Longitudinal Cracking in Widened Portland Cement Concrete Pavements

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16. Abstract

The Wisconsin Department of Transportation constructed certain concrete pavements with lane widths greater than the standard 12 feet in order to reduce stress and deflection caused by vehicle tires running near the edge of the concrete slabs. Many of these pavements are approaching 20 years of service life and some are experiencing longitudinal cracking. Research was needed to determine whether the use of wider slabs made the pavement more susceptible to other forms of distress. This study investigated the occurrence of longitudinal cracking in doweled jointed plain concrete pavements (JPCP) to determine the maximum allowable pavement width as a function of pavement thickness in order to achieve optimal JCPC performance. A set of guidelines was developed for JPCP panel width usage.

The researchers evaluated and statistically compared the performance of doweled JPCP having wider panels (14 and 15 feet wide) to the performance of concrete pavements with standard with panels (12 to 13 feet), while incorporating the interactive effects of other variables. The investigation was limited to doweled JPCP aged 25 years or less. A standard panel width of 14 ft with a width-to thickness-ratio in the range of 1.2 (12 in thickness) to 1.5 (9.5 in thickness) was found to minimize cracking severity and extent.

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EXECUTIVE SUMMARY

This report investigated the occurrence of longitudinal cracking in doweled jointed plain concrete pavements (JPCP) to determine the maximum allowable pavement width as a function of pavement thickness in order to achieve optimal JPCP performance. In addition, a set of guidelines was developed for JPCP panel width usage. The study was commissioned by the Wisconsin DOT to address concerns about the appearance of longitudinal cracking on wider (≥14-ft) JPCP approaching 20 years of service life. Qualitatively, it appears that while the current pavement section has been successful in reducing edge cracking and shoulder maintenance, it may have made the pavement more susceptible to other forms of distress. The scope of the investigation evaluated and statistically compared the performance of doweled JPCP having wider panels (14 and 15 ft wide) to the performance of concrete pavements with standard width panels (12 to 13 feet), while incorporating the interactive effects of other variables. The investigation was limited to doweled JPCP having an age of 25 years of less.

The guidelines and the research findings were developed through literature findings, survey of professional engineers from six Midwest states (Iowa, Ohio, Michigan, Wisconsin, Illinois, and Minnesota), and in-service performance and life cycle cost analyses involving concrete pavement panels ranging in width from 12 ft to 15ft.

The literature review suggested that cracking of concrete slabs occurs when tensile stresses exceed tensile strength from initial shrinkage from moisture loss, restraint by base or subbase friction from expansion and contraction caused by temperature changes, and thermal and moisture gradients between the top and bottom of the slabs. Differential thermal contraction from temperature variations throughout the pavement depth has been shown to induce random cracking. This random cracking that first occurs or continues to develop well after paving and sawing has been attributed to slab restraint or movement that results in high tensile stress development within the slab. The movement may be the result of grade settlement or frost heave, while the restraint may be from the presence of a stabilized subbase.

The results of the online survey of engineers and pavement professionals in the six Midwest states found that pavement thickness is the primary criterion input considered in the selection of panel width for JPCP, followed by traffic volume, truck percentage, ease of construction, and construction and maintenance costs. For 2-lane bi-directional pavements, the 12-ft wide panel is most commonly used followed by the 15-ft panel. Despite key design inputs such as traffic volume and truck traffic, 12-ft panels are more likely to be used for multi-lane rural JPCP than any other width. The survey also found a relational frequency of longitudinal cracking occurrence in relation to panel width, pavement thickness, joint spacing, tie bars, construction-related practices, panel location, topography and structures. The 12-ft and 15-ft wide panels were reported to have higher longitudinal cracking frequencies compared to 13-ft and 14-ft wide panels. Thicker pavements (≥11 in) do not exhibit longitudinal cracking compared to more vulnerable thinner pavements. A greater frequency of longitudinal cracking tends to occur with shorter joint spacing; however, some respondents reported having higher frequencies in panels with 20-ft transverse joint spacing. There is a split opinion regarding whether tie bars have an effect on longitudinal cracking. High longitudinal cracking frequencies were associated with inadequate subbase compaction and poor joint saw-cut timing. Misaligned dowel bars and faulty vibrators were also reported as contributing factors. Longitudinal cracking occurs more near panel edges and at mid-panel locations compared to the vicinity of sawn longitudinal joints. Finally, the survey found that cut/fills, highway structures (bridges, drainage, culverts etc.) and areas subject to differential subgrade heaving contribute to the occurrence of longitudinal cracking. For both 2-lane JPCP and rural multi-lane facilities, cracking frequency on 12-ft panels is higher than 13-ft and 15-ft panels.

The in-service performance and life cycle cost analysis of the JPCP was derived from a total of 1,008 concrete segments (Sequence Numbers) within the state, averaging 1.14 miles in length. Performance was defined in terms of the presence or absence of cracking, the length of cracking, and severity of cracking. On the basis of the analysis, the following observations are made:

- Approximately 60% (599/1,008) of the 1.14-mile segments in the state had longitudinal cracking while 40% did not (409/1,008). Approximately 56% (502/891) of 14-ft panels experienced longitudinal cracking compared to 100% (8/8) of 13-ft panels. The respective proportions of cracked pavements were 81% (58/72) and 84% (31/37) for the 12-ft and 15-ft panels.

- The significant factors explaining the presence or absence of longitudinal cracking included width-to-thickness (w/t) ratio, joint spacing, longitudinal jointing method, tining orientation, dowel bar installation, traffic level, age, and region.
- The significant factors explaining the length and/or severity of longitudinal cracking included offset of crack, pavement thickness, w/t ratio, joint spacing, transverse joint orientation (skewed or normal), rumble strips, base gradation (dense or open), dowel bar installation, Average Annual Daily Truck Traffic (AADTT), age, and region.
- A majority of longitudinal cracking across all panel widths is between wheel paths or in the right wheel path compared to pavement edges.
- For 14 ft panels, a 1 in thickness increase from 9 in (w/t=1.6) to 10 in (w/t=1.4) reduced the number of cracks by approximately 25%. Conversely, if the w/t ratio is raised from 1.4 to 1.6, the average cracking length within a pavement segment increases by 45% for the 14-ft panels. If the w/t ratio is raised from 1.5 to 1.7 for 15-ft panels, the average cracking length within a pavement segment increases by 18%.

A life cycle cost analysis determined the following:

- For a given thickness, the width-to-thickness ratio increases with increasing panel width and initial construction cost.
- The 12-ft panel has the lowest overall rehabilitation and NPW costs but the highest maintenance costs among 9-in and 10-in pavements.
- The largest rehabilitation cost is associated with the 15-ft panel and is approximately 1.7 times ($466,567 / $280,191) that of the 12-ft panels and 1.1 times ($466,567 / $436,167) that of the 14 ft panels.
- For all panel widths, a one-inch increment in thickness from 9 in. to 10 in. results in 70-80 ft reduction in the mean observed crack length per 1.14-mi segment. The incremental cost associated with the crack length reduction varies from approximately $25,000 to $28,500.
- The 12-ft panel produces the minimum overall incremental cost of $312 per foot reduction of crack length for an inch increase in pavement thickness. The corresponding incremental costs per foot reduction of crack length for the 14-ft and 15-ft panels are respectively about 1.2 and 1.3 times that of the 12-ft panel.

The following recommendations are made:

- A standard panel width of 14 ft is to be specified to limit cracking severity and extent. Field performance analysis coupled with the literature indicates that it exhibits the lowest cracking frequency compared to all other panels.
- For the specified 14-ft panel, a width-to thickness-ratio of 1.2 (12 in thickness) to 1.5 (9.5 in thickness) must accompany it to minimize cracking severity and extent.
- It was statistically determined that several interrelated factors influence cracking severity and extent for specific panels and that panel width selection cannot be treated in isolation. For the recommended 14-ft panel width, better performance is expected when used in conjunction with a normal transverse joint spaced at 15 ft, untreated aggregate base, dowel basket installation, and longitudinal tining.
- Cracking can occur at various locations across the pavement including wheel paths, edges, and between wheel paths. For 14-ft panels, cracking extent at all locations, with the exception of the left edge, can be reduced through the use of 15-ft joint spacing in conjunction with normal joint application, PCC rumble strip installation, and open graded base. However, for mid-panel cracking, the width-to-thickness ratio is another factor to consider. Normal joint orientation will minimize severity at both wheel paths and mid-panel locations for 14-ft panels.

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TABLE OF CONTENTS

EXECUTIVE SUMMARY iii
ACKNOWLEDGMENTS vii
TABLE OF CONTENTS viii
LIST OF FIGURES x
LIST OF TABLES xii
CHAPTER 1 INTRODUCTION 1
1.1 Background and Problem Statement 1
1.2 Research Objectives 1
1.3 Significance of Work 2
1.4 Organization of Report 2
CHAPTER 2 JOINTED PLAIN CONCRETE PAVEMENT PRACTICES 3
2.1 Introduction 3
2.2 Cracking Phenomenon in Concrete Pavements 3
2.2.1 Saw Cut Characteristics on Cracking in Concrete Pavement 4
2.2.2 Weather Influence on Cracking in Pavements 5
2.2.3 Subbase Influence on Cracking in Pavements 6
2.2.4 Longitudinal Cracking Treatment Practices 7
2.3 Survey on Practices of JPCP in Selected Midwestern States 8
2.3.1 Criteria Inputs for Pavement Cross-section Selection 9
2.3.2 Panel Widths on 2-Lane, 2-Way Rural JPCP 10
2.3.3 Panel Widths on Multilane Rural JPCP 12
2.3.4 Frequency of Longitudinal Cracking Occurrence 14
2.4 Other Surveys 22
2.5 Online Discussion on Longitudinal Cracking on Iowa Concrete Pavements 23
2.5 Summary and Conclusions 25
CHAPTER 3 DATA COLLECTION 27
3.1 Introduction 27
3.2 Databases 27
3.2.1 Meta Manager Database 28
3.2.2 Pavement Inventory Files 29
3.2.3 New Construction Reports 29
3.3 Database Merge 30
3.4 Database Development 30
3.5 Database Summary Statistics 36
CHAPTER 4 DATA ANALYSIS 40
4.1 Introduction 40
4.2 Analysis Framework 40
4.3 Analysis of Segments with and without Longitudinal Cracking 43
4.3.1 Design Factors 44
4.3.2 Construction Factors 50
4.3.3 Traffic Factors 52

4.3.4 Environmental Factors 52
4.3.5 Summary of Factors influencing Cracking Observation 55
4.4 Analysis of Factors affecting Extent and Severity of Longitudinal Cracking 57
4.4.1 Crack Offset 57
4.4.2 Design Factors 61
4.4.3 Construction Factors 69
4.4.4 Traffic Factors 72
4.4.5 Environmental Factors 76
4.4.6 Summary of Factors affecting Length and Severity of Cracking 78
4.6 Summary of Hypothesis Test for Factors affecting Longitudinal Cracking 83
CHAPTER 5 GUIDELINES TO OPTIMIZE JPCP PERFORMANCE THROUGH PANEL WIDTH SELECTION 85
5.1 Introduction 85
5.2 Understanding Longitudinal Cracking from a Literature Review 86
5.2.1 Approaches to Limiting Cracking Impact from Induced Stresses 87
5.2.2 Panel Width Considerations in Limiting Cracking Impacts on JPCP 88
5.3 Survey of JPCP Panel Width Practices in Selected Midwestern States 89
5.4 Statistical Analysis of Wisconsin JPCP Panel Widths 90
5.5 Recommended Practices for JPCP Panel Width 92
5.6 Design Practice to Minimize Cracking Severity and Extent at Pavement Cross-section Locations 96
5.7 Life Cycle Cost Analysis 107
5.7.1 Pavement Cross-Section for LCCA 107
5.7.2 Life Cycle Sequence for Panel Width Alternatives 108
5.7.3 Cost Data 113
CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS 124
6.1 Summary and Conclusions 124
6.1.1 Literature review 124
6.1.2 Survey of Midwest States 125
6.1.3 In-Service Performance Data Analysis 126
6.1.4 Life Cycle Cost 127
6.2 Recommendations 128
References 129
Appendix A Online Survey Questionnaire 132

