 SB	Dry - Warm	Very Good	588,000	9.0 miles	No	Yes	No	Core log spreadsheet	92+
89	88	El Paso	El Paso	US 62 EB	Dry - Warm	Poor	3,344,000	3.8 miles	No	Yes	No	Core log spreadsheet	90+
90	89	El Paso	El Paso	US 62 WB	Dry - Warm	Poor	2,415,000	4.2 miles	No	Yes	No	Core log spreadsheet	90+
91	90	El Paso	Culberson	SH 54 SB	Dry - Warm	Very Good	778,000	4.489 miles	No	Yes	No	log and pavement de	70+
92	91	El Paso	El Paso	SH 20	Dry - Warm	Poor	543,000	5.216 miles	No	Yes	No	Core log	130
93	92	Corpus Christi	Live Oak	FM 2049	Wet - Warm	Very Poor	132,000	0.5 miles	No	No	No	d analysis request D	70+
94	93	Pharr	Starr	FM 1017	Dry - Warm	Very Good	887,000	5.63 miles	No	No	No	d analysis request D	80+
95	94	Pharr	Starr	FM 1017	Dry - Warm	Very Good	887,000	4.665 miles	No	No	No	d analysis request D	70+
96	95	Lubbock	Floyd	FM 28 NB	Dry - Cold	Poor	6	1.02 miles	No	No	Yes	DCP readings	120+
97	96	Lubbock	Floyd	FM 28 NB	Dry - Cold	Poor	6	1.0 miles	No	No	Yes	DCP readings	120+
98	97	Lubbock	Floyd	FM 28 P1, P2, P3	Dry - Cold	Poor	6	900 feet	No	No	Yes	DCP readings	120+
99	98	San Antonio	Atascosa	FM 476	Dry - Warm	Good	1,222,000	8.001 miles	No	No	No	Description	70+
100	99	San Antonio	Atascosa	FM 3175	Dry - Warm	Fair	1,425,000	8.388 miles	No	No	No	Description	70+
101	100	San Antonio	Bexar	FM 1346	Dry - Warm	Fair	624,000	6.673 miles	No	No	No	Description	80+
102	101	Lufkin	Angelina	FM 1669	Wet - Warm	Fair	1,225,000	0.71	No	No	No	Description	230
103	102	Houston	Harris	FM 2553	Wet - Warm	Fair	1,910,000	0.50 miles	No	No	No	Description	230
104	103	Amarillo	Sherman	FM 1290	Dry - Cold	Fair	626,000	11.753	No	No	No	d analysis request D	70
105	104	Ft. Worth	Palo Pinto	FM 1821	Wet - Cold	Good	3,813,000	1.0 miles	No	No	No	d analysis request D	125
106	105	Ft. Worth	Palo Pinto	FM 3027	Wet - Cold	Very Good	1,809,000	1.722 miles	No	No	No	d analysis request D	60+
107	106	Atlanta	Cass	FM 2327	Wet - Cold	Good	761,000	6.0 miles	No	No	No	d analysis request D	60+
108	107	Atlanta	Titus	FM 2882	Wet - Cold	Poor	142,000	1.4 miles	No	No	No	d analysis request D	60+

Test Section Number	District	County	Route	Environmental Region	Subgrade Soil Category	20 Yr ESALs	Length (miles)	Ground Penetrating Radar Data	Cores	Dynamic Cone Penetrometer	Typical Sections	Average Bedrock Depth (in)
108	Atlanta	Titus	FM 21	Wet - Cold	Very Poor	152,000	1.8 miles	No	No	No	d analysis request D	60+
109	Atlanta	Titus	FM 71	Wet - Cold	Poor	225,000	13.6 miles	No	No	No	d analysis request D	90+
110	Yoakum	Wharton	FM 1299	Wet - Warm	Good	685,000	3.1 miles	No	No	No	Description	300+
111	Atlanta	Cass	FM 3129	Wet - Cold	Very Good	1,159,000	2.8 miles	No	No	No	d analysis request D	70
112	Atlanta	Cass	FM 3129	Wet - Cold	Very Good	1,159,000	1.98 miles	No	No	No	d analysis request D	70
113	Beaumont	Orange	FM 1135	Wet - Warm	Poor	655,000	3.9 miles	No	No	No	Description	100
114	Corpus Christi	San Patricio	FM 796	Wet - Warm	Very Poor	43,000	3.9 miles	No	No	No	Description	100
115	Houston	Waller	FM 2979	Wet - Warm	Fair	332,000	4.15 miles	No	No	No	Description	120
116	Houston	Waller	FM 1736	Wet - Warm	Fair	553,000	6.5 miles	No	No	No	Description	135
117	Austin	Lee	FM 180	Mixed	Fair	772,000	13.3 miles	No	No	No	d analysis request &	100
118	Waco	Bell	FM 93	Mixed	Very Good	1,002,000	6.0 miles	No	No	No	d analysis request &	87
119	Waco	Bell	FM 93	Mixed	Very Good	1,323,000	0.3 miles	No	No	No	d analysis request &	100
120	Waco	Bell	FM 93	Mixed	Poor	1,165,000	0.6 miles	No	No	No	d analysis request &	95
121	Waco	Bell	FM 93	Mixed	Poor	1,901,000	3.4 miles	No	No	No	d analysis request &	200
122	Waco	Bell	FM 93	Mixed	Fair	1,838,000	3.75 miles	No	No	No	d analysis request &	125
123	Waco	Bell	FM 439	Mixed	Good	1,719,000	2.6 miles	No	No	No	d analysis request &	85
124	Waco	McLennan	FM 933	Mixed	Good	614,000	5.22 miles	No	No	No	34R LZ road analysis	85
125	Waco	McLennan	FM 933	Mixed	Fair	968,000	7.22 miles	No	No	No	34R LZ road analysis	90
126	Waco	McLennan	FM 933	Mixed	Very Good	2,243,000	5.35 miles	No	No	No	34R LZ road analysis	115
127	Waco	McLennan	FM 2188	Mixed	Poor	377,000	2.22 miles	No	No	No	34R LZ road analysis	105
128	Waco	McLennan	FM 3148	Mixed	Very Good	887,000	5.5 miles	No	No	No	34R LZ road analysis	250
129	Waco	McLennan	FM 308	Mixed	Very Good	1,168,000	3.05 miles	No	No	No	34R LZ road analysis	180+
130	Waco	McLennan	FM 107	Mixed	Good	1,513,000	6.838 miles	No	No	No	34R LZ road analysis	110
131	Waco	Limestone	FM 937	Mixed	Very Good	229,000	6.53 miles	No	No	No	34R LZ road analysis	215
132	Waco	Limestone	FM 3371	Mixed	Fair	310,000	3.35 miles	No	No	No	34R LZ road analysis	80
133	Waco	Limestone	FM 1633	Mixed	Very Good	510,000	9.28 miles	No	No	No	34R LZ road analysis	300
134	Waco	Hill	FM 310	Mixed	Good	335,000	11.85 miles	No	No	No	34R LZ road analysis	300
135	Waco	Hill	FM 933	Mixed	Very Good	600,000	5.82 miles	No	No	No	34R LZ road analysis	300



Test Section Number	District	County	Route	Environmental Region	Subgrade Soil Category	20 Yr ESALs	Length (miles)	Ground Penetrating Radar Data	Cores	Dynamic Cone Penetrometer	Typical Sections	Average Bedrock Depth (in)
136	Waco	Hill	FM 933	Mixed	Very Good	526,000	2.90 miles	No	No	No	34R LZ road analysis	300
137	Waco	Hill	FM 933	Mixed	Very Good	1,687,000	2.94 miles	No	No	No	34R LZ road analysis	300
138	Yoakum	Jackson	FM 530	Wet-Warm	Good	150,000	18.9 miles	No	No	No	Description	300
139	Yoakum	Wharton	FM 1160	Wet-Warm	Good	160,000	9.804 miles	No	No	No	Description	300
140	Yoakum	Jackson	FM 234	Wet-Warm	Good	1,111,000	10.25 miles	No	No	No	Description	300
141	Waco	Hamilton	FM 1602	Wet-Warm	Very Good	159,000	9.63 miles	No	No	No	34R LZ road analysis	150
142	Waco	Falls	FM 712	Wet-Warm	Very Good	103,000	5.76 miles	No	No	No	34R LZ road analysis	300
143	Waco	Falls	FM 1671	Mixed	Good	100,000	6.03 miles	No	No	No	34R LZ road analysis	300
144	Waco	Bosque	FM 1637	Mixed	Very Good	326,000	4.14 miles	No	No	No	34R LZ road analysis	65
145	Waco	Bosque	FM 2490	Mixed	Very Good	939,000	7.93 miles	No	No	No	34R LZ road analysis	55
146	Waco	Bell	FM 2843	Mixed	Very Good	415,000	2.43 miles	No	No	No	34R LZ road analysis	55
147	Waco	Bell	FM 2843	Mixed	Very Good	415,000	8.603 miles	No	No	No	34R LZ road analysis	60
148	Austin	Travis	FM 734 EB	Mixed	Very Good	3,486,000	0.98 miles	No	Yes	No	Description and core	280
149	Austin	Travis	FM 734 WB	Mixed	Very Good	3,486,000	0.98 miles	No	Yes	No	Description and core	300
150	Austin	Travis	US 290 EB	Mixed	Very Good	9,568,000	3.558 miles	No	No	No	Description	150
151	Austin	Travis	FM 2304	Mixed	Good	1,827,000	0.883 miles	No	No	No	Description	80
152	Austin	Llano	SH 71	Mixed	Fair	1,216,000	1 mile	No	No	No	Description	85
153	Austin	Burnet	US 281 A	Mixed	Very Good	10,288,000	0.54 miles	No	No	No	Description	65
154	Austin	Burnet	US 281 B	Mixed	Good	13,132,000	0.98 miles	No	No	No	Description	65
155	Austin	Burnet	US 281 C	Mixed	Very Good	13,285,000	4.267 miles	No	No	No	Description	100
156	Wichita Falls	Wichita	FM 369	Dry-Cold	Good	949,000	1.734 miles	No	No	No	ic Investigation and	55
157	Austin	Travis	IH 35 R1 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	ic Investigation and	75
158	Austin	Travis	IH 35 R2 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	ic Investigation and	75
159	Austin	Travis	IH 35 L1 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	ic Investigation and	75
160	Austin	Travis	IH 35 L2 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	ic Investigation and	75
161	Austin	Travis	35 Center Lane 20	Mixed	Very Good	49,150,000	0.2 miles	No	No	No	ic Investigation and	75
162	Austin	Travis	35 NB Left Lane 20	Mixed	Good	49,150,000	0.3 miles	No	No	No	ic Investigation and	75
163	Austin	Travis	5 NB Right Lane 2	Mixed	Fair	49,150,000	0.3 miles	No	No	No	ic Investigation and	75