LIST OF FIGURES

Figure 2.1 Late Sawing Induced Longitudinal Crack Formation Locations (Voigt 2002) 4
Figure 2.2 Subbase Related Longitudinal Cracking Patterns (After Voigt 2002) 6
Figure 2.3 Responses Based on Criteria Inputs for Selecting Pavement Cross-section 10
Figure 2.4 Responses based on Panel Width Usage for 2-lane 2-Way JPCP.......................... 11_
Figure 2.5 Responses based on Panel Width Usage for Multilane Rural JPCP 13
Figure 2.6 Responses based on Panel widths exhibiting more Longitudinal Cracking 14
Figure 2.7 Responses based on Thicknesses Exhibiting More Longitudinal Cracking 15
Figure 2.8 Responses based on Transverse Joint Spacing Exhibiting more Longitudinal Cracking 16
Figure 2.9 Response based on Tie Bar Impact on Longitudinal Cracking.................................. 16
Figure 2.10 Responses based on Construction Practices on Longitudinal Cracking Frequency... 17
Figure 2.11 Construction Practices Impacting Longitudinal Cracking in Panels on Rural 2-lane JPCP 18
Figure 2.12 Construction Practices Impacting Longitudinal Cracking in Panels on Rural Multi-lane JPCP 18
Figure 2.13 Longitudinal Cracking Locations on JPCP... 19
Figure 2.14 Responses based on Topography and Structures' Impact on Longitudinal Cracking 20
Figure 2.15 Longitudinal Cracking Location Frequency in Relation to Highway Structures and Cut/Fill Sections on Rural 2-lane JPCP 21
Figure 2.16 Longitudinal Cracking Location Frequency in Relation to Highway Structures and Cut/Fill Sections on Rural Multi-lane JPCP........ 21
Figure 3.1 Sample Portion of Constructed Database 33
Figure 4.1 Relative Frequency of Observed Cracking among 1,008 Pavement Segments........... 44
Figure 4.2 Width-to-Thickness Ratio and presence of Longitudinal Cracking by Panel Width ... 46
Figure 4.3 Width-to-Thickness Ratio Dispersion and Observed Cracking for Panel Widths....... 47
Figure 4.4 Joint Spacing and Longitudinal Jointing Method for 14 ft Panels............................. 48
Figure 4.5 Tining and observed Longitudinal Cracking for 14 ft Panels.................................... 49
Figure 4.6 Shoulder Crack Filler and observed Longitudinal Cracking for 14 ft Panels.......... 50_
Figure 4.7 Dowel Bar Installation and presence of Longitudinal Cracking in 14 ft Panels.......... 51
Figure 4.8 Age and presence of Longitudinal Cracking by Panel Width 53
Figure 4.9 Region and presence of Longitudinal Cracking by Panel Width............................. 54_
Figure 4.10 Frequency of Longitudinal Cracking and Offset by Panel Width............................ 59
Figure 4.11 Cumulative length of Longitudinal Cracking by offset for Panel Width 60
Figure 4.12 Comparison of Longitudinal Cracking distribution by Offset and Panel Width 61
Figure 4.13 Pavement Thickness and severity frequency of Longitudinal Cracking 63
Figure 4.14 Width-to-Thickness Ratio and Cumulative Length and Severity of Longitudinal Cracking 65
Figure 4.15 Joint Spacing and Cracking length and severity by Panel Width 66
Figure 4.16 Transverse Joint orientation and Cracking distribution by Panel Width................... 67
Figure 4.17 Rumble Strip placement and Cracking length and severity by Panel Width............. 68
Figure 4.18 Base Gradation and Cracking length and severity by Panel Width .... 69_
Figure 4.19 Dowel Bar Installation and Cracking Length and Severity in Panel Widths............. 71
Figure 4.20 Topography effect on Cracking Length and Severity by Panel Width 72
Figure 4.21 AADTT and Cracking Length and Severity by Panel Width 74

Figure 4.22 Posted Speed with Average crack length and severity by Panel Widths 75
Figure 4.23 Age and severity of Longitudinal Cracking for Panel Wdith 77
Figure 4.24 Region and Average Cracking length and severity by Panel Width 78
Figure 5.1 Panel Width Guidelines Development Framework 85
Figure 5.2 Cumulative Length of Longitudinal cracking by location and Panel Width 96
Figure 5.3 Panel Width Cross-section Alternatives for Life Cycle Cost 107
Figure 5.4 Life Cycle Sequence for 12-ft Panel 111
Figure 5.5 Life Cycle Sequence for 14-ft Panel 112
Figure 5.6 Life Cycle Sequence for 15-ft Panel 113

LIST OF TABLES

Table 2.1 Recommended Repairs of Longitudinal Cracking in Concrete Pavements (ACPA 2001) .... 8_
Table 2.2 Additional Panel Width Selection Criterion Inputs besides Pavement Thickness 10
Table 2.3 Responses based on Panel Width Relationship to Width Criterion Input for 2-lane, 2-way JPCP 12
Table 2.4 Responses based on Panel Width Relationship to Width Criterion Input for Multilane Rural JPCP .... 13_
Table 2.5 Ramp Cross-section Practices 23
Table 2.6 Summary of Factors causing Longitudinal Cracking 26
Table 3.1 Databases Accessed 28
Table 3.2 Data Collection measures for Crack Offset and Severity 31
Table 3.3 Potential Factors and Measures causing Longitudinal Cracking 34
Table 3.4 Basic Statistics for 1,008 Pavement Segments 36
Table 3.5 Basic Statistics for Observed Longitudinal Cracking Segments 38
Table 4.1 Frequency of Pavement Segments with and without Longitudinal Cracking 43
Table 4.2 ANOVA Results for Design Factors 45
Table 4.3 ANOVA Results for Construction Factors 51
Table 4.4 ANOVA Results for Traffic Factors 52
Table 4.5 ANOVA Results for Environmental Factors 52
Table 4.6 Significant Factors affecting the presence of Longitudinal Cracking in 1,008 Pavement Segments 56
Table 4.7 ANOVA Results for Crack Offset 58
Table 4.8 ANOVA Results for Design Factors 62
Table 4.9 ANOVA Results for Construction Factors 70
Table 4.10 ANOVA Results for Traffic Factors 73
Table 4.11 ANOVA Results for Environmental Factors 76
Table 4.12 Factors affecting the Length and Severity of Longitudinal Cracking 79
Table 4.13 Results of ANOVA for Presence, Length, and Severity of Cracking 83
Table 5.1 Proportion of Pavement Segments with and without Longitudinal Cracking 90
Table 5.2 Results of ANOVA for Presence, Length, and Severity of Cracking 91
Table 5.3 Recommended Practices for JPCP Panel Width Usage 93
Table 5.4 Design Factors for 14-ft Wide Panels to Control Cracking by Offset 97
Table 5.5 Design Factors for 15-ft Wide Panels to Control Cracking by Offset 98
Table 5.6 Model Parameters for 14-ft Wide Panels 99
Table 5.7 Model Parameters for 15-ft Wide Panels 102
Table 5.8 Recommended Design Parameters for 14-ft Panels to Address Cracking Occurrence at Targeted Pavement Cross-section Locations 105
Table 5.9 Recommended Design Parameters for 15-ft Panels to Address Cracking Occurrence at Targeted Pavement Cross-section Locations 106
Table 5.10 Life Cycle Cost Related Models 108
Table 5.11 Initial and Rehabilitation Service Lives (Adapted from WisDOT 2012a) 109
Table 5.12 Rehabilitation Sequence Options (Adapted from WisDOT 2012a) 110
Table 5.13 Maintenance Cost (Adapted from WisDOT 2012a) 110
Table 5.14 Input Cost Values for Life-Cycle Cost Analysis 114

Table 5.16 Cost Estimate for 12-ft Panel Configuration 115
Table 5.16 Cost Estimate for 14-ft Panel Configuration 116
Table 5.17 Cost Estimate for 15-ft Panel Configuration 118
Table 5.18 Net Present Worth Cost for 12-ft Panel 120
Table 5.19 Net Present Worth Cost for 14-ft Panel 121
Table 5.20 Net Present Worth Cost for 15-ft Panel 122
Table 5.21 Categorical Cost Comparison of Panel Alternatives 122
Table 5.22 Average Segment Crack Length and Cost Relationship for Panel Widths 123

CHAPTER 1 INTRODUCTION

1.1 Background and Problem Statement

Since the early 1990's, the Wisconsin Department of Transportation (WisDOT) has constructed widened concrete pavements with widths of 26 feet for a rural four-lane divided highway and 30 feet for a rural two-lane highway. For rural four-lane divided highways, the standard pavement section includes the outside lane paved at 14 feet wide. The rationale behind these sections on mainline paving was to reduce stress and deflection at the pavement edge of the concrete slabs due to tire loads near the slab edge. Subsequent field evaluation found that extension of the additional 2-3 feet paved beyond the normal traffic path was successful in meeting the intended objective. Based on this evaluation, it was assumed that the widened sections would result in additional service life of the concrete pavement and significantly reduce shoulder maintenance. The revised section was also attractive from a safety standpoint because it eliminated the hazard of edge drop off at the edge of the 12-foot driving lane.

Many of these pavements are approaching 20 years of service life and some are experiencing longitudinal cracking in the slabs. Qualitatively, it appears that while the current pavement section was a success in reducing edge cracking and shoulder maintenance, it may have made the pavement more susceptible to other forms of distress. WisDOT commissioned this research study to evaluate the performance of these pavements to determine if there has been an increase in longitudinal cracking in concrete pavement due to the use of wider concrete slabs (i.e., 14 feet or greater).

1.2 Research Objectives

The objectives of this investigation are to:

a. Evaluate and statistically compare the performance of concrete pavements with wider panels (14 feet wide or greater) to the performance of concrete pavements with standard width panels (12 to 13 feet).

b. Determine the maximum allowable pavement width as a function of pavement thickness in order to achieve optimal concrete pavement performance

1.3 Significance of Work

At the present time, WisDOT has very little information on which to base the performance evaluation of widened PCC pavements. Past studies performed by other researchers have focused on design and construction practices to minimize edge stresses and deflections to reduce shoulder maintenance cost. A broader perspective is needed to allow the performance of concrete pavement width alternatives to be evaluated for cost effectiveness. This is only possible with a thorough investigation of all concrete width alternatives, including those that have been employed in other states and in Wisconsin, as well as an analysis of their cost effectiveness and applicability for Wisconsin. The work contained in this research is significant since it will help guide WisDOT, and possibly other highway agencies, with a scientific understanding of the relationships between the performance and costs of concrete pavement width alternatives. Such an understanding will validate concrete pavement cross-section design, construction and maintenance practices and better predict concrete pavement performance. In addition, it will provide justification of concrete pavement width selection procedures and designs based on life-cycle costs.

1.4 Organization of Report

The report is organized into six chapters to summarize the research investigation. Chapter 2 summarizes a literature review and questionnaire survey of pavement engineers around the Midwest. Chapter 3 describes data collection activities to assemble a comprehensive database for analysis. Chapter 4 summarizes basic statistics and advanced statistics to determine those factors affecting widened slab performance. Chapter 5 incorporates findings from the data analysis to formulate guidelines for panel width considering life-cycle costs. Finally, Chapter 6 summarizes the research work with conclusions and recommendations.

CHAPTER 2 JOINTED PLAIN CONCRETE PAVEMENT PRACTICES

2.1 Introduction

This chapter synthesizes prior research and a questionnaire survey on the causes and treatment practices for cracking in jointed plain concrete pavement (JPCP). The scope of the survey includes county engineers around the Midwest region regarding rural 2-lane, 2-way and multi-lane JPCP cross-section practices and their relationship to longitudinal cracking occurrence, treatment, and cost.

2.2 Cracking Phenomenon in Concrete Pavements

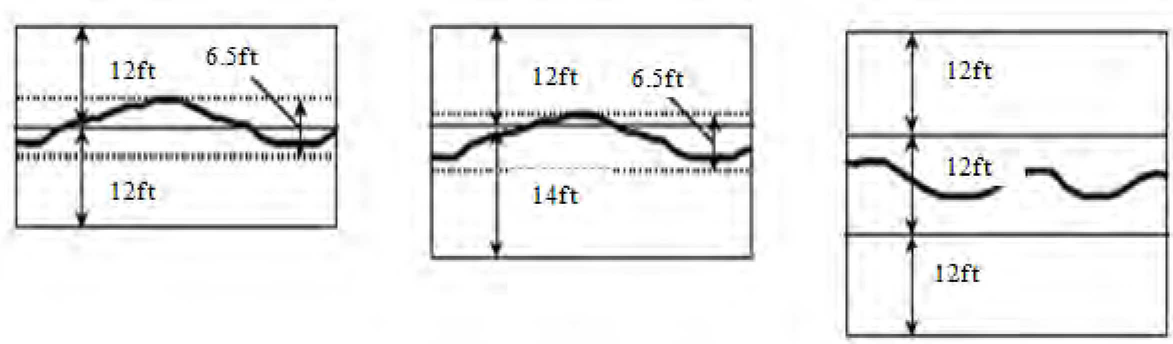
Cracking of concrete slabs are known to occur when the tensile stresses exceed the tensile strength within the concrete. The most common factors cited for the development of the internal stresses include (1) initial shrinkage from moisture loss during curing, (2) restraint by base or subbase friction during longitudinal expansion and contraction from temperature changes, and (3) thermal and moisture gradients between the top and bottom of the slabs. The stresses vary considerably, especially during the early ages (Weiss 1999; Richardson and Armaghani 1987).

In an effort to minimize the induced stresses, transverse and longitudinal saw cut joints are created to induce a plane of weakness where a crack is intended to initiate and then propagate to the bottom of the slab. However, concrete pavements often do not crack at the saw cut joints but rather at unexpected locations, resulting in random cracking. Random cracks were reported to have surfaced in some new pavements within the first 60 days of their construction, initially appearing at large intervals (30-150 ft) and then forming at closer intervals over time. Several interrelated factors have been cited by Voigt (2002) to provide clues to the causes of uncontrolled or random cracking. These factors include saw cut characteristics (timing, sawing process, saw cut depth, saw blade), weather and ambient conditions, subbase condition, concrete mix properties, joint spacing, alignment of dowel at the joint, and orientation of uncontrolled cracks. The following sections detail saw cut characteristics, weather influences, subbase influences, and longitudinal cracking treatment practices.

2.2.1 Saw Cut Characteristics on Cracking in Concrete Pavement

Raoufi et al. (2008) reported that the introduction of a saw cut creates a stress concentration at the tip of the saw cut where a facture process zone develops when the stresses approach the tensile strength of the concrete. When the fracture process zone develops to sufficient size, the crack propagates through the thickness of the slab, resulting in visible cracks. Okamoto et al. (1994) reported that crack formation can be controlled when contraction joints are sawn within an optimum short time window after placement of the concrete pavement. The optimum window was reported to begin when concrete strength is acceptable to saw without excessive raveling along the cut and ends when the concrete volume reduces significantly due to drying shrinkage or contraction. Okamoto et al. (1994) and FHWA (2005) concluded that sawing too early outside the optimum time window can induce raveling of the concrete from the saw blade, while sawing too late may result in pop-off cracks.

Raoufi et al. (2008) used a finite element model to show that the age of cracking is initially independent from the timing of saw cut placement; however, if the saw cut is placed at later ages, cracking occurs as the saw cut is placed. In addition, the end of the saw cut window can be estimated using a combination of variables including the average stress from an uncut pavement, the tensile strength of the pavement, and a strength reduction factor. It was concluded that the latest age a saw cut should be placed should be based on a comparison of the predicted residual stress of an uncut pavement with the product of the pavement strength values and the strength reduction factor. Common random longitudinal cracking locations resulting from late sawing as presented by Voigt (2002) are shown in Figure 2.1 for various pavement cross sections.



a) 2-lane-section **b) Extended truck lane** **c) 3-lane section**

Figure 2.1 Late Sawing Induced Longitudinal Crack Formation Locations (Voigt 2002)

Saw-cut depth influence on early cracking has been linked to the time of sawing. Zollinger (1994) reported that early-age sawing methods with depths less than 1/4 × slab thickness provide better crack control than conventional methods with depths of 1/4 × slab thickness or 1/3 × slab thickness. Shallow saw cuts, less than 1/4 × slab thickness or 1/3 × slab thickness, resulting from use of conventional diamond-blade sawing, are reported to be a symptom of late sawing rather than a direct cause of cracking through poor equipment set-up. When cracking is imminent near the end of the sawing window, Voigt (2002) indicated that there is the tendency for saw operators to push a saw too fast, causing the saw blade to ride up out of its full cut. In addition, worn abrasive saw blades can result in shallow saw cut.

Saraf and McCollough (1985) reported that a saw depth cut of 1/4 × slab thickness controls longitudinal cracking with 98% reliability in mixtures containing crushed limestone aggregate, and with 86% reliability in mixtures containing river gravel. Raoufi et al. (2008) concluded that saw cut depths shallower than 1/4 × slab thickness can increase stress to 50% of the tensile strength of the slab leading to micro-cracking development and reduction in long-term performance.

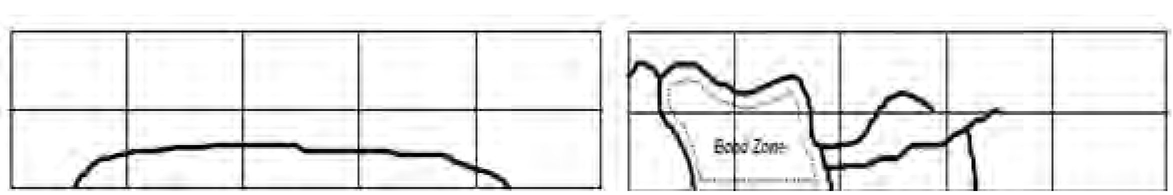
2.2.2 Weather Influence on Cracking in Pavements

The role of weather in the occurrence of random cracking in concrete pavements has been highly recognized. According to Voigt (2002), substantial changes in the weather during and after construction can induce random cracking despite the application of proper jointing techniques. It was reported that concrete paved in early morning under warm, sunny summer conditions exhibit more instances of random cracking than concrete paved during the late morning or afternoon because it receives more radiant heat under the early morning, warm summer conditions. Differential thermal contraction resulting from temperature variations throughout the pavement depth has also been shown to induce random cracking. Okamoto et al. (1994) reported that a sudden drop in surface temperature more than 15˚F can result in cracking from excessive surface contraction, hydration and shrinkage.

In response to these temperature gradients during construction, the FHWA developed HIPERPAV® (HIgh PERformance Concrete PAVing) software to analyze the early age behavior of jointed concrete pavements (FHWA 2005). The software guides designers and contractors with appropriate timelines to saw cut the pavement based on project inputs for ambient air temperature, wind speed, forecast weather conditions, strength development rate of concrete, and other input properties.

2.2.3 Subbase Influence on Cracking in Pavements

Random cracking that first occurs or continues to develop well after paving and sawing has been attributed to slab restraint or movement that result in high tensile stress development within the slab. The movement may be the result of grade settlement or frost heave while the restraint may be from the presence of a stabilized subbase. Random cracking has been linked with the use of stabilized subbases (cement-treated, asphalt-treated, econocrete, and permeable asphalt-treated subbases) on concrete pavement projects (Halm et al.1985; Voigt 1992; Voigt 1994). Cores from such projects have shown significant bonding between the subbase and the concrete pavements. The bonding is reported to reduce the effective saw cut depth necessary to control cracking with normal sawing equipment and timing. In addition, the bonding tends to result in bottom initiated cracks that are erratic in orientation. Subbase related random cracking location and pattern examples are as shown in Figure 2.2.



a) Edge-to-Edge (typical of support frost heave/settlement)

b) Erratic (typical of friction or bonding to subbase)

Figure 2.2 Subbase Related Longitudinal Cracking Patterns (After Voigt 2002)

An analysis of a 33-year performance history of jointed concrete test sections in North Carolina revealed significant longitudinal cracking distress on pavement sections with cement subbase or cement-treated base. For doweled sections, 80% of slabs experienced longitudinal cracking when placed on cement subbase. The result was similar to non-doweled sections (82%) placed on same thickness (6 in) of cement subbase as the dowel sections. Longitudinal cracking was minimum (0-7%) for sections that had crushed aggregate base courses (Corley-Lay and Morrison 2002).

Janda (1935) reported on excessive longitudinal cracking on both sides of the center parting strip at 2.5 ft to 4.2 ft from the centerline on STH 13 in Clark and Taylor Counties, Wisconsin. The pavement consisted of a variable thickness cross-section (9" - 6.5" - 9") with a total width of 20 ft. Tie bars at the center joint were placed at 2-ft or 4-ft centers. The study showed that much of the cracking occurred at locations with Colby silt loam soil, which is an excessive fine-grained soil, dense, plastic and prone to frost heaving. It was concluded that the combination of tie bar stiffening of the center section of the pavement and the irregular heaving resulted in the longitudinal cracking at a short distance from the ends of the bar. In addition, it was observed that the amount of cracking was much reduced at locations where the roadbed was elevated above surrounding land on fill material taken from wide ditches.

Ardani et al. (2003) evaluated premature longitudinal cracking on concrete pavements in Colorado along IH-70 and USH-287. Results from visual observations plus field and lab investigations revealed that the premature longitudinal cracking was attributed to a combination of factors including untreated native soil with high swelling potential, poor compaction, shallow saw-cut at the shoulder joints, and malfunctioning or improper paver vibrators. The study found that 14-ft wide slabs did not contribute to longitudinal cracking occurrence and highly recommended using the 14-ft slab design on rural highways. In addition, contractors were required to equip paving machines with vibrator monitoring devices.

2.2.4 Longitudinal Cracking Treatment Practices

Recommended longitudinal cracking repair methods are summarized in Table 2.1. The methods vary depending on the nature of the longitudinal crack and its location. Repair methods range from a simple saw and seal to more involved options of cross-stitching and panel replacement.

Table 2.1 Recommended Repairs of Longitudinal Cracking in Concrete Pavements (ACPA 2001)

Uncontrolled Longitudinal Crack Location (1)	Crack Description (2)	Recommended Repair (3)	Alternate Repair (4)
Relatively parallel & within 1 ft of joint; may cross or end at longitudinal joint	Full-depth	Saw and seal the crack; epoxy uncracked joint	Cross-stitch or slot-stitch crack
Relatively parallel & in wheel path (1-4.5 ft from joint)	Full-depth, hairline or spalled	Remove & replace panel (slab)	Cross-stitch or Slot-stitch crack
Relatively parallel & further than 4.5 ft from a long. joint or edge	Full-depth	Cross-stitch or Slot-stitch crack; Seal longitudinal joint	N/A
Anywhere	Spalled	Repair spall by partial-depth repair if crack not removed	N/A

2.3 Survey on Practices of JPCP in Selected Midwestern States

An online survey was designed to solicit information from 522 county engineers and pavement professionals in the six Midwest states (Iowa, Ohio, Michigan, Wisconsin, Illinois, and Minnesota) regarding JPCP practices and how those practices impact longitudinal cracking development in JPCP. The information sought pertained to cross-section practices including criteria for determining panel widths on rural highways, commonly used panel widths, the frequency of longitudinal cracking occurrence, and probable causes of cracking from construction practice and design features such as thickness, tie bar longitudinal cracking treatment practices and typical costs.

The survey was posted on-line on August 1, 2011 and closed on November 21, 2011. The study recognized at the onset that not all county engineers at the time might have concrete pavements under their jurisdiction, but it was necessary to target as many engineers as possible based on the assumption that some of the engineers might have had prior experience working with JPCP elsewhere. The majority of the invitees responded immediately to indicate their inability to participate in the survey because of lack of JPCP in their respective jurisdictions. With 100 visits to the online site, 37 invitees ultimately responded to the surveys during the survey period after two reminder notices. The online survey form is presented in Appendix A.

2.3.1 Criteria Inputs for Pavement Cross-section Selection

Invitees were asked to specify the criteria inputs used for determining panel widths for JPCP along rural highways. All 37 invitees responded to this question and the results are shown in Figure 2.3. The results indicate pavement thickness as the dominant criterion input (15 of 37 responses, 41%) considered in the selection of panel width for JPCP, followed by traffic volume. The category labeled "Other, please specify" shows a higher percentage value compared to each of the remaining criteria inputs but a review of the invitee statements revealed that 12 of 16 (75%) respondents did not have any concrete pavements under their jurisdictions. The remaining 25% stated using their state roads "standards."