Test Section Number	District	County	Route	Environmental Region	Subgrade Soil Category	20 Yr ESALs	Length (miles)	Ground Penetrating Radar Data	Cores	Dynamic Cone Penetrometer	Typical Sections	Average Bedrock Depth (in)
152	Austin	Llano	SH 71	Mixed	Fair	1,216,000	1 mile	No	No	No	Description	85
153	Austin	Burnet	US 281 A	Mixed	Very Good	10,288,000	0.54 miles	No	No	No	Description	65
154	Wichita Falls	Wichita	FM 369	Dry-Cold	Good	949,000	1.734 miles	No	No	No	ic Investigation and	55
155	Austin	Travis	IH 35 R1 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	ic Investigation and	75
156	Austin	Travis	IH 35 R2 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	ic Investigation and	75
157	Austin	Travis	IH 35 L1 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	ic Investigation and	75
158	Austin	Travis	IH 35 L2 2002	Mixed	Poor	49,150,000	0.3 miles	No	Yes	Yes	ic Investigation and	75
159	Austin	Travis	35 Center Lane 20	Mixed	Very Good	49,150,000	0.2 miles	No	No	No	ic Investigation and	75
160	Austin	Travis	35 NB Left Lane 20	Mixed	Good	49,150,000	0.3 miles	No	No	No	ic Investigation and	75
161	Austin	Travis	5 NB Right Lane 2	Mixed	Fair	49,150,000	0.3 miles	No	No	No	ic Investigation and	75
162	Austin	Travis	35 SB Left Lane 20	Mixed	Fair	49,150,000	0.3 miles	No	No	No	ic Investigation and	75
163	Austin	Travis	5 SB Right Lane 2	Mixed	Very Good	49,150,000	0.3 miles	No	No	No	ic Investigation and	110
164	Austin	Travis	FM 973 SB	Mixed	Very Good	2,695,000	0.3 miles	No	No	No	Description	280
165	Austin	Travis	FM 973 NB	Mixed	Fair	2,695,000	0.3 miles	No	No	No	Description	120
166	Waco	Falls	SH 6 EB	Mixed	Very Good	10,636,000	6.003 miles	No	No	No	Plans	150
167	Waco	Bell	FM 2410	Mixed	Fair	789,000	1.14 miles	No	No	No	34R LZ road analysis	80
168	Waco	Bell	FM 2305	Mixed	Good	5,105,000	1.3 miles	No	No	No	34R LZ road analysis	75
169	Waco	Bell	FM 2305	Mixed	Very Good	1,556,000	3.6 miles	No	No	No	34R LZ road analysis	180
170	Waco	Bell	FM 2305	Mixed	Very Good	1,229,000	1.3 miles	No	No	No	34R LZ road analysis	120
171	Waco	Bell	FM 2271	Mixed	Very Good	1,052,000	1.949 miles	No	No	No	34R LZ road analysis	85
172	Waco	Bell	FM 1741	Mixed	Very Good	1,405,000	2.66 miles	No	No	No	34R LZ road analysis	125
173	Waco	Bell	FM 1741	Mixed	Fair	1,757,000	0.6 miles	No	No	No	34R LZ road analysis	100
174	Waco	Bell	FM 1741	Mixed	Very Good	503,000	0.9 miles	No	No	No	34R LZ road analysis	100
175	Waco	Bell	FM 1741	Mixed	Fair	253,000	1.85 miles	No	No	No	34R LZ road analysis	65
176	Waco	Bell	FM 1671	Mixed	Fair	59,000	1.07 miles	No	No	No	34R LZ road analysis	300
177	Waco	Bell	FM 485	Mixed	Good	456,000	6.24 miles	No	No	No	34R LZ road analysis	300
178	Waco	Bell	FM 437	Mixed	Good	526,000	1.946 miles	No	No	No	34R LZ road analysis	300
179	Austin	Travis	US 183 NB	Mixed	Very Good	6,116,000	2.634 miles	No	No	No	Plans	150+/-
180	Austin	Travis	US 183 SB	Mixed	Very Good	6,116,000	2.682 miles	No	No	No	Plans	135+/-

Appendix C: SCI Algorithm Coding

```
Sub SCIRun()
Dim xlApp As Object
Dim xlSht As Excel.Worksheet
Set xlApp      =       CreateObject("excel.application")
Set xlSht      =       ActiveSheet
FinalRow       =       Range("B65536").End(xlUp).Row
sheetname      =       ActiveSheet.Name
Range("U3")    =       FinalRow

If (Range("ZY4").Value Or Range("ZY5").Value) Then
  Range("V23:V" & CStr(FinalRow)) = "ST"
Else
  Range("V23:V" & CStr(FinalRow)) = "AC"
End If

For i = 23 To FinalRow
district = Range("C" & CStr(i))

Select Case district
Case "Abilene", "Amarillo", "Lubbock", "Childress", "Wichita Falls"
  Range("D" & CStr(i)) = "Dry-Cold"
Case "Austin", "Brownwood", "Waco", "Bryan"
  Range("D" & CStr(i)) = "Mixed"
Case "Fort Worth", "Dallas", "Paris", "Atlanta", "Tyler"
  Range("D" & CStr(i)) = "Wet-Cold"
Case "Corpus Christi", "Yoakum", "Houston", "Beaumont", "Lufkin"
  Range("D" & CStr(i)) = "Wet-Warm"
Case "El Paso", "Odessa", "San Angelo", "San Antonio", "Laredo", "Pharr"
  Range("D" & CStr(i)) = "Dry-Warm"
End Select

Next i

For i = 23 To FinalRow
  For j = 1 To 7
  Cells(i, 22 + j) = Round((9000 * 25.4 * Cells(i, 13 + j).Value) / (Cells(i, 13)), 2)
  Next j
Next i

For i = 23 To FinalRow
    Cells(i, 30) = Round(0.33 * 0.24 * Cells(i, 13) / ((Cells(i, 20) / 1000) * 72), 2) 'AASHTO MR
  Cells(i, 31) = Round(1.5 * 25.4 * Cells(i, 7).Value, 2)
Next i
```

```
i = 23
While i >= 2 And i <= FinalRow 'Offset for every row
'Calculate offset
Cells(1, 100) = 0
Cells(2, 100) = 305
Cells(3, 100) = 610
Cells(4, 100) = 914
Cells(5, 100) = 1219
Cells(6, 100) = 1524
Cells(7, 100) = 1829
For j = 1 To 7
  Cells(j, 101) = Abs(Cells(i, 31) - Cells(j, 100))
  Cells(j, 102) = Cells(i, 22 + j)
Next j
j = 0

k = 7
While k > 0
  Range("CW1:CW" & CStr(k)).Select
  minval = xlApp.WorksheetFunction.Min(xlSht.Range("CW1:CW" & CStr(k)))
  For mincount = 1 To k
    If Range("CW" & CStr(mincount)).Value = minval Then
      minrow = mincount
      Exit For
    End If
  Next mincount
  Range("CV" & minrow & ":CX" & minrow).Select
  Selection.Cut
  Range("CY" & 8 - k & ":DA" & 8 - k).Select
  ActiveSheet.Paste
  Range("CV" & minrow & ":CX" & minrow).Select
  Selection.Delete Shift:=xlUp
  k = k - 1
Wend
Range("CY1:DA7").Select
Selection.Cut
Range("CV1:CX7").Select
ActiveSheet.Paste

Ra = Cells(1, 100)
Rb = Cells(2, 100)
Rc = Cells(3, 100)
Rab = Ra - Rb
Rac = Ra - Rc
Rba = Rb - Ra
```

```
  Rbc = Rb - Rc
  Rca = Rc - Ra
  Rcb = Rc - Rb
  Rxa = Cells(i, 31) - Ra
  Rxb = Cells(i, 31) - Rb
  Rxc = Cells(i, 31) - Rc
  Da = Cells(1, 102)
  Db = Cells(2, 102)
  Dc = Cells(3, 102)
  Cells(i, 32) = Round(((Rxb * Rxc * Da) / (Rab * Rac)) + ((Rxa * Rxc * Db) / (Rba *Rbc)) +
((Rxa * Rxb * Dc) / (Rca * Rcb)), 2)
  i = i + 1
  Wend

Range("CV1:CX7").Select
Selection.Delete Shift:=xlUp
Range("AC2").Select

For i = 23 To FinalRow
  Cells(i, 33) = Round(Cells(i, 23) - Cells(i, 32), 2) 'W1-W1.5Hp
  If (Cells(i, 22) = "AC") Then
    k1 = 0.4728
    k2 = -0.481
    k3 = 0.7581
  Else
'  If (Cells(i, 12) = "ST") Then
    k1 = 0.1165
    k2 = -0.3248
    k3 = 0.8241
  End If
  Cells(i, 34) = Round(k1 * Cells(i, 33) ^ k2 * (25.4 * Cells(i, 7)) ^ k3, 2)
  Cells(i, 35) = Round(SNreq(Cells(i, 21), Cells(i, 30)), 2)
  Cells(i, 36) = Round(Cells(i, 34) / Cells(i, 35), 2)
Next i

Range("AJ23:AJ" & CStr(FinalRow)).Select
Selection.NumberFormat = "0.00"

ActiveSheet.Shapes.AddChart.Select
ActiveChart.ChartType = xlLineMarkersStacked
ActiveChart.SeriesCollection.NewSeries
ActiveChart.SeriesCollection(1).Values = "='" + sheetname + "'!$AJ$23:$AJ$"
+CStr(FinalRow)
ActiveChart.SeriesCollection(1).XValues = "='" + sheetname + "'!$F$23:$F$"
+CStr(FinalRow)
ActiveChart.Legend.Select
```

```
Selection.Delete
ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
ActiveChart.Axes(xlCategory).AxisTitle.Select
ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "TRM"

ActiveChart.ChartArea.Select
ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
ActiveChart.Axes(xlValue).AxisTitle.Select
ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "Structural Condition Index (SCI)"

ActiveChart.ChartArea.Select
ActiveChart.SetElement (msoElementChartTitleAboveChart)
ActiveChart.ChartTitle.Text = " SCI vs TRM Plot"


ActiveSheet.Shapes.AddChart.Select
ActiveChart.ChartType = xlLineMarkersStacked
ActiveChart.SeriesCollection.NewSeries
ActiveChart.SeriesCollection(1).Values = "='" + sheetname + "'!$AJ$23:$AJ$"
+CStr(FinalRow)
ActiveChart.SeriesCollection(1).XValues = "='" + sheetname + "'!$E$23:$E$"
+CStr(FinalRow)
ActiveChart.Legend.Select
Selection.Delete
ActiveChart.SetElement (msoElementPrimaryCategoryAxisTitleAdjacentToAxis)
ActiveChart.Axes(xlCategory).AxisTitle.Select
ActiveChart.Axes(xlCategory, xlPrimary).AxisTitle.Text = "FWD Stations"

ActiveChart.ChartArea.Select
ActiveChart.SetElement (msoElementPrimaryValueAxisTitleRotated)
ActiveChart.Axes(xlValue).AxisTitle.Select
ActiveChart.Axes(xlValue, xlPrimary).AxisTitle.Text = "Structural Condition Index(SCI)"

ActiveChart.ChartArea.Select
ActiveChart.SetElement (msoElementChartTitleAboveChart)
ActiveChart.ChartTitle.Text = " SCI vs FWD Stations Plot"
End Sub

Function SNreq(ByVal X As Double, ByVal Y As Double) As Double

n = Range("ZX4").Value
For i = (11 * (n - 1) + 6) To (11 * (n - 1) + 10)
minval = Sheets("SNReq").Cells(i, 4)
If Y >= minval Then yindex = i Else Exit For
Next i
```

```
For j = 6 To 10
minval = Sheets("SNReq").Cells((11 * (n - 1) + 4), j)
If X >= minval Then xindex = j Else Exit For
Next j

SNreq = Sheets("SNReq").Cells(yindex, xindex)

End Function
```

Appendix D: SCI Algorithm User Manual

This document provides a user manual for the Structural Condition Index (SCI) Algorithm Tool developed under the Project 5-4322-01: Implementation of a Network-Level Structural Condition Index Based on Falling Weight Deflectometer Data. This user manual is prepared so as to address Task 7 of assisting TxDOT in implementing the SCI.

D1. Introduction to the Tool

The user manual for the SCI Algorithm Tool is prepared so that the necessary material to assist TxDOT is provided with the implementation of the SCI upon completion of validating and testing the SCI. The tool is an interface between SCI methodology and the users. The SCI Algorithm Tool allows the user to input the required data, run the algorithm, and view SCI analysis results for any pavement section. This user manual will specifically address the new SCI index and give necessary guidelines on how it can be used to evaluate the condition of a roadway. This manual will further provide background in FWD testing and analysis concepts for network-level applications.

D2. Important Features of the Tool

D2.1 System Requirements

To use the SCI Algorithm, Microsoft Office should be installed on the computer. The algorithm was written in macro-enabled Excel using Visual Basic for Applications (VBA). Visual Basic for Applications, Excel's powerful built-in programming language, permits users to easily incorporate user-written functions into a spreadsheet.

D2.2 Programming Structure

The SCI algorithm is stored in a module in a workbook called as "SCI Analysis Workbook." This workbook has to be saved in the user's computer as a macro-enabled Excel workbook to run the analysis. The workbook contains a total of four worksheets as shown in Figure D1: Example SCI Analysis, SCI Analysis Module, SNReq, and Drop Down Box inputs.

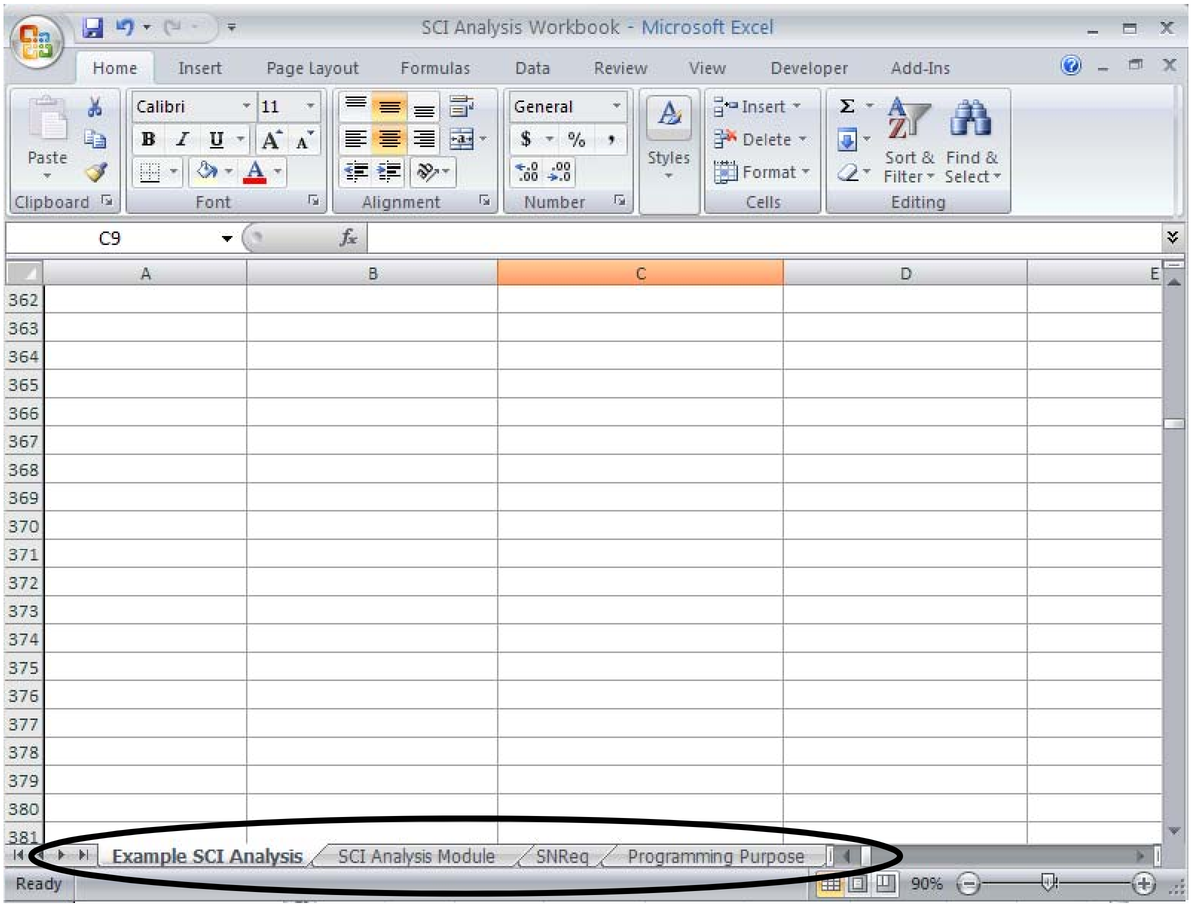


Figure D1: "SCI Analysis Workbook" Macro-enabled Excel Workbook

D2.3 Tab 1: Example SCI Analysis

The first worksheet is the "Example SCI Analysis" worksheet used for demonstration purposes in the SCI Analysis workbook. This worksheet acts as a quick reference for the user to understand how to specify the inputs. The input units of measurement are specified in the input headings. The SCI analysis code works well only when certain measurement units are used for inputs. The input data must be in the correct units to avoid debug problems later (see Figure D2).

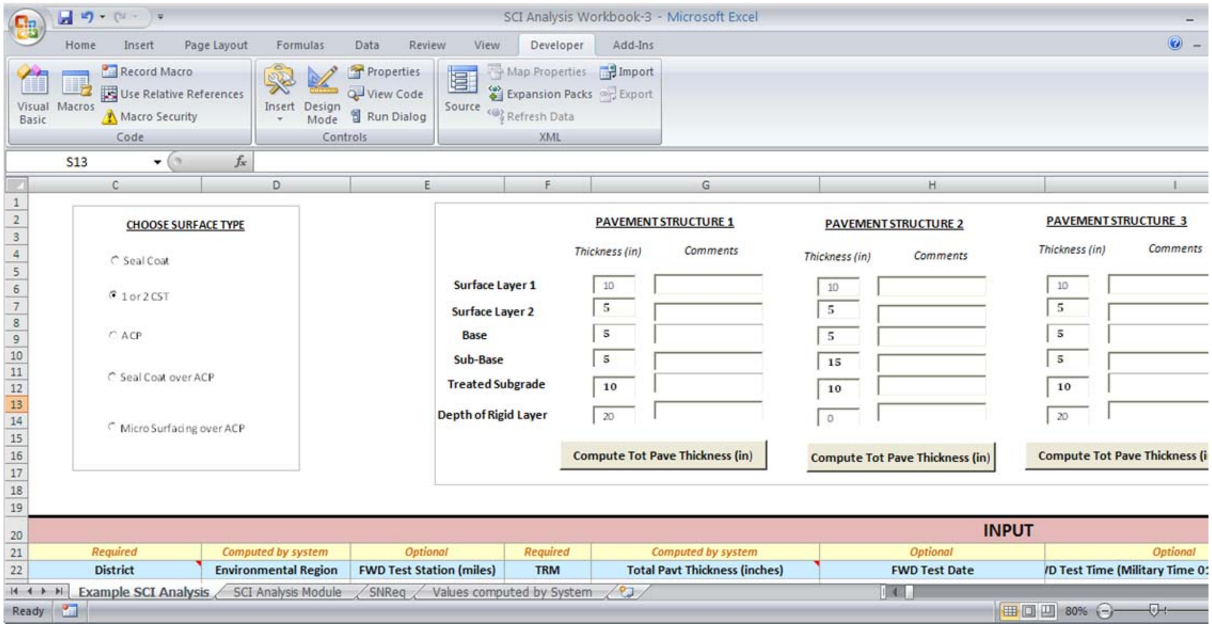


Figure D2: Input data screen 1

The input data and output data are separated. Not all of the potential input data is necessary. Hence, input data is labeled as either required or optional. Some data, such as environmental region, is computed by the tool and hence the Environmental Region column is labeled as "Computed by system," as shown in Figure D3.