A cross-tabulation analysis was further conducted to ascertain whether the dominant pavement thickness criterion input is used in isolation or in combination with other factors in the selection of panel width. The results shown in Table 2.2 suggest that additional factors including traffic volume, truck percentage, ease of construction, and construction and maintenance costs dictate panel width selection. Highway functional class was not a critical factor (only 1 of 15 respondents, 6.7%) indicated it was a factor.

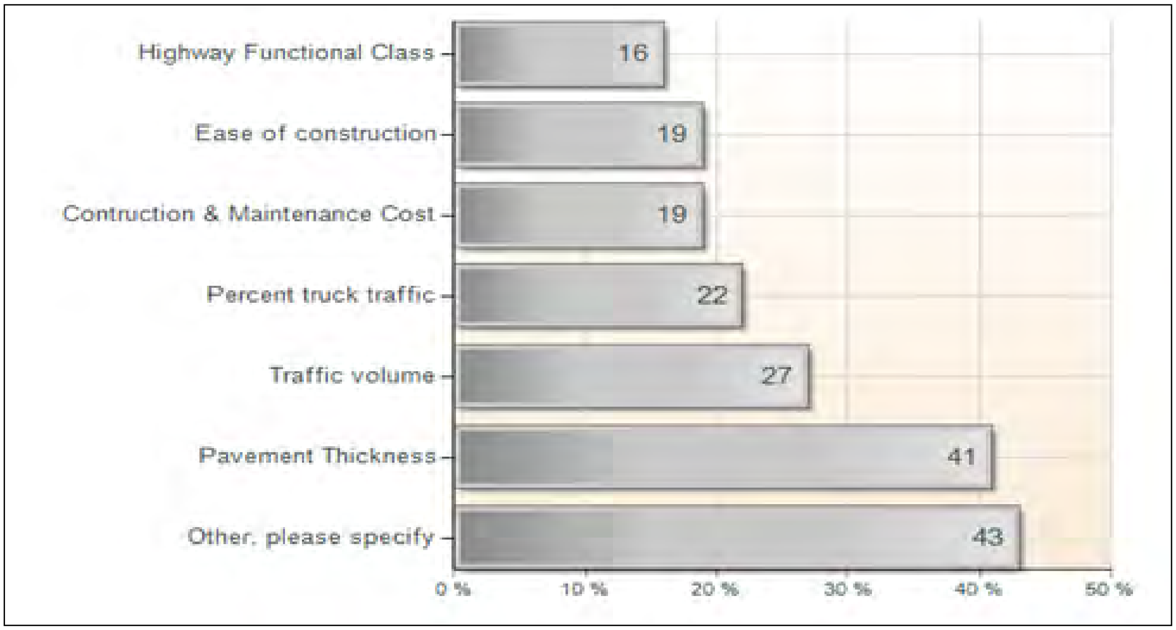


Figure 2.3 Responses Based on Criteria Inputs for Selecting Pavement Cross-section

Table 2.2 Additional Panel Width Selection Criterion Inputs besides Pavement Thickness

Panel Width Criterion Input	Responses based on Factors Considered in Conjunction with Pavement Thickness
Traffic volume	40% (n=6)
Percent truck traffic	40% (n=6)
Ease of construction	33.3% (n=5)
Highway Functional Class	6.7% (n=1)
Construction & Maintenance Cost	26.7% (n=4)

2.3.2 Panel Widths on 2-Lane, 2-Way Rural JPCP

Typical panel widths applied on 2-lane, 2-way rural JPCP was investigated in the survey. Thirty-three invitees responded to this question and the results are summarized in Figure 2.4. The 12-ft wide panel appears to be the most commonly used followed by the 15-ft panel; no one reported using 14-ft panels. A review of the "Other, please specify" category revealed the use of 11-ft panels by five of the responding counties and 13.5-ft panels also used by two counties.

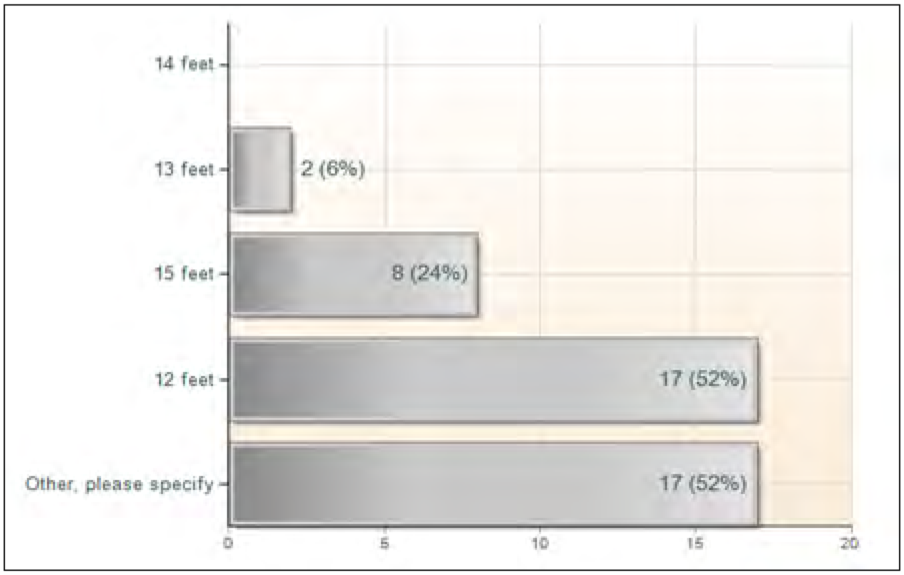


Figure 2.4 Responses based on Panel Width Usage for 2-lane 2-Way JPCP

A cross-tabulation analysis involving panel width and the criterion inputs determined previously in section 2.3.1 is summarized in Table 2.2. For example, of the 15 respondents that indicated pavement thickness is used in selecting panel width, nearly 67% (10/15) indicated 12-ft panels are used in their jurisdictions while 33% (5/15) indicated 15-ft panels are used. Table 2.2 further suggests that regardless of the input chosen, 12 ft or 15 ft panels are more likely to be used for 2-lane, 2-way JPCP.

Table 2.3 Responses based on Panel Width Relationship to Width Criterion Input for 2-lane, 2-way JPCP

Panel Width	Criterion Input for Panel Width Selection					
	Traffic volume	Percent truck traffic	Ease of construction	Highway Functional Class	Pavement Thickness	Construction & Maintenance Cost
	#Responding, n=10	n=8	n=7	n=6	n=15	n=7
12 feet	10 (100%)	6 (75%)	5 (71.4%)	4 (66.7%)	10 (66.7%)	5 (71.4%)
13 feet	1(10%)	0(0.0%)	1(14.3%)	0(0.0%)	0(0.0%)	1(14.3%)
14 feet	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)	0(0.0%)
15 feet	1(10%)	1 (12.5%)	4 (57.1)	2(33.3%)	5(33.3%)	4(57.1%)
Other, please specify	3(30%)	2 (25.0%)	2(28.6%)	1 (16.7%)	4(26.4%)	4(57.1%)

2.3.3 Panel Widths on Multilane Rural JPCP

Panel width usage on multilane rural JPCP highways is presented in Figure 2.5. Panel widths in use range from 12 ft to 15 ft with 12-ft panels being the most common (12 of 31 respondents, ≈39%). In the "Other, please specify" category, respondents mostly indicated they had no multi-lane JPCP under their respective jurisdictions.

A cross-tabulation analysis involving panel width and the criterion inputs determined previously in section 2.3.1 is summarized in Table 2.4. For example, for the 10 respondents that indicated that traffic volume is used in selecting multi-lane panel width, 70% indicated 12-ft panels are used. Table 2.2 further suggests that regardless of the input chosen, 12-ft panels are more likely to be used for multilane rural JPCP compared to other panel widths.

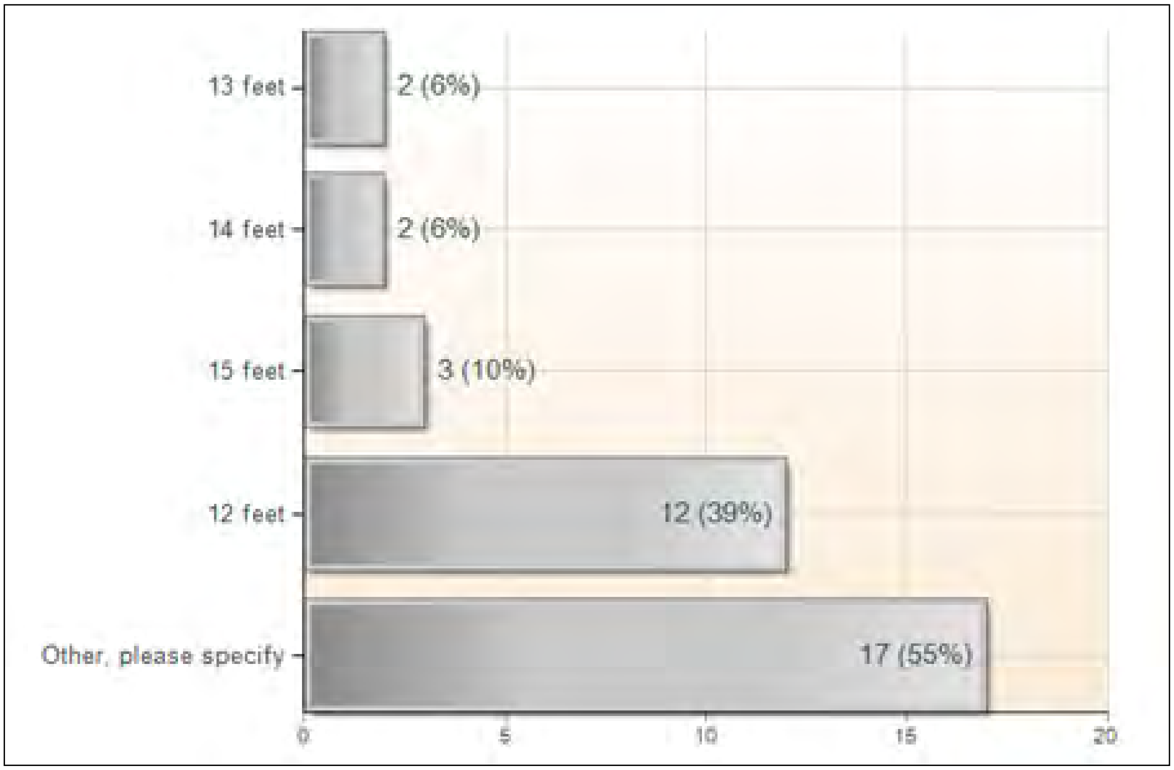


Figure 2.5 Responses based on Panel Width Usage for Multilane Rural JPCP

Table 2.4 Responses based on Panel Width Relationship to Width Criterion Input for Multilane Rural JPCP

PANEL WIDTH FOR MULTILANE JPCP	**Traffic volume**	**Percent truck traffic**	**Ease of construction**	**Highway Functional Class**	**Pavement Thickness**	**Construction & Maintenance Cost**
	# Responding, n=10	n=8	n=7	n=6	n=14	n=7
12 feet	7(70%)	5(62.5%)	5(71.4%)	2(33.3%)	8(57.1%)	4(57.1)
13 feet	1(10%)	0(0.0%)	2(28.6%)	0(0.0%)	0(0.0%)	2(28.6%)
14 feet	1(10%)	0(0.0%)	2(28.6%)	0(0.0%)	1(7.1%)	2(28.6%)
15 feet	0(0.0%)	0(0.0%)	1(14.3%)	1(16.7%)	1(7.1%)	2(28.6%)
Other, please specify	3(30.0%)	3(37.5%)	2(28.6%)	3(50%)	5(35.7)	2(28.6%)

2.3.4 Frequency of Longitudinal Cracking Occurrence

Frequency of longitudinal cracking occurrence was investigated as part of the survey in relation to factors such as panel width, joint spacing, pavement thickness, tie bars, construction related practices, topography, and proximity to existing structures.