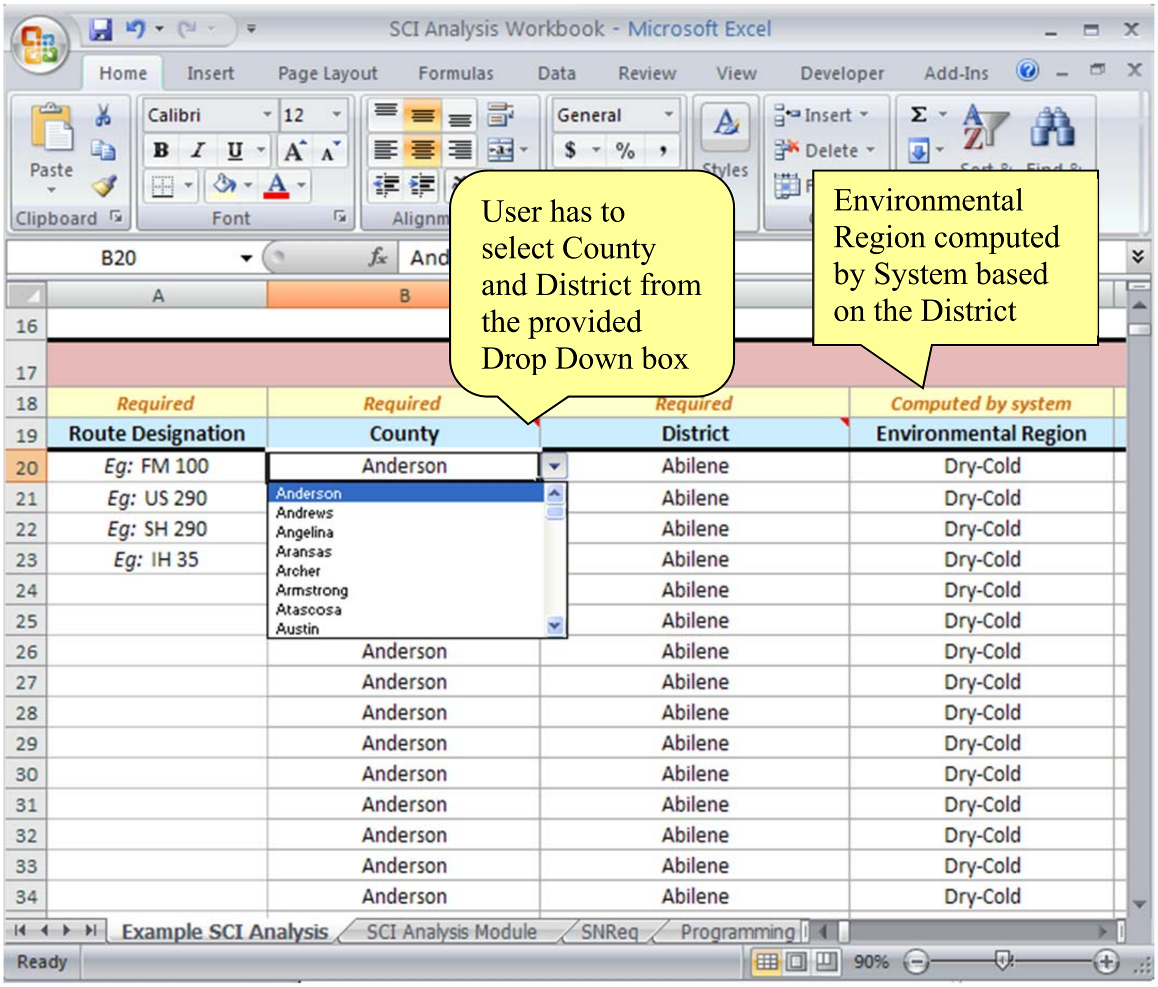


Figure D3: Input data screen 2

Figure D3 indicates that Column A of a pavement section is the Route Designation. The user needs to specify the route. For example, the Column A could be either FM 100 or US 290 or SH 290 or IH 35. Column B and Column C are the County and District. Texas has a total of 254 counties, 25 Districts, and 5 environmental zones. The user has to select the county and district from the provided drop down box. The tool processes the district data to get the appropriate environmental region in Column D for the selected county.

The surface type can be either surface treatment or asphalt concrete. The user can choose the appropriate surface type by choosing the right box out of the given five options (see Figure D4). The next step is to input the pavement thickness information. A route may consist of more than one pavement structure. In this tool, a total of five pavement structure thickness levels can be recorded. The user should select the cell, and then click on "Compute Tot Pavement Thickness (in)" under Pavement Structure 1. Similarly, the user has to select the corresponding Texas Reference Marker (TRM) thickness cell at that point where the pavement structure 2 begins before clicking on "Compute Tot Pavement Thickness (in)" under Pavement Structure 2. The user must provide values for the layer thickness information cells, including '0' inches of any layer, to avoid debug problems later.

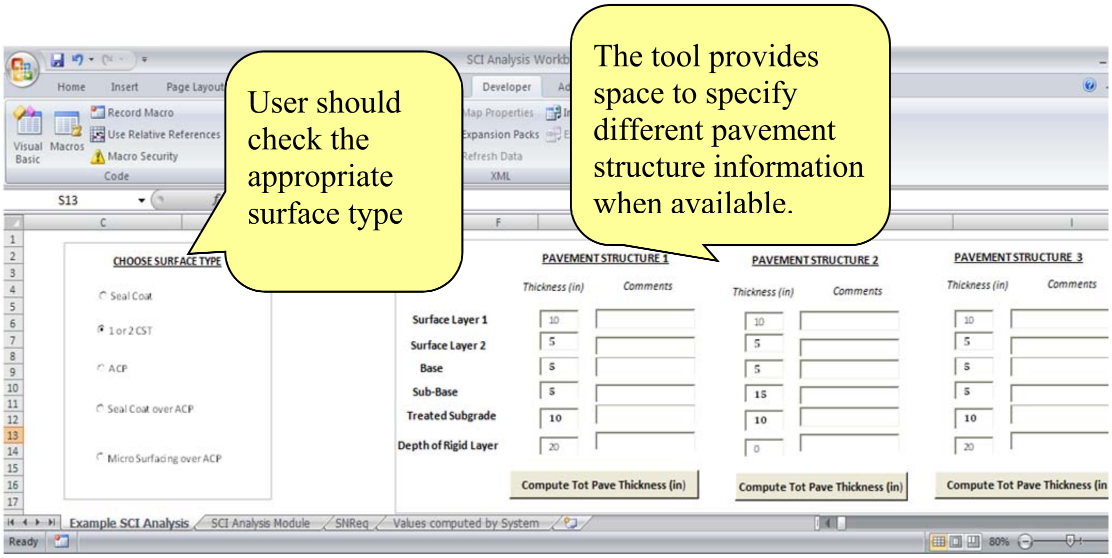


Figure D4: Surface type and pavement structure data

As shown in Figure D5, Column E is the FWD Test Station in miles and Column F is used to specify TRM for identifying the location. Column G stores the computed Total Pavement Thickness, which is the thickness of better materials above the natural or prepared sub-grade. The user has the option of providing Date and FWD Test Time (in military hours) in Column H and Column I, respectively.

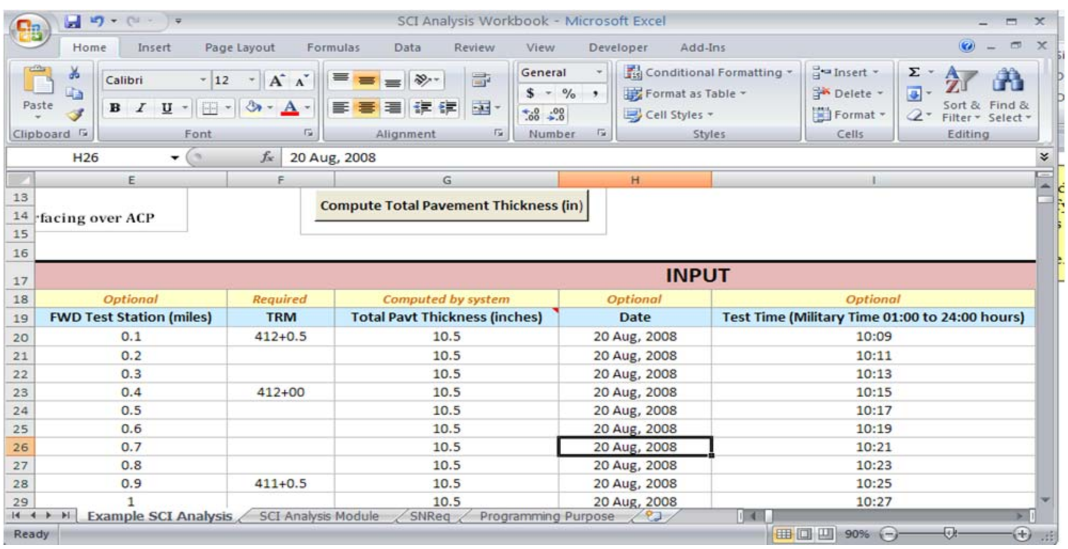


Figure D5: Input data screen 3

Pavement temperature, air temperature, and surface temperature (in Fahrenheit) is to be noted in Columns J, K, and L, respectively. At this time, the SCI methodology does not take temperature into account for the analysis. Columns for FWD testing time and temperatures have been provided so as to facilitate temperature corrections of SCI in the future. The tool also provides descriptions of pavement temperature, air temperature, and surface temperature, as shown in Figure D6.

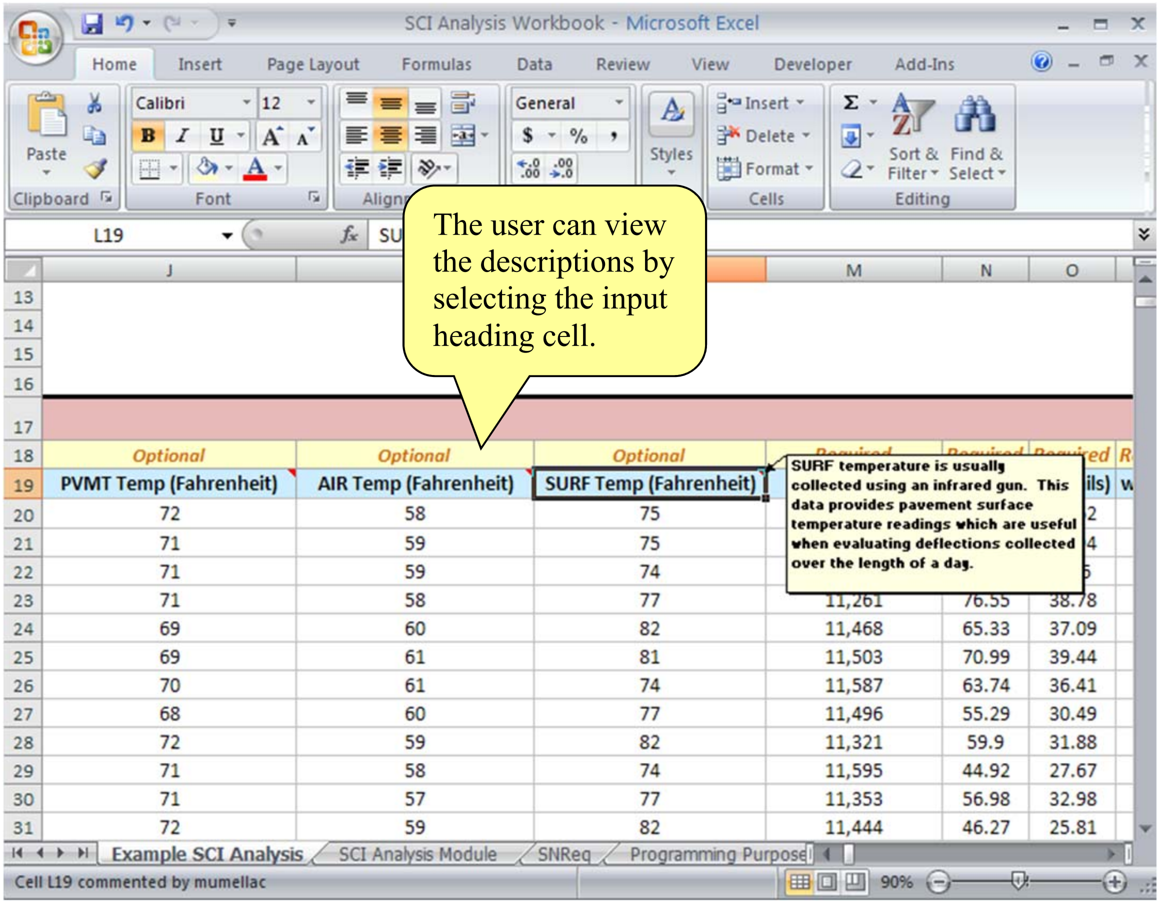
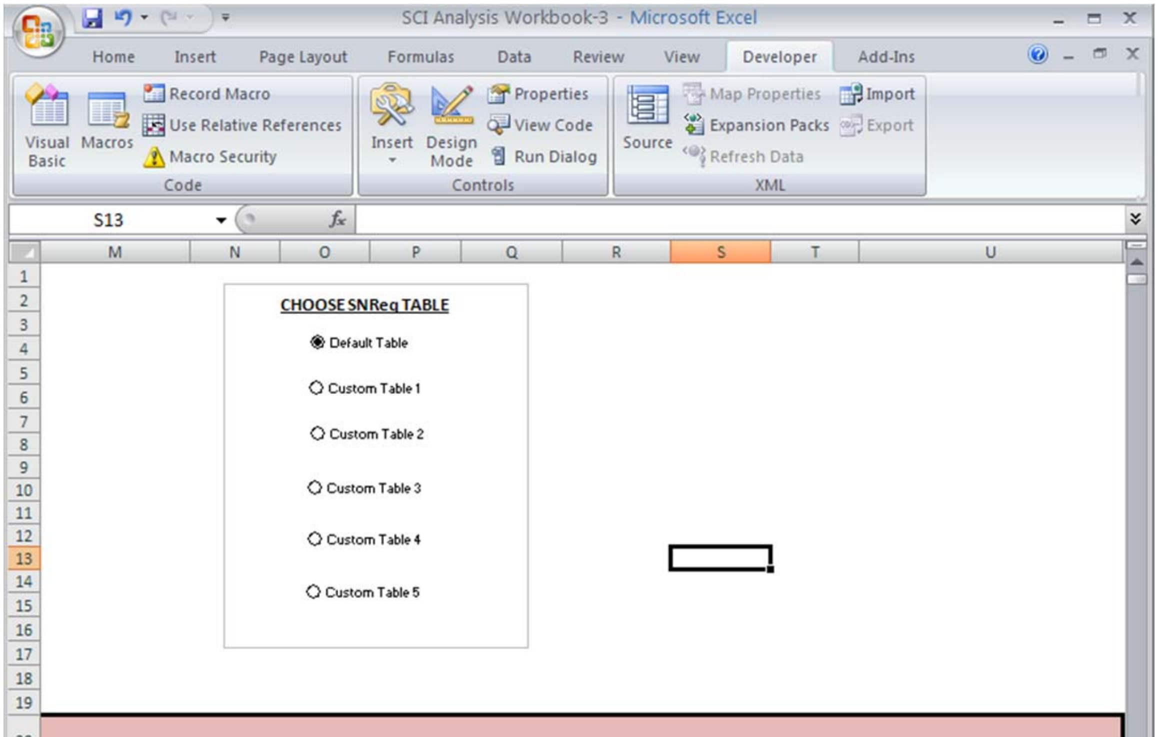


Figure D6: Optional input data

The user is provided with the option of choosing SNReq Table (see Figure D7). The current SCI Analysis is based on the values taken from the default table. More details about the SNReq Table are given in Section 2.5 of the report. The load at which FWD measurements are recorded is in Column M. The recorded FWD reading (in mils) for seven sensors are to be inputted in Column N to Column T. Column U includes the estimated 20-year ESALS traffic.



Required	Required	Required	Required	Required	Required	Required	Required	Required
Load (Pounds)	w1 (mils)	w2 (mils)	w3 (mils)	w4 (mils)	w5 (mils)	w6 (mils)	w7 (mils)	Traffic (20 year estimated ESALS)
11,905	29.31	21.62	14.64	8.33	6.36	4.67	3.79	467000
11,754	59.85	37.94	19.43	9.36	7.84	6.42	5.21	467000
11,587	68.15	38.6	16.95	8.11	6.96	5.88	4.83	467000
11,261	76.55	38.78	14.52	7.59	6.65	5.66	4.69	467000
11,468	65.33	37.09	15.85	7.63	6.41	5.26	4.28	467000

Figure D7: Choosing SNReq table

D2.4 Tab 2: SCI Analysis Module

Based on the reference worksheet “Example SCI Analysis,” the user can now input the data into Sheet 2 of the workbook, “SCI Analysis Module” (shown in Figure D8). The user has to carefully follow the instructions and specifications mentioned in the “Example SCI Analysis” to work with new data in “SCI Analysis Module.”

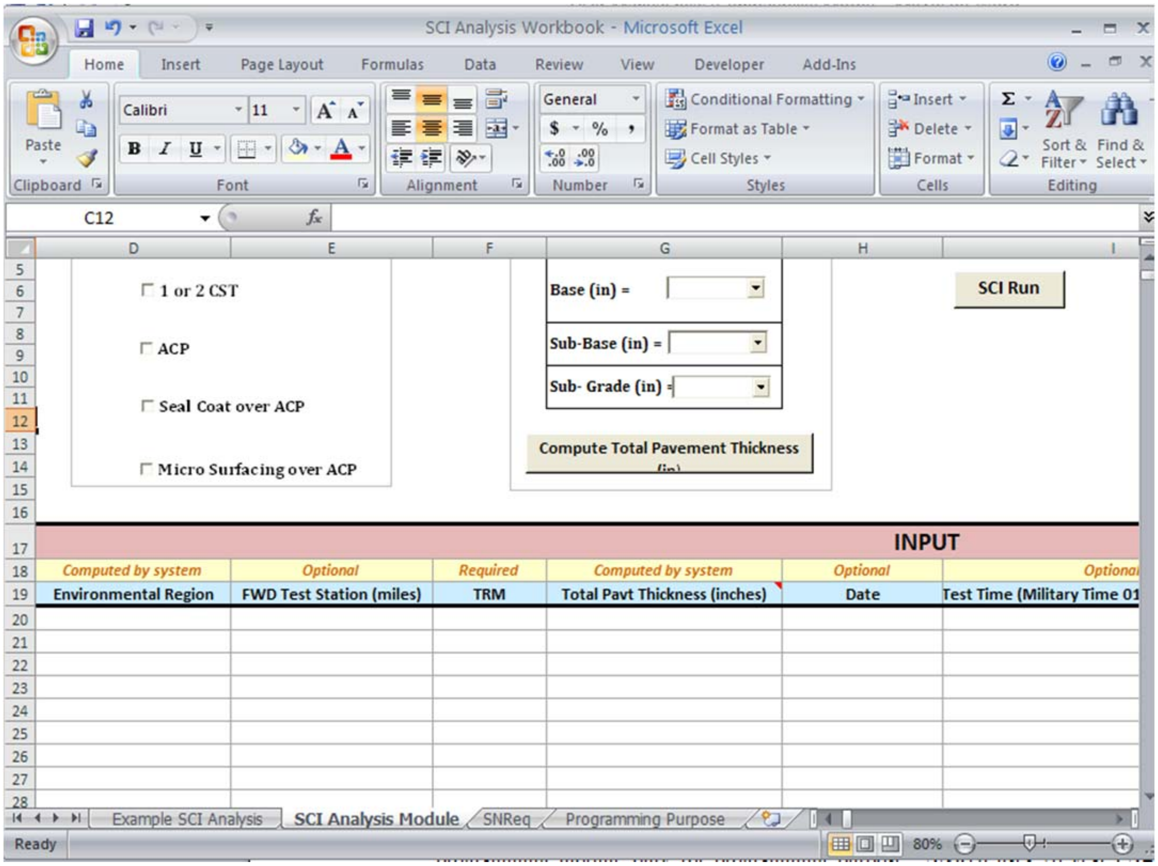
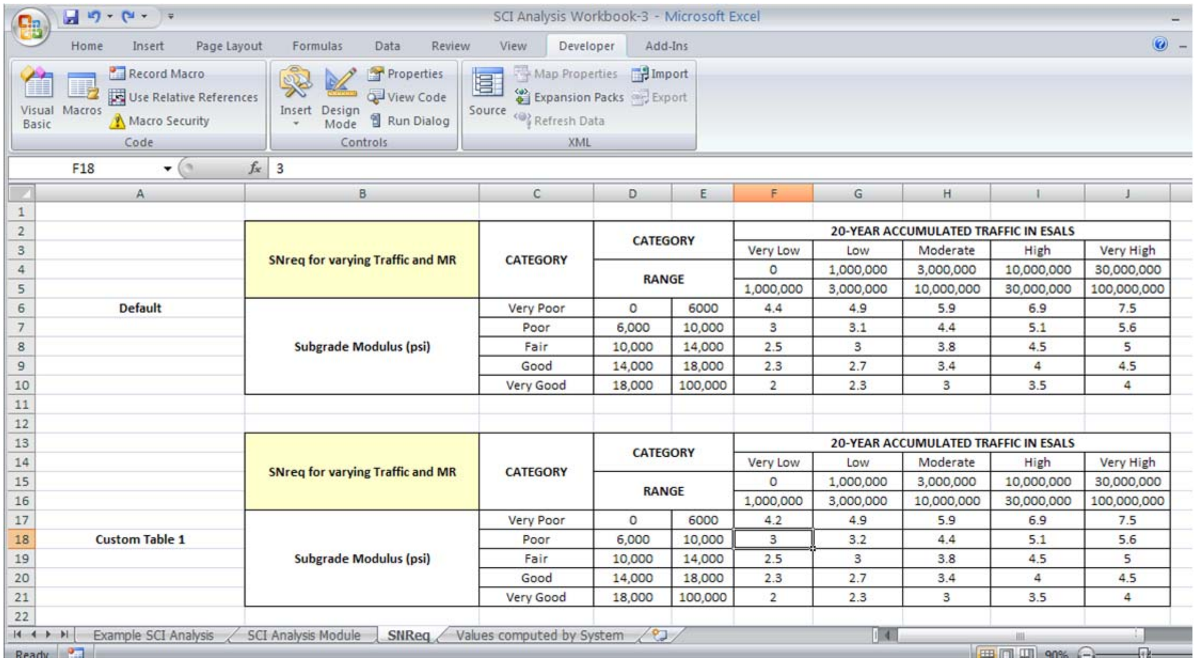


Figure D8: Sheet 2 "SCI Analysis Module"

D2.5 Tab 3: SNReq

Within the workbook, the "SNReq" worksheet (Sheet 3) is included as a database for the programming module only for the SCI Algorithm applications. SNReq uses 20-year ESALS traffic and subgrade modulus as part of the SCI analysis, as shown in Figure D9. This worksheet further gives an understanding of the new ranges for traffic and subgrade modulus that are used in SCI analysis. This tool also provides the flexibility of choosing between different custom SNReq tables. The user can input SNReq data in the custom tables and view the analysis results. However, note that current SCI analysis is based on the values taken from the default table.