2.3.4.1 Panel width relationship with longitudinal cracking frequency

Figure 2.6 shows the distribution of respondents and their perceptions of longitudinal frequency in various panel widths. The 12-ft and 15-ft wide panels were reported to have higher longitudinal cracking frequencies compared to 13-ft and 14-ft wide panels. From a review of the "Other, please specify" category, respondents had varied opinions. Some indicated that the longitudinal cracking occurrence is a subgrade issue rather than width. Others also indicated no significant differences between panel widths when it comes to longitudinal cracking, but one respondent linked higher longitudinal cracking frequency with 20-ft older panels.

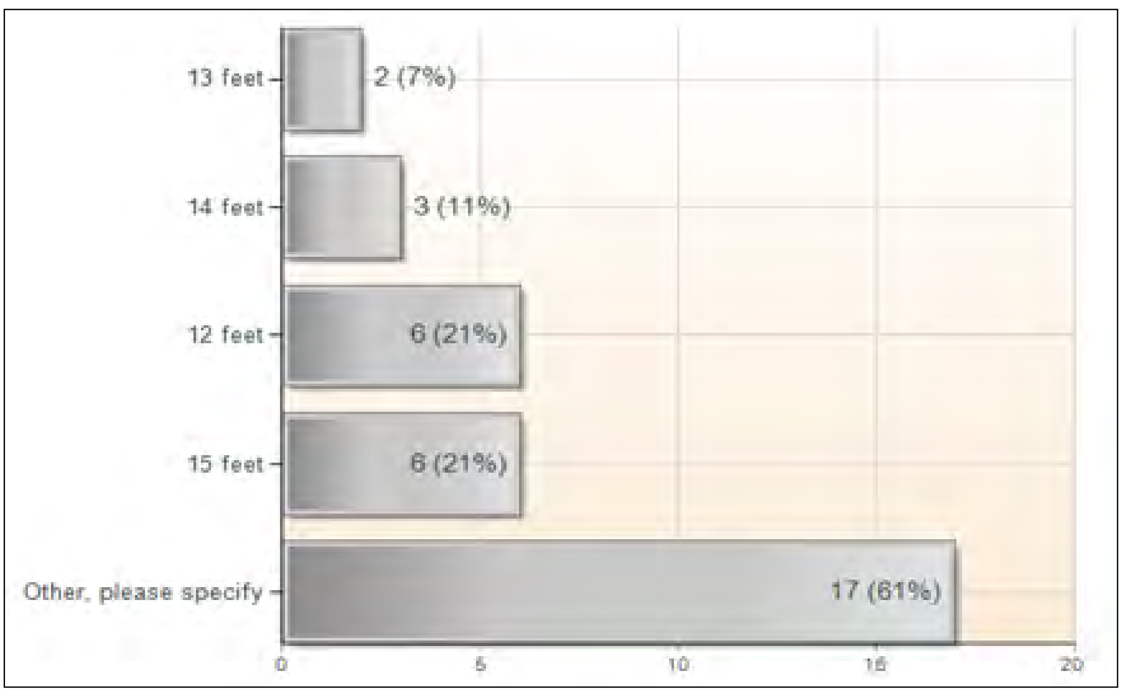


Figure 2.6 Responses based on Panel widths exhibiting more Longitudinal Cracking

2.3.4.2 Pavement Thickness Relationship with Longitudinal Cracking Frequency

Pavement thickness relationship and longitudinal cracking frequency relationship based on survey responses are shown in Figure 2.7. Thicker pavements (≥11 in) do not exhibit longitudinal cracking compared to the thinner pavements, which are more vulnerable. In the "Other, please specify" category, the majority specified 6-in thickness as having the highest frequency of longitudinal cracking.

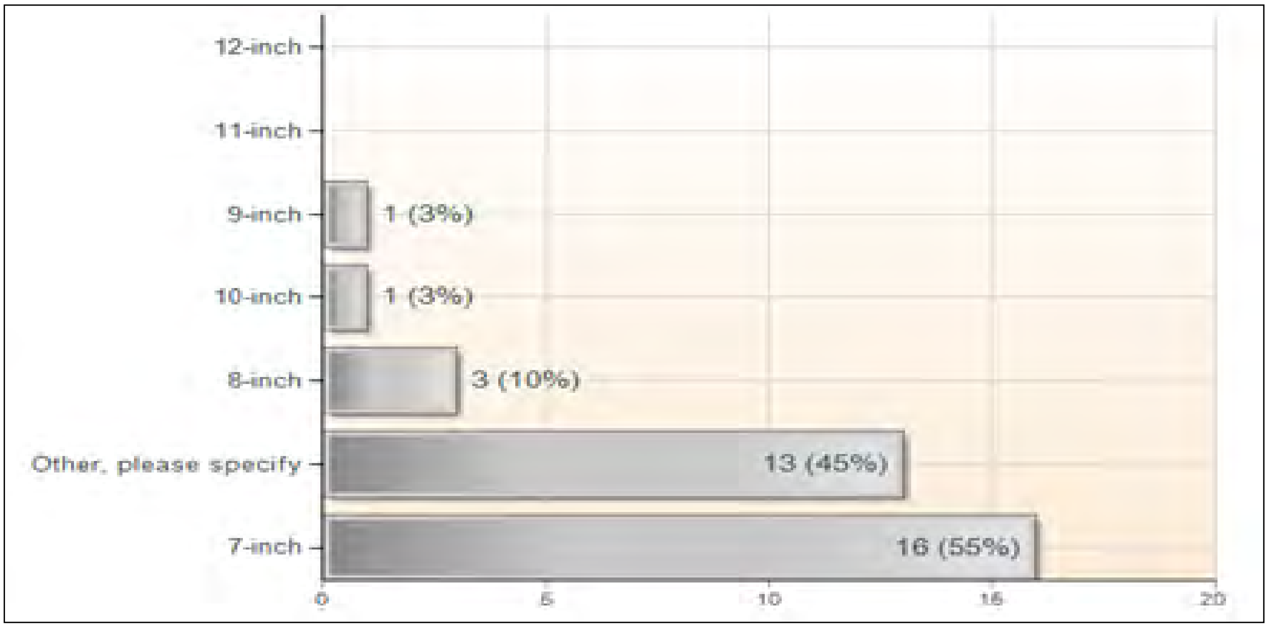


Figure 2.7 Responses based on Thicknesses Exhibiting More Longitudinal Cracking

2.3.4.3 Transverse Joint Spacing Relationship with Longitudinal Cracking Frequency

Figure 2.8 shows the relationship between transverse joint spacing and longitudinal cracking based on survey responses. The results indicate that more longitudinal cracking tend to occur with shorter joint spacing. However, in the "Other, please specify" category, four respondents reported having higher frequencies in panels with 20-ft transverse joint spacing. It does appear from these two conflicting views that longitudinal cracking would occur irrespective of the magnitude of the transverse joint spacing and the frequency may be attributed to other factors besides joint spacing.

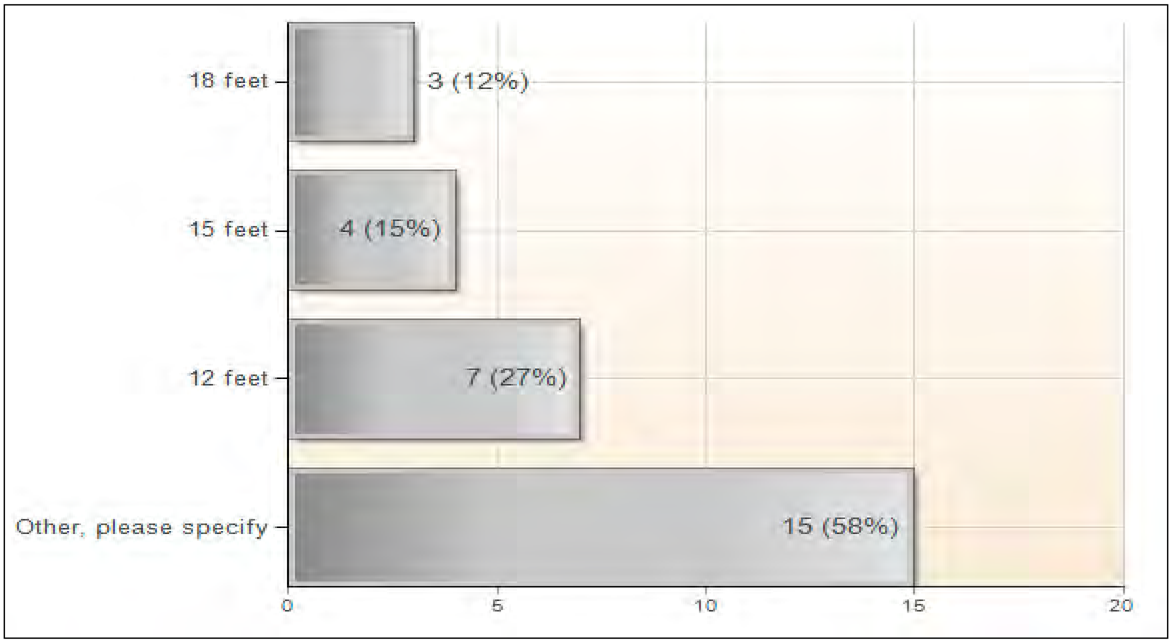


Figure 2.8 Responses based on Transverse Joint Spacing Exhibiting more Longitudinal Cracking

2.3.4.4 Tie Bar Impact on Longitudinal Cracking Frequency

Responses shown in Figure 2.9 indicate an even split opinion regarding whether tie bars have an effect on longitudinal cracking.

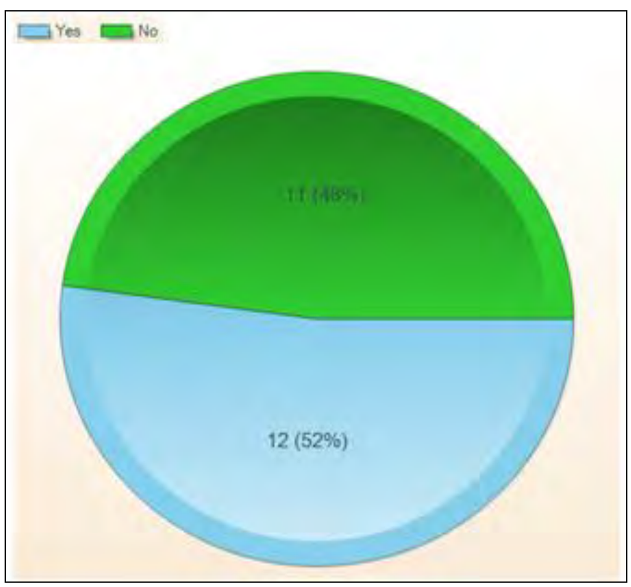


Figure 2.9 Response based on Tie Bar Impact on Longitudinal Cracking

2.3.4.5 Construction Variables Impact on Longitudinal Cracking Frequency

Figure 2.10 indicates a wide range of construction variables have impact on the frequency of longitudinal cracking. Experience of high longitudinal cracking frequencies was associated with JPCP with inadequate subbase compaction and poor joint saw-cut timing. Misaligned dowel bars and faulty vibrators were also reported as contributing factors to longitudinal cracking frequency.