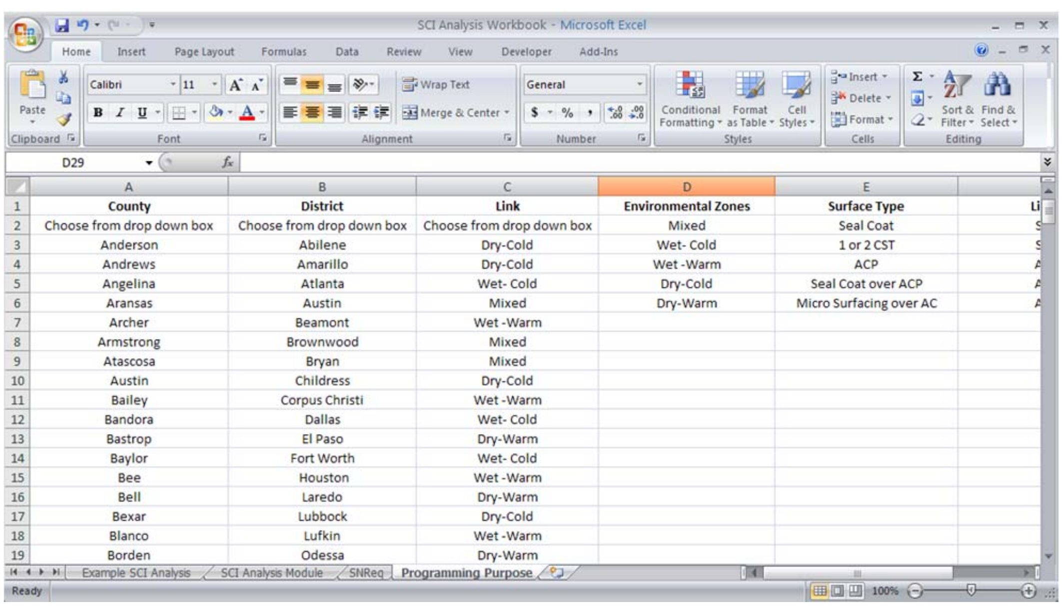
					20-YEAR ACCUMULATED TRAFFIC IN ESALS				
	SNreq for varying Traffic and MR	CATEGORY	CATEGORY		Very Low	Low	Moderate	High	Very High
			RANGE		0	1,000,000	3,000,000	10,000,000	30,000,000
					1,000,000	3,000,000	10,000,000	30,000,000	100,000,000
Default	Subgrade Modulus (psi)	Very Poor	0	6000	4.4	4.9	5.9	6.9	7.5
		Poor	6,000	10,000	3	3.1	4.4	5.1	5.6
		Fair	10,000	14,000	2.5	3	3.8	4.5	5
		Good	14,000	18,000	2.3	2.7	3.4	4	4.5
		Very Good	18,000	100,000	2	2.3	3	3.5	4

					20-YEAR ACCUMULATED TRAFFIC IN ESALS				
	SNreq for varying Traffic and MR	CATEGORY	CATEGORY		Very Low	Low	Moderate	High	Very High
			RANGE		0	1,000,000	3,000,000	10,000,000	30,000,000
					1,000,000	3,000,000	10,000,000	30,000,000	100,000,000
Custom Table 1	Subgrade Modulus (psi)	Very Poor	0	6000	4.2	4.9	5.9	6.9	7.5
		Poor	6,000	10,000	3	3.2	4.4	5.1	5.6
		Fair	10,000	14,000	2.5	3	3.8	4.5	5
		Good	14,000	18,000	2.3	2.7	3.4	4	4.5
		Very Good	18,000	100,000	2	2.3	3	3.5	4

Figure D9: Sheet 3 "SNReq"

D2.6 Tab 4: Inputs for Drop Down Boxes

The last sheet in the workbook (Sheet 4) is labeled "Programming Purposes," and is used only for Drop Down Box inputs. The sheet gives an overview of the counties and districts in Texas. It further gives an idea of how each district has been linked with environmental regions. Similarly, this worksheet further tells how each of the five surface type descriptions has been linked with the Surface Type input to be used in the SCI Analysis.



County	District	Link	Environmental Zones	Surface Type
Choose from drop down box	Choose from drop down box	Choose from drop down box	Mixed	Seal Coat
Anderson	Abilene	Dry-Cold	Wet- Cold	1 or 2 CST
Andrews	Amarillo	Dry-Cold	Wet -Warm	ACP
Angelina	Atlanta	Wet- Cold	Dry-Cold	Seal Coat over ACP
Aransas	Austin	Mixed	Dry-Warm	Micro Surfacing over AC
Archer	Beamont	Wet -Warm		
Armstrong	Brownwood	Mixed		
Atascosa	Bryan	Mixed		
Austin	Childress	Dry-Cold		
Bailey	Corpus Christi	Wet -Warm		
Bandora	Dallas	Wet- Cold		
Bastrop	El Paso	Dry-Warm		
Baylor	Fort Worth	Wet- Cold		
Bee	Houston	Wet -Warm		
Bell	Laredo	Dry-Warm		
Bexar	Lubbock	Dry-Cold		
Blanco	Lufkin	Wet -Warm		
Borden	Odessa	Dry-Warm		

Figure D10: Sheet 4 "Hard-wired input values for drop down boxes"

D3. Using the Tool

This section explains how to use the tool from a user's perspective. A hypothetical project named "SCI Analysis Workbook" is used for demonstration purposes.

D3.1 Location of the Tool

The first step in the process is to locate the macro-enabled Excel workbook, "SCI Analysis Workbook," on the computer.

D3.2 Security Settings

The SCI algorithm requires that the macro settings are enabled in workbook. To do this, the user needs to go to Office button–>Excel Options–>Trust Center–>Enable all macros–>OK (Figure D11). Otherwise, a security question might pop up.

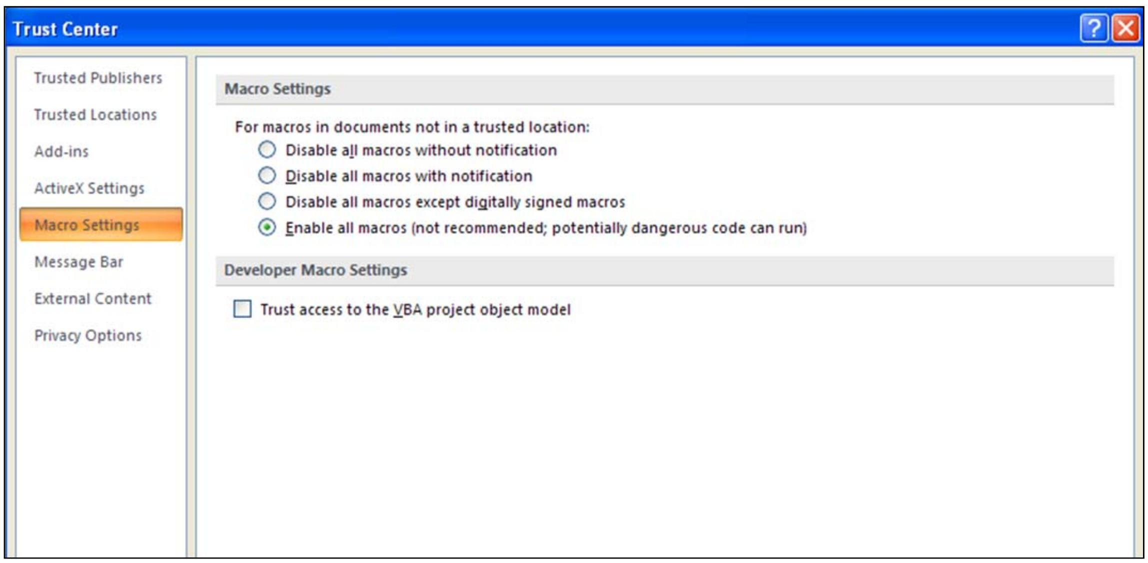


Figure D11: Macro settings

D3.3 Input Data

The user has to input the following data as explained in a new worksheet in the respective columns with correct units. The SCI Algorithm can handle any number of stations in the input data and the user should not worry about the number of rows. The user should make sure that the input data captioned "required" is inputted for the SCI algorithm tool.

D3.4 Running the Algorithm

The algorithm has been written in the form of a macro that has been assigned to a button labeled "SCI Run" in the worksheet (see Figure D12). A right click on the button will run the analysis.

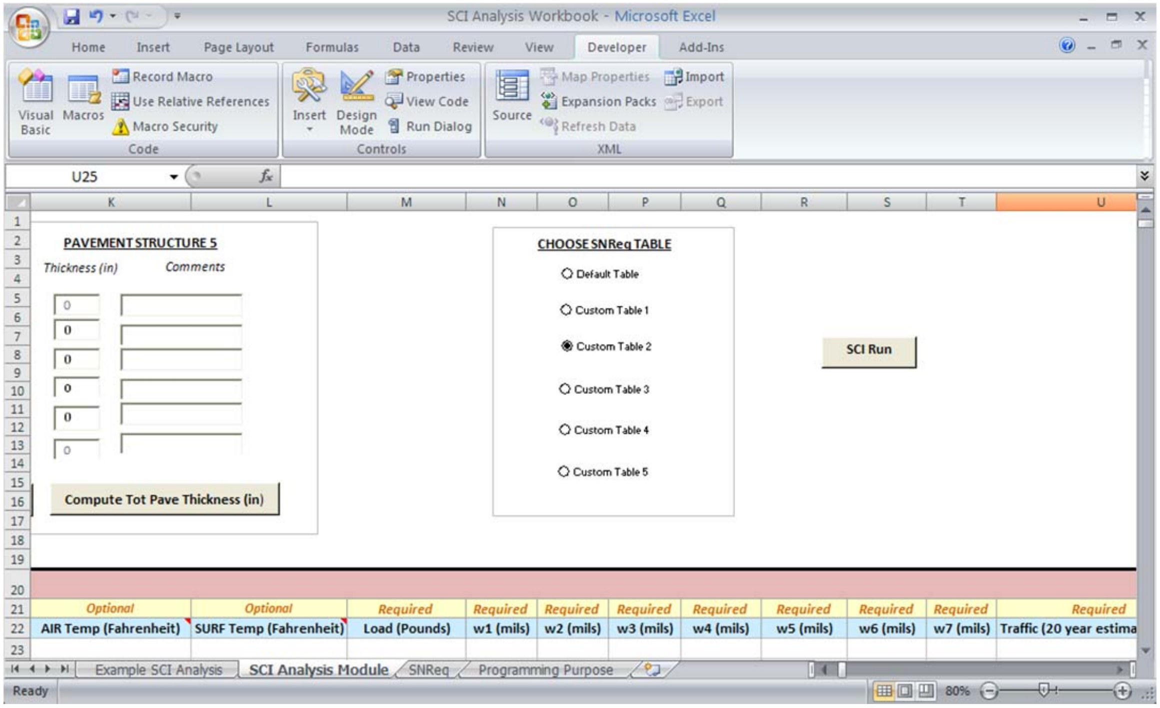


Figure D12: Running the SCI algorithm

D3.5 SCI Analysis Results

The final output, the SCI, is reported under Column AJ as in Figure D13. The user can further view the normalized deflections, AASHTO calculated Subgrade Modulus (M_R), Effective Structural Number (SN_{eff}), and Required Structural Number (SN_{req}) in the worksheet, which are part of the intermediate steps to obtain the SCI. The tool automatically generates graphs for SCI vs. TRM as well as SCI vs. FWD Stations.

Figure D13: SCI analysis results

D4. Guidelines for Maintenance and Rehabilitation (M&R) Options

A survey analysis has been conducted as part of the Project 5-4322-01 by taking expert opinions with regard to SCI Threshold Analysis. This exercise involved selecting the appropriate PMIS treatment level for the traffic, pavement conditions, SCI, soil conditions, and other factors given. The results obtained from the SCI Threshold Analysis as in Figure D14 formed the basis to establish guidelines for Maintenance and Rehabilitation (M&R) options. However, the survey results of PMIS treatment level varied quite a bit within the experts and an average of the results was taken to establish a brief guideline about the PMIS treatment level based on SCI. Hence, it is to be noted that the suggested PMIS treatment levels in Table D1 only act as a guideline at the network level and not as a cut-off point at the project level.

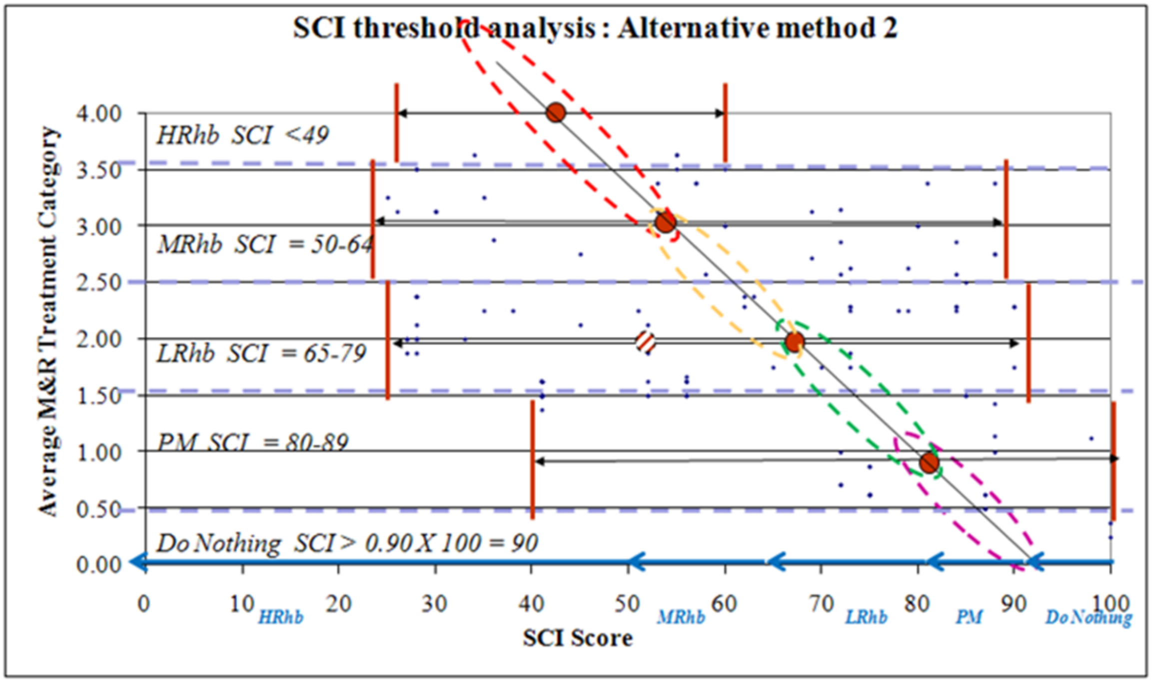


Figure D14: Survey results of PMIS treatment levels with SCI

Table D1: Guidelines for PMIS Treatment Level Based on SCI

SCI	PMIS Treatment Level
<0.49	HRhb
0.64–0.50	MRhb
0.79–0.64	LRhb
0.89–0.80	PM
>0.90	Do Nothing

D5. Falling Weight Deflectometer

FWD readings are obtained through load produced by dropping weight measured by seven sensors located at typical offsets of 12 inches. The recorded pavement deflections in response to applied pulse load will result in a deflection basin. The test sections obtained for the implementation study included short sections of 1000 ft with tests performed every 25 ft +/-; long routes up to 19 miles in length with consistent test spacing on 100 ft or 500 ft intervals as well as other route lengths and test spacing. The interval at which the FWD data was collected varied from section to section depending on the purpose of testing. For some projects, FWD measurements were recorded for every 50 feet, whereas for others, FWD measurements were taken at 0.5 mile intervals. It is very well known that conducting more FWD tests will yield more accurate results about pavement section; however, the economic constraints of implementation make it essential to establish ideal testing frequency. Research further suggests that the appropriate time for FWD deflection testing for various regions of the state needs to be identified.

D5.1 FWD Deflection Testing Interval

In the research done under the Project 5-4322-01, the dataset obtained from 0.2-mile equal spacing compares well with the original dataset. Hence, the FWD data collected at test spacing of 0.2 miles is recommended for the SCI analysis. The FWD testing at 0.25-mile spacing can be recommended as a second alternative for the SCI analysis, because the FWD testing at 0.2-mile spacing will not coincide well with the PMIS section lengths of 0.5 miles. However, the FWD testing at 0.25-mile spacing will achieve a standard test pattern in relation to the PMIS section (beginning, middle, end) as shown in Figure D15.

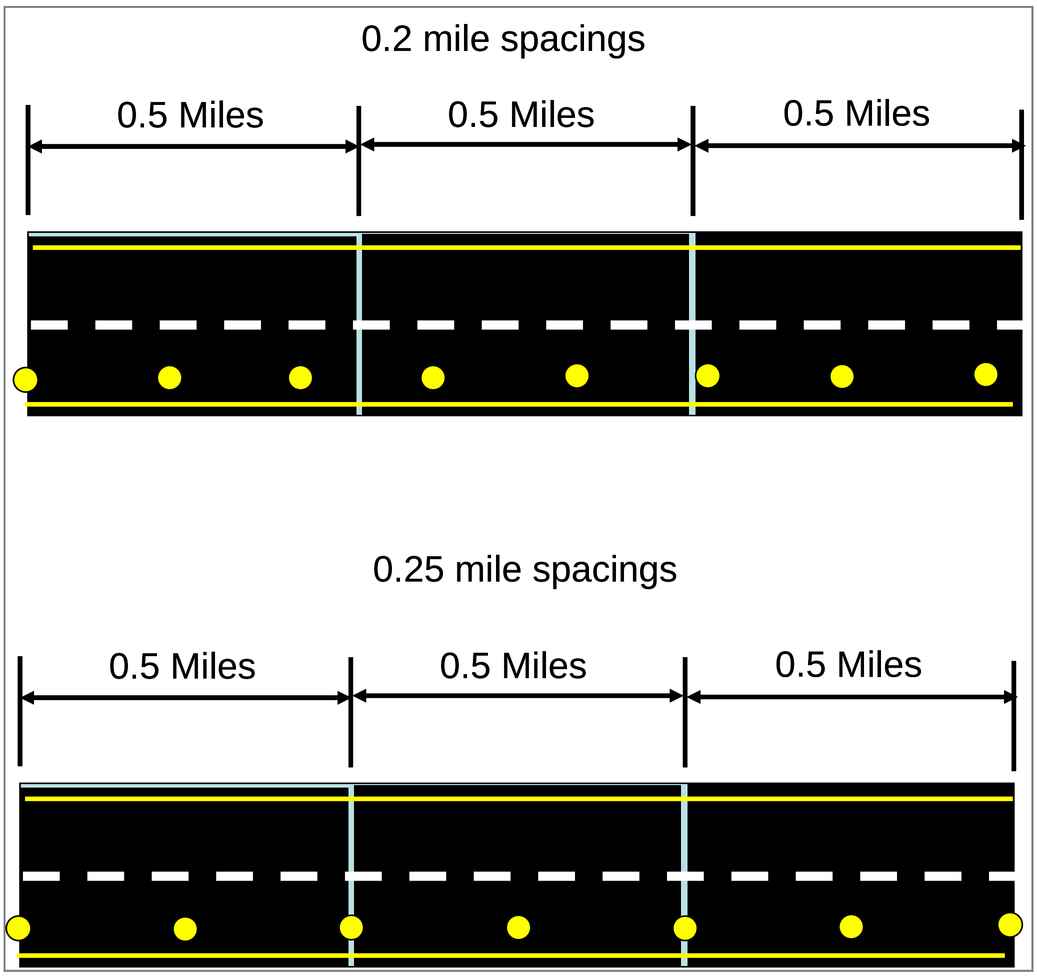


Figure D15: FWD testing interval

D5.2 FWD Deflection Testing time

The literature review revealed that FWD readings are affected by many parameters, including the seasonal variations in any region. Significant seasonal variations usually affect pavement strength determined through FWD deflections. Such FWD deflections might misinterpret the pavement's true condition. As such, most of the researchers suggest that deflection testing should be discouraged during winter months when the sub-grade and base may be frozen. The magnitude of variation and the ideal time for deflection testing has been established by setting up different experiments across the country as well as Texas by different researchers.

Literature review suggests that FWD testing should be performed during the season of the year when permanent deformations are most likely to occur. Generally, the highest pavement deflections could either be in the hottest or wettest part of the year. The research done by Poehl and Scrivner in 1971 to determine ideal FWD data collection in Texas indicates that the annual rainfall affects the timing of annual maximum deflection observed at a point in Texas more than the annual temperatures. Poehl and Scrivner found that the above average deflections occur in spring in East Texas, and above average deflections occur in summer in West Texas. Also, the annual percentage change in deflections (max-min) was usually greater in the eastern part (wet part) of Texas than in the western (dry part). Hence, it is recommended that users follow the seasons when conducting FWD deflection testing, as shown in Figure D16.