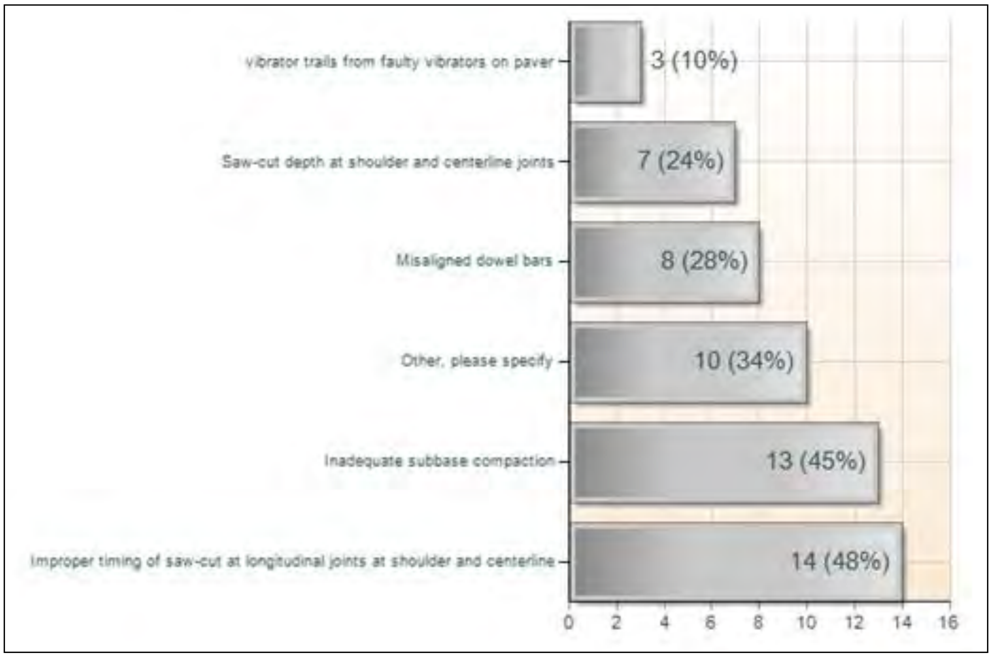


Figure 2.10 Responses based on Construction Practices on Longitudinal Cracking Frequency

The next step was to investigate the construction practices respondents attributed to longitudinal cracking regarding particular panel widths either on 2-lane or multi-lane JPCP. For 2-lane JPCP results shown in Figure 2.11, no data is associated with the 14-ft panels because respondents did not report using the 14-ft panels on 2-lane, 2-way highways as determined under section 2.2.2 of this report. The 12-and 15-ft panels are affected more by saw cut and subbase issues compared to the 13-ft panels. The effects are, however, more pronounced in the 12-ft panels. Vibrator trail and misaligned dowel-related longitudinal cracking were not found in 13-ft panels.

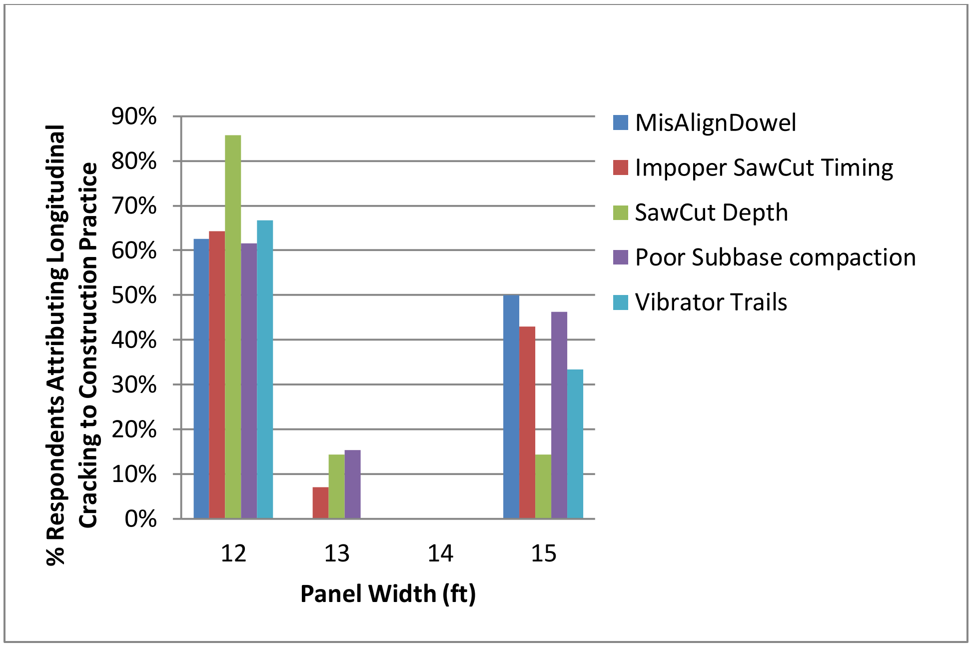


Figure 2.11 Construction Practices Impacting Longitudinal Cracking in Panels on Rural 2-lane JPCP

For the multi-lane facility, Figure 2.12 suggests all panel widths experience problems with subbase and timing window for joint saw cut. In addition, the 12-ft panels are prone to more construction related longitudinal cracking compared to all other panels.

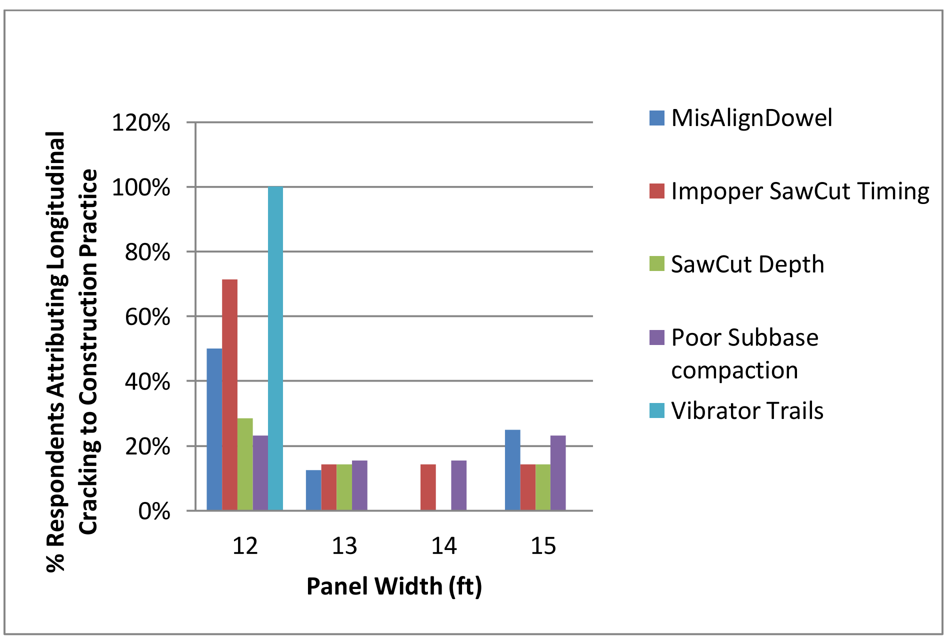


Figure 2.12 Construction Practices Impacting Longitudinal Cracking in Panels on Rural Multi-lane JPCP

2.3.4.6 Longitudinal Cracking Locations on JPCP

As indicated in Figure 2.13, longitudinal cracking occurs more near panel edge and at mid-panel locations compared to the vicinity of sawn longitudinal joints. One respondent in the "Other, please specify" category indicated cracking occurs along tie bar ends.

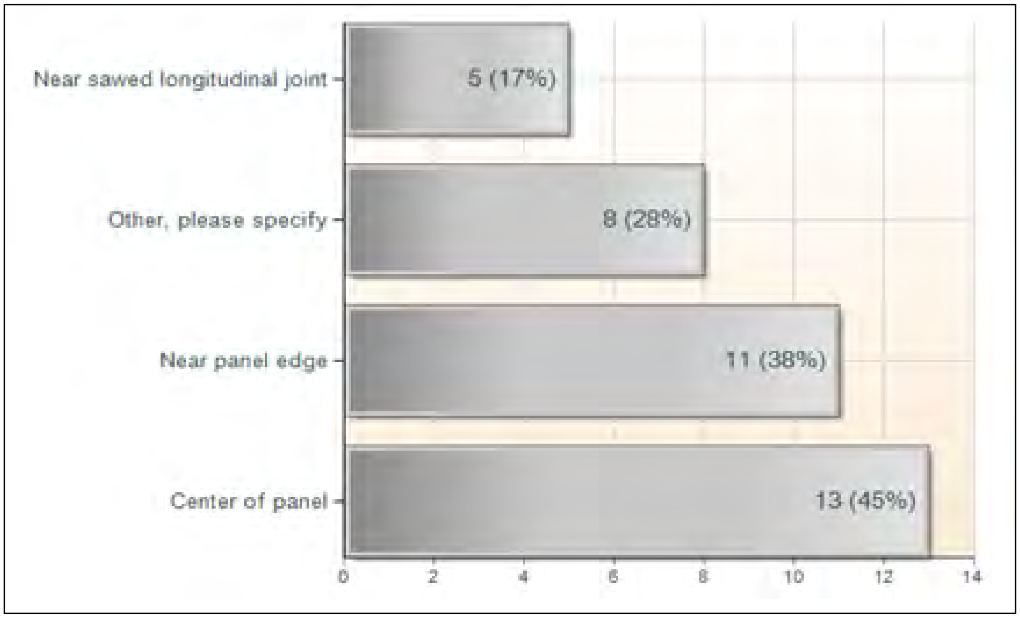


Figure 2.13 Longitudinal Cracking Locations on JPCP

2.3.4.6 Topography and Structures' Impact on Longitudinal Cracking Frequency

The survey explored the likelihood of topography (cut/fills) and highway structures such as bridges and other drainage structures contributing to the occurrence of longitudinal cracking. Figure 2.14 shows longitudinal cracking will be common at all locations but higher at areas subject to differential heaving of subgrade, vicinity of culverts, and at fill sections. In the "Other, please specify" category, respondents noted that cracking also occurs at poorly drained areas and at cut-to-fill transitions and vice versa.

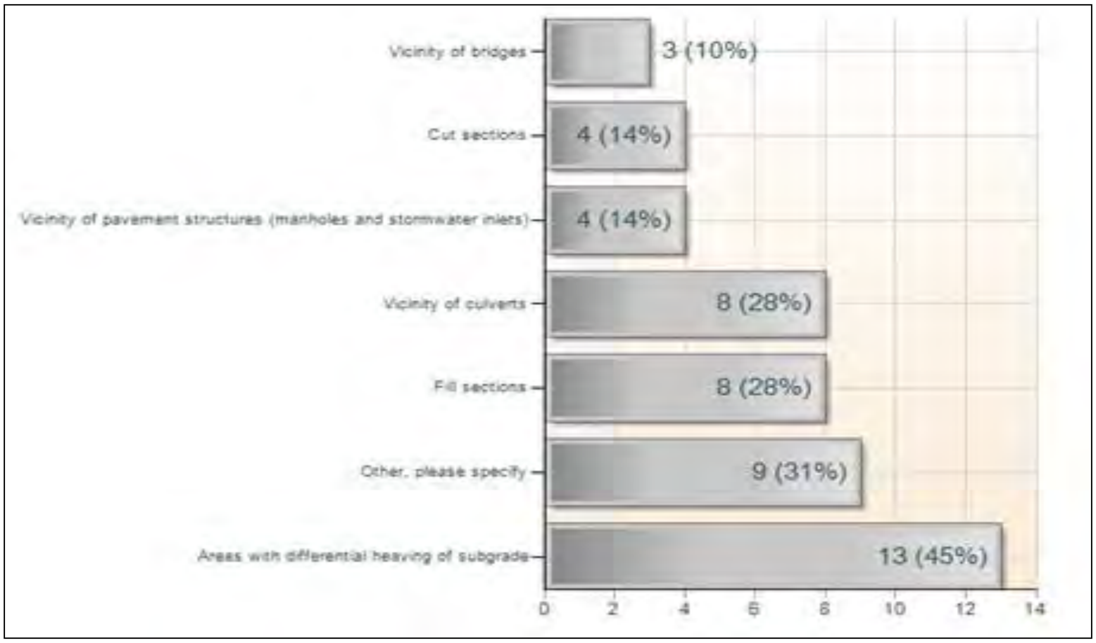


Figure 2.14 Responses based on Topography and Structures' Impact on Longitudinal Cracking

When the data are stratified by panel width for 2-lane JPCP, as shown in Figure 2.15, the survey results seem to suggest that longitudinal cracking frequency on 12-ft panels is higher than frequencies found on 13-ft and 15-ft panels located in cut/fill sections and in the vicinity of highway structures.

For multi-lane facilities, longitudinal cracking is linked with differential subgrade heaving in all panel widths as shown in Figure 2.16. Longitudinal cracking appears more frequently on 12-ft panels compared to all other panels. The 14-ft panel is the least impacted.

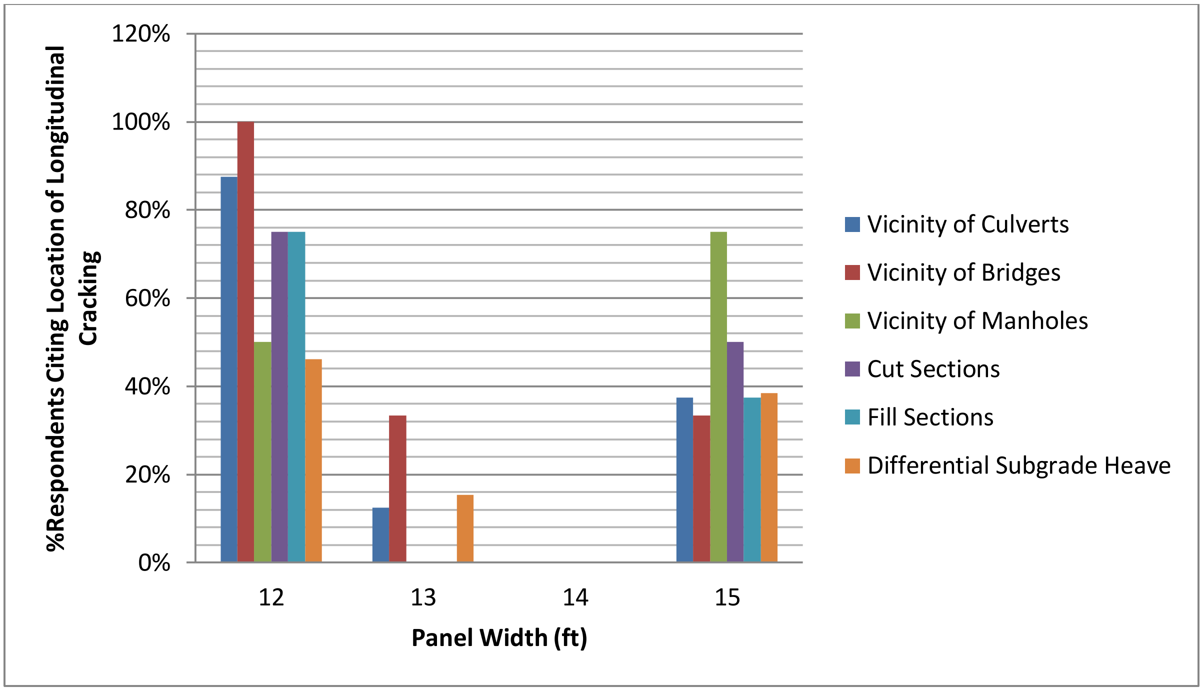


Figure 2.15 Longitudinal Cracking Location Frequency in Relation to Highway Structures and Cut/Fill Sections on Rural 2-lane JPCP

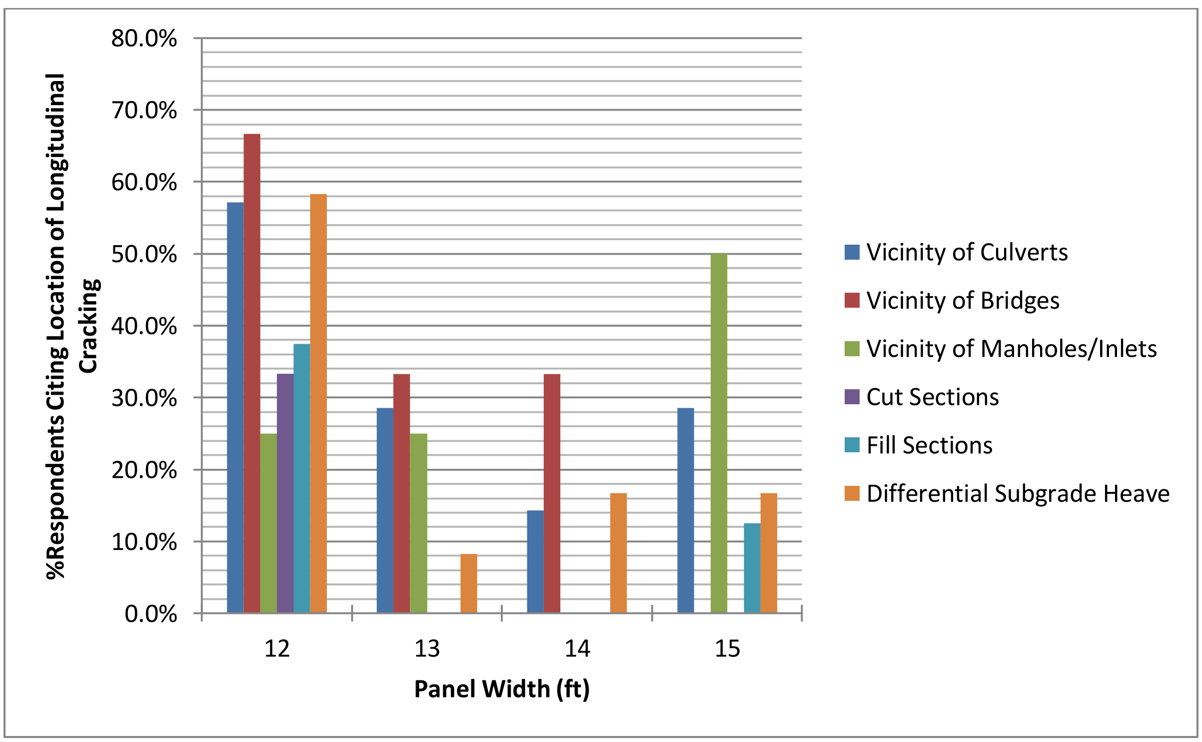


Figure 2.16 Longitudinal Cracking Location Frequency in Relation to Highway Structures and Cut/Fill Sections on Rural Multi-lane JPCP

2.3.4.7 Method for Fixing Longitudinal Cracking

The methods for fixing premature and normal or expected longitudinal cracks are the same according to the survey results. The main methods used include rout and seal, cross-stitching, and partial or full-panel replacement.

2.3.4.8 Initial Appearance of Premature Longitudinal Cracking

The survey responses from 24 respondents indicate that premature longitudinal cracking initiation time varies from less than a month to as high as 60 months (5 years) with an average initiation time of approximately 24 months.

2.3.4.9 Cost to Fix Premature Longitudinal Cracking

The prices for fixing premature cracks vary considerably as reported in the survey. It ranged from \$0.50 to \$300 per linear foot (lf). The price data was broken into two sets to focus on a low-end (<\$10) versus a high-end (≥\$10) repair cost. The price range for the low-end was reported to be \$0.50 to \$9 with a mean repair cost of \$1.20/lf. The high-end range was reported to be \$15 to \$300 with an average repair cost of \$122/lf. One respondent rightly noted that the cost would vary depending on the treatment type (a simple crack filling versus cross-stitching or full-panel replacement).

2.4 Other Surveys

The Ohio Department of Transportation (ODOT) reported on a survey regarding concrete pavement ramp construction practices and problems with longitudinal cracking. Survey responses from 12 ODOT districts reported the occurrence of longitudinal cracking on 16-foot wide ramps in 5 of 12 districts. The cracks mostly occurred at center of slabs with some also occurring within 2 ft of sawed longitudinal joints. Some cracks were reported to have appeared within 3 to 6 months after the placement of the concrete. The cracks were reported to have been fixed using a wide range of methods including cross stitching, epoxy injection, removal and replacement, and placement of a sealant. The ODOT survey also examined practices in other states, which have been summarized in Table 2.5. The table suggests that all the states examined use JPCP for ramps with tied PCC shoulders. Longitudinal joint spacing ranges from 14 ft to 16 ft, while the 15-ft transverse joint is mostly used. Ramp section inside-to-out however, varies considerably. With the exception of Illinois, all states reported having no performance problems with their cross-section design details. Illinois reported moving away from its inside-to-out 4'-16'-8' design and replacing it with a 4'-8'-8'-8' section design. Illinois implemented the latter design at few locations and reported having no problems.

After examining practices in other states, ODOT (2003) recommended alternative panel widths of 8 ft and 12-1/2 ft for curtailing longitudinal cracking on its ramps compared to its original section that consisted of 16-ft panel widths with 6-foot right side and 3-ft left side tied shoulders with cross slope breaks at the shoulders.

Table 2.5 Ramp Cross-section Practices

State	Pavement Type	Shoulder Type	Maximum Longitudinal joint spacing, ft	Transverse Joint spacing, ft	Inside-to-out section	Performance problems with design	
						Yes	No
Indiana	JPCP	Tied PCC	16	18	7'-16'-11'		X
Pennsylvania	JPCP	Tied PCC	14	15	4'-8'-8'-8'		X
Illinois	JPCP	N/A	16	15	4'-16'-8'	X	
Michigan	JPCP	Tied PCC	14	15	4'-12' asphalt		X
Kansas	JPCP	Tied PCC	14	15	8'-12'-10'		X

2.5 Online Discussion on Longitudinal Cracking on Iowa Concrete Pavements

An online/email discussion was initiated with the president of the Iowa Concrete Pavement Association regarding the sudden appearance of a significant amount of longitudinal cracking within 2-3 ft of the edge of 14-ft widened concrete pavements in Iowa (Smith 2011). Iowa started building widened lane pavements 10-15 years ago and had never seen this distress pattern until now and was looking for some understanding of the causes of the distress pattern. The pavements under consideration were reported to be 10 to 12 in thick with 8 to 9 in granular subbase in the outer wheel path area. The pavements had edge drains with transverse joint spacing at 20 ft. The subgrade slope was reported to be 1% greater than top of subbase.

The executive director of the Concrete and Aggregates Association of Louisiana reported that Louisiana constructed 15-ft widened lanes in the past 20 years but no cracking has appeared yet (Temple 2011). It was discussed whether any evaluation of the location of load transfer devices in relation to the locations of the cracks had been done. It was suggested that the problem could be a combination of load transfer device issue and truck tire loading since the sample photos provided showed all the cracking occurring in the wheel path.

The executive vice president of the South Dakota ACPA reported that South Dakota used 30-ft widened non-doweled lane pavement until 1986 when longitudinal cracking was noticed between mid-slab and the outside wheel path (Engbrecht 2011). South Dakota then switched to the 28-ft wide pavements with 20-ft transverse joints in two lane environments with dowels and has not encountered any problems. On the interstates, South Dakota has used 26-ft PCC with a widened outside lane for 20+ years with no problems and 15-ft transverse joints on thinner pavements and 20-ft transverse joints on 10-in thick (or greater) pavements.

The executive director of the ACPA pointed out that the cracking pattern exhibited by the Iowa pavements was probably the first of its kind that professionals in the ACPA network had witnessed and it would be premature to attribute it to the widened lane (Voigt 2011). It was noted that the occurrence of the cracking only 2-3 ft from the edge many years after construction makes the degree of support either from settlement or heaving a probable cause. It was also possible, although unlikely, that the cracking may have been caused by wide loads that are overloads, in which case the cracking may be related to fatigue. However, even if this were true, it would be related to some degree to the support. The following were recommended by Voigt (2011):

(a) An investigation of the subbase widening constructed to accommodate the widened lane from the previous lane configuration may be warranted. In addition, it is necessary to determine if the cracked segments tip away (settle down) or not from the rest of the slab.

(b) Investigate the start and end locations of the cracking because field experience suggests that longitudinal cracks that are close to the edge of a pavement, and that begin or end at the edge of the pavement are likely caused by loading on slabs with non-uniform support along the lane edge.

2.5 Summary and Conclusions

This chapter reviewed literature and research on the causes and treatment practices for longitudinal cracking in JPCP. A survey was also conducted among county engineers around the Midwest region regarding rural 2-lane and multi-lane JPCP and their relationship to longitudinal cracking occurrence, treatment, and cost.

The literature review found that cracking of concrete slabs occurs when tensile stresses exceed tensile strength from initial shrinkage from moisture loss, restraint by base or subbase friction from expansion and contraction caused by temperature changes, and thermal and moisture gradients between the top and bottom of the slabs. Transverse and longitudinal saw cut joints are created to induce a plane of weakness where a crack is intended to initiate and then propagate to the bottom of the slab. Early-age sawing with depths of 1/4 × slab thickness provide better crack control than greater saw depths. The literature also reported that differential thermal contraction results from temperature variations throughout the pavement depth has been shown to induce random cracking. Random cracking that first occurs or continues to develop well after paving and sawing has been attributed to slab restraint or movement that result in high tensile stress development within the slab. The movement may be the result of grade settlement or frost heave whilst the restraint may be from the presence of a stabilized subbase.