The results obtained from this review have been linked up with Texas environmental zones to give users more flexibility. Table D2 summarizes the recommended FWD deflection testing times based on Texas environmental zones.

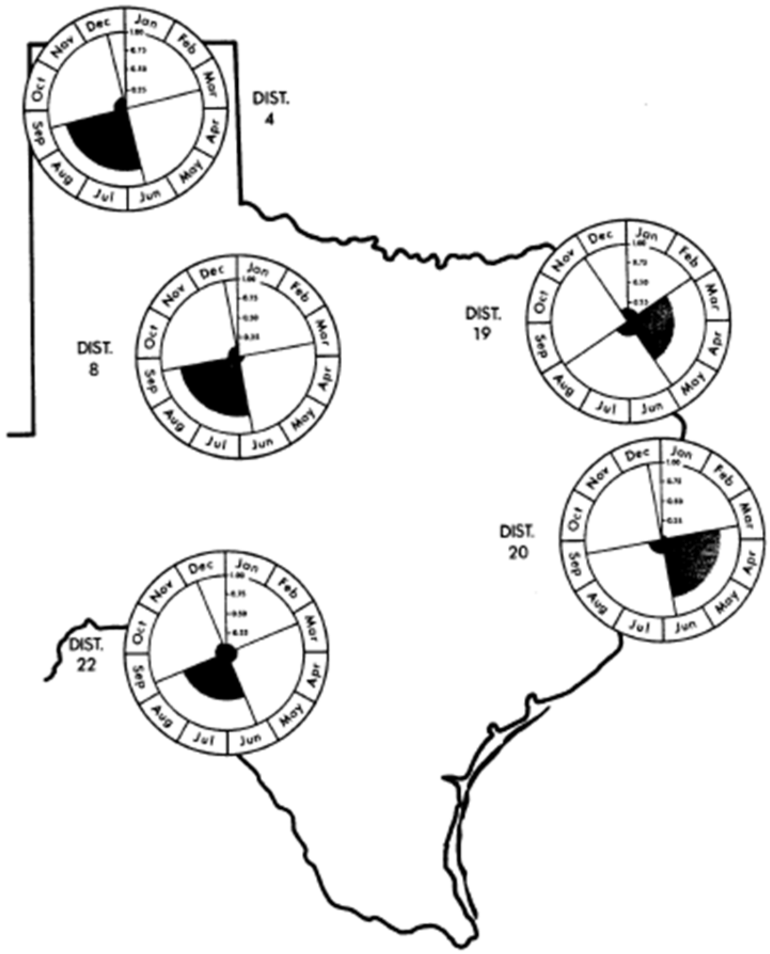


FIGURE 16 - Data from Table 10 plotted on annual clocks. Radii of shaded segments are proportional to probability of occurrence of above-average deflections.

Figure D16: Highest deflections in Texas with season (from Poehl and Scrivner 1974)

Table D2: Guidelines for FWD Deflection Testing Time Based on Environmental Zones

Environmental Region	FWD Deflection Testing Time
Dry–Cold	Mid June–Mid September
Wet–Cold	March–May
Mixed	Mid June–Mid September / March–May
Dry–Warm	Mid June–Mid September
Wet–Warm	Mid March–Mid June

D6. Summary

The development of the SCI Algorithm Tool had three basic objectives: assist TxDOT with the implementation of SCI, evaluate the condition of a roadway using the new SCI index, and provide background in FWD deflection testing and analysis concepts. It is important that the user has the macro-enabled Excel workbook and follows the data base structure: use the required units and inputs as indicated in this user manual for effective SCI analysis. By establishing guidelines about PMIS treatment levels in relation to SCI, the manual addresses how SCI can be used to evaluate the condition of a roadway. This manual provides the ideal FWD deflection intervals as well as deflection testing times for extracting accurate information about a pavement's condition.

D6.1 Additional FWD Network-Level Testing Considerations

- The network-level FWD data collection protocol should be updated to ensure that visual distress and FWD deflection data are collected on a PMIS rating section within a similar timeframe.
- FWD testing should be performed continuously along an entire route, rather than on randomly selected short segments.
- FWD testing should be performed on a given route within the same season.
- A managed network-level test program should be considered that provides a complete network-level sample every 3 years.

References

[AASHTO 1986] *AASHTO Guide for Design of Pavement Structures,* AASHTO, Washington DC, 1986.

[AASHTO 1993] *AASHTO Guide for Design of Pavement Structures.* AASHTO, Washington DC, 1993.

[Abdullah 1999] Abdullah and Swailem, *Pavement Condition Data collection and evaluation of Riyadh Main Street Network,* J.King Saud University, Vol. 11, Eng. Sci(1), pp 1-18.

[Baus 2001] Baus R.L., Pierce C.E, and Hong.W., *Feasibility of Including Structural Adequacy Index as an Indicator of Overall Pavement Quality in the SCDOT Pavement Management System,* University of South Carolina, Report Number FHWA-SC-01-03, February, 2001.

[Binod 2003] Binod Sapkota, *Use of Fwd in the Network Level Pavement Condition Survey-Experience from Western Australia,* Terracon Consulting Engineers (2003 FWD Users Group presentation) URL: http://pms.nevadadot.com/, Accessed November 2010.

[Brian 2008] Brian K., *Network-Level Pavement Evaluation of Virginia's Interstate System using the Falling Weight Deflectometer*, VTRC 08-R18, June 2008.

[de Jong 1973] de Jong, D. L., Peutz, M. G. F and Korswagen, A.F., *Computer Program BISAR - Layered Systems Under Normal and Tangential Surface Loads*, External Report AMSR.0006.73, Royal Dutch Shell Research B.V., The Hague, Netherlands, January, 1973

[FHWA 2007] *Evaluation of Pavement Performance on DEL-23,* Ohio DOT Research Paper, FHWA/OH-2007/05.

[Horak 2008] Horak.E, *Benchmarking the structural condition of flexible pavements with deflection bowl parameters,* Journal of the South African Institution of Civil Engineering, Vol. 50 No 2, Paper 652, 2008, pp-2.

[Lubinda 2010] Lubinda F. Walubita and Scullion, *Texas Perpetual Pavements New Design Guiedlines,* Research Report Number 0-4822, Texas Transportation Institute, June 2010

[Murphy 1998] Michael Ray Murphy, *A Mechanistic-Empirical Approach to Characterizing Sub-grade Support and Pavement Structural Condition for Network-level Applications,* PhD Dissertation, The University of Texas at Austin, 1998

[Murphy 2010] Murphy.M, Zhang.Z and Harrison, *Multi-tier pavement Condition Goals: DOT MTG Summary,* Technical Memorandum Number 0-6655-02, June 2010.

[Mustaque 2000] Mustaque, Tanveer, Swetha and Andrew, *Network-Level Pavement Deflection Testing and Structural Evaluation,* Journal of Testing and Evaluation, May 2000.

[Noureldin 2005] Noureldin. S, Zhu.K, Harris.D and Li.S, *Non-Destructive Estimation of Pavement Thickness, Structural Number and Sub grade Resilience along INDOT Highways* , Purdue 2005.

[Pradeep 2006] Pradeep Kumar Agarwal, Animesh Das and Partha Chakroborty, *Simple model for Structural Evaluation of Asphalt Concrete Pavements at Network Level,* Journal Of Infrastructure Systems ASCE, March 2006.

[Rohde 1990] Rohde. G. T., *The Mechanistic Analysis of FWD Deflection Data on Sections with Changing Subgrade Stiffness with Depth*, PhD Dissertation, Texas A&M University, College Station, TX, December, 1990. pp 10 - 12

[Rohde 1994] Rohde G.T., *Determining Pavement Structural Number from FWD Testing,* Transportation Research Record 1448, Washington DC, 1994.

[Sameh 2004] Sameh Zaghloul, Ivana Marukic and Zubair Ahmed, *Development of a Network Level Structural Adequacy Index Model for NJDOT,* PMS TRB 83rd Annual Meeting, Paper Number 04-3282, 2004.

[Scullion 1988] Scullion, *Incorporating a Structural Strength Index into the Texas Pavement Evaluation System,* Research Report Number 409-3F, Texas Transportation Institute, April 1988.

[Sergio 2009] Sergio, Hernan and Tomas, *Proposal of a segmentation procedure for skid resistance data,* The Arabian Journal for Science and Engineering, Volume 33, Number 1B.

[Tammy 2010] Tammy and Zhang, *Texas Pavement Performance and Maintenance Management System,* Compendium of papers from the First International Conference on Pavement Preservation, Paper 13, 2010.

[TAI 1982] The Asphalt Institute - Finn, F. N., Monismith, C. L., Witczak, M. W., *Research and Development of The Asphalt Institute's Thickness Design Manual (MS-1),* Ninth Edition, Asphalt Institute Research Report Number. 82-2 RR-82-2, The Asphalt Institute, College Park, Maryland, August, 1982, pp-204.

[Thiery 2008] Thierry Goger, *Performance indicators for Road Pavements,* COST Action 354 with participation by FHWA. Research planned to conclude September 16, 2008

[TxDOT 1994] *Pavement Management Information System User's Manual,* Texas Department of Transportation, 1994.

[TxDOT 2000] *Managing Texas Pavements*, Texas Department of Transportation, Design Division, Pavements section, November 2000.

[TxDOT 2002] *FWD Operator's manual,* Texas Department of Transportation, Pavement & Material Systems Branch, 2002.

[TxDOT 2008] Texas Department of Transportation, URL:http://www.dot.state.tx.us/local_information/, Accessed November 2010.

[Van Cauwelaert 1989] Frans J. Van Cauwelaert, Don R. Alexander, Thomas D. White, and Walter R. Barker, *Multilayer Elastic Program for Backcalculating Layer Moduli in Pavement Evaluation,* American Society of Testing and Materials, Philadelphia, 1989, pp. 171-188.

[Williams 2006] Williams, Martin, Maser, and McGovern, *Evaluation of Network Level Ground Penetrating Radar Effectiveness,* TRB 85th Annual Meeting, Paper Number 06-2243, 2006.

[Zhang 2003] Zhanmin Zhang, Lance Manuel, Ivan Damnjanovic and Zheng Li, *Development of a New Methodology for characterizing pavement structural condition for network-level applications,* Research Report Number 0-4322-1, Center for Transportation Research, The University of Texas at Austin, 2003.

[Zhang 2009] Zhanmin Zhang, Murphy.M, Persad and Harrison, *Pavement Condition Analysis based on TxDOT funding projections,* Technical Memorandum Number 0-6581, Center for Transportation Research, November 2009.