The results of an online survey of engineers and pavement professionals in the six Midwest states found that pavement thickness is the primary criterion input considered in the selection of panel width for JPCP, followed by traffic volume, truck percentage, ease of construction, and construction and maintenance costs. For 2-lane 2-way pavements, the 12-ft wide panel is most commonly used (2/3 respondents) followed by the 15-ft panel (1/3); no respondents reported using 14-ft panels, although this panel width is a WisDOT design policy. Despite key design inputs such as traffic volume and truck traffic, 12-ft panels are more likely to be used for multi-lane rural JPCP than any other width.

Frequency of longitudinal cracking occurrence was investigated in relation to factors, with the findings in Table 2.6.

Table 2.6 Summary of Factors causing Longitudinal Cracking

Factor	Finding
Panel Width	The 12-ft and 15-ft wide panels were reported to have higher longitudinal cracking frequencies compared to 13-ft and 14-ft wide panels.
Pavement Thickness	Thicker pavements (≥11 in) do not exhibit longitudinal cracking compared to more vulnerable thinner pavements.
Joint Spacing	More longitudinal cracking tends to occur with shorter joint spacing. However, some respondents reported having higher frequencies in panels with 20-ft transverse joint spacing.
Tie Bars	There is a split opinion regarding whether tie bars have an effect on longitudinal cracking.
Construction-related Practices	High longitudinal cracking frequencies were associated with inadequate subbase compaction and poor joint saw-cut timing. Misaligned dowel bars and faulty vibrators were also reported as contributing factors.
Panel Location	Longitudinal cracking occur more near panel edge and at mid-panel locations compared to the vicinity of sawn longitudinal joints.
Topography and Structures	Cut/Fills, highway structures (bridges, drainage, culverts etc.) and areas subject to differential subgrade heaving contribute to the occurrence of longitudinal cracking. For 2-lane JPCP, cracking frequency on 12-ft panels is higher than 13-ft and 15-ft panels located in cut/fill sections and in the vicinity of highway structures. For multi-lane facilities, longitudinal cracking is related to differential subgrade heaving in all panel widths, and appears more frequent on 12-ft panels.

CHAPTER 3 DATA COLLECTION

3.1 Introduction

The previous chapter provided valuable considerations for potential factors causing longitudinal cracking in doweled JPCP pavements. This chapter describes the collection of data for doweled JPCP pavements having an age of 25 years of less in Wisconsin. The relationship of maximum allowable pavement width as a function of pavement thickness is of primary importance in this study, thus, data for a range of panel widths was collected, including wider panels (14 and 15 ft) and standard width panels (12 and 13 ft). The following sections describe the databases from the Pavement Management Unit of WisDOT that were obtained for design, construction, traffic, and performance data. The individual databases were merged by pavement Sequence Number (a defined length of roadway for pavement management) to form a single holistic database for data analysis. Then, length (extent) and width (severity) of actual longitudinal cracking from doweled JPCP pavements having ages 25 years or less were measured and added to the database by using line-point measurement tools at the WisDOT Truax Lab and with visual field measurement of segments, primarily in the Northwest Region of the state.

3.2 Databases

Databases from the Pavement Management Unit of WisDOT were obtained for design, new construction reports, traffic, and performance data. The purpose of collecting these databases was to assemble doweled JCPC pavements (Type 8) having a variety of panel widths. Three primary databases accessed were Meta Manager, Pavement Inventory Files (PIF), and New Construction Reports. Table 3.1 provides a brief description of each database.

Table 3.1 Databases Accessed

Database	Description
Meta Manager	This database compiles traffic data and forecasts anticipated traffic levels for the 5 WisDOT regions. Key data fields obtained were highway number, sequence number, reference point (RP), termini of segment, pavement type, functional class, number of lanes, AADT, and percent trucks.
Pavement Inventory Files (PIF)	Descriptions and pavement distress data for each sequence number are in the PIF database, such as the PCI, IRI, and both extent and severity of individual pavement distresses (slab cracking, etc.). This database also includes highway number, termini description, directional lane of measurement, year of measurement, region number, and county.
New Construction Reports	Attributes of projects constructed in a given year are detailed in the New Construction Reports and include such fields as prime contractor, thickness of PCC pavement, base type (dense or open graded base course), lane-miles of paving, and project identification number. This database was compared to paving year of sequence numbers in the Meta Manager and PIF databases.

3.2.1 Meta Manager Database

Meta Manager is a comprehensive, integrated database system for conducting needs and performance analyses for pavements and bridges. It is updated and distributed quarterly. Meta Manager is comprised of independent databases organized by five regions in the state. Each region consists of one Excel™ spreadsheet workbook with multiple datasheets. The workbook datasheets include information on base, roadway, unimproved pavement condition, improved pavement condition, safety, pavement treatment scoping, mobility, unimproved bridge condition, and improved bridge condition. The primary datasheet accessed for this investigation was 'roadway'. The roadway datasheet provides the most current traffic volume data pavement segments using sequence numbers, traffic segment identification numbers, and from-and-to reference points. Other relevant fields include highway number by direction, projected two-way AADT, and percent trucks for 1, 5, 10, 15, and 20 year periods from the base year.

3.2.2 Pavement Inventory Files

The pavement performance database, commonly referred to as PIF, is a relational database model designed to store pavement inventory information, capture distress characteristics, and summarize continuous ride, faulting, and rutting data. The key datasheets include the descriptive (DESC), Pavement Condition Index (PCI), and International Roughness Index (IRI) data. Microsoft Access^{TM} software compiles the PIF file with export to Microsoft Excel^{TM} spreadsheet format as needed.

Descriptive fields identify pavement segments by sequence numbers, county name, county number, district, from-to reference points, highway number, highway direction, functional class number, national highway system designation, surface year and original construction year. In addition, the datasheet has fields for the segment length, cumulative mileage, and roadbed soil type.

The IRI datasheet contains roughness of the pavement in inches per mile in the ordinal travel direction (N, S, E, and W) and the wheel path (left or right). Fields represent the sequence number, inverse year, the day-month-year the segment was tested, the surface year, surface type, air temperature, average values for PSI and rut depth. In addition, it lists the speed and vehicle number used to conduct the tests.

PCI history datasheet has separate text files for both rigid and flexible pavement segments tested between 1984 and present. It lists the segment sequence number, inverse year, test day-month-year, surface year, distress type severity and extent for quantifying PCI.

3.2.3 New Construction Reports

The New Construction database, also known as the Ride Report, consists of spreadsheets organized by year from 1989 to present for projects built in a given year. Prior to 2000, spreadsheets were created in Microsoft Excel^{TM}. Since 2000, the Ride Reports (New Construction Reports) can be found in Microsoft Access^{TM} files or PDF file formats organized by year. In the Access^{TM} format, each file has two key datasheets, namely, the Office (ACOffice or

PCCOffice) and Field (ACField or PCCField). The Office datasheet identifies pavement location (rural or urban, district, county, termini by descriptive start and end points), construction style (reconstruction, resurfacing, rehabilitation), contract identification numbers (contract1, contract2), project length, pavement surface thickness, milling depth for AC, base type (DGBC, CABC, OGBC2, pulverized, etc.), pavement surface paved over), flexible/rigid pavement type, surface year. The ACField and PCCField datasheet has fields representing site identification number, sequence number for 2000 to present, beginning reference point (RP), contract identification number, highway name by direction, survey length, lane, direction, Asphalt or PCC, set value, measured IRI, and rut depth immediately after construction.

3.3 Database Merge

The Meta Manager, PIF, and Ride Report databases were merged by pavement Sequence Number to yield a single composite database for every PCC pavement segment constructed in Wisconsin. Pavements built prior to 1989 lack construction data (PCC thickness, base type, etc.) since electronic reports were only available from 1989 to present. For pavement constructed before 2000, no Sequence Number is provided in the Ride Reports, so a merge procedure was developed using a hierarchal level of surface year, county number, and highway number. Then, a manual verification was performed to determine accuracy.

The merged database was then reduced to pavement segments that were 25 years or less in age and JPCP with dowels (Type 8). A simple sorting procedure removed all PCC pavements from consideration that were jointed reinforced pavements (Type 4), non-doweled jointed plain concrete pavements (Type 5), and continuously reinforced concrete pavements (Type 6). All urban sections were also removed from consideration due to potential effects from shoulder tie bars, surface drainage, and curb and gutter. This reduction in pavement types and urban sections created a database of 1,767 unique Sequence Numbers for evaluation.

3.4 Database Development

The merged database was enhanced by including the extent and severity of observed longitudinal cracking from Type 8 pavements of age 25 years or less. Since the PCI measurement in the PIF database does not explicitly measure the extent and severity of longitudinal cracking, the research team chose to measure actual cracking using a combination of computer images and field measurements.

The research team met the Pavement Management Unit at WisDOT to explore the use of the electronic PIF database files for longitudinal crack measurement. It was learned that four of five regions in the PIF database (NC, NE, SE, SW) have electronic images of the pavement recorded at intervals of 28 ft. It was also learned that the Northwest Region did not have electronic photos, but rather VCR photolog images to rate the pavement. With the cooperation of WisDOT staff, the research team collected data at the Truax Center using the Roadview™ software to measure the length, severity, and offset of the observed longitudinal crack. Length was recorded between the beginning and ending point of the crack within one of five offsets: left edge, left wheel path, between wheel path, right wheel path, right edge. The offset location was defined by transverse distance across the entire panel width from the left longitudinal joint to the right longitudinal joint. Severity was recorded as the width of crack corresponding to three levels of low, medium, and high. Table 3.2 reports the measures of offset and severity when recording the length of a crack. Segments having no cracking were also recorded. If a crack migrated from one offset to another, the crack was discretely assigned to the specific offset, then the length and severity were recorded.

Table 3.2 Data Collection measures for Crack Offset and Severity

Classification	Value
(a) Crack Offset	
Left Edge	0 to 1.5 ft
Left Wheel Path	1.5 to 4.5 ft
Between Wheel Path	4.5 to 7.5 ft
Right Wheel Path	7.5 to 10.5 ft
Right Edge	> 10.5 ft
(b) Crack Severity	
Low	≤ 1/2 in
Medium	> 1/2 in to ≤ 2 in
High	> 2 in

Project geometric features of the cracking location were recorded including features for pavement cross-section, shoulder material, rumble strip, sealed longitudinal shoulder, cut/fill, tangent/curve, and the presence of bridges or pavement structures. Due to substantial time necessary to enter cracking data for individual pavement Sequence Numbers at the Truax Center, it was decided in some cases to collect data from every other or every third pavement Sequence Number. An inventory of longitudinal cracking in the Northwest Region was recorded by physically traveling to the pavement segments and recording similar information using the same data entry format as the electronic photo files. The sampling approach is considered random since all segments in the state were given an equal chance of selection.

An illustration of the database from the initial Sequence Numbers on USH 2 in Douglas County is shown in Figure 3.1. Individual observed cracks in these Sequence Numbers are shown, where Sequence #1300 had five observed longitudinal cracks with low severity level (≤ 1/2 in) within a 1.01-mile pavement segment. A pair of longitudinal cracks were observed in Sequence Numbers #1310, #1320, and #1330. In several cases, data were not available for each variable within a given Sequence Number as denoted with a period, or ".". This was primarily the case with construction data where base type, dowel bar installation, and thickness data were missing.

The developed database was segregated into factors associated with design, construction, traffic, and the environment, as well as the performance measures. Table 3.3 segregates the factors, identifies specific measures, and offers a rationale for investigating (or not investigating) the factors.

Sequence Number	High-way	Crack 0N1Y	Panel Width	Thick -ness	Joint Spacing	Skewed Joint	Sawed 1 Parting Strip2	Tined	Rumble Strip	Shoulder Type	Shoulder Crack Filler
1300	2	1	14	9	16	0	1	1	1	1	0
1300	2	1	14	9	16	0	1	1	1	1	0
1300	2	1	14	9	16	0	1	1	1	1	0
1300	2	1	14	9	16	0	1	1	1	1	0
1300	2	1	14	9	16	0	1	1	1	1	0
1310	2	1	14	9	16	0	1	1	1	1	0
1310	2	1	14	9	16	0	1	1	1	1	0
1320	2	1	14	9	16	0	1	1	1	1	0
1320	2	1	14	9	16	0	1	1	1	1	0
1330	2	1	14	9	16	0	1	1	1	1	0
1330	2	1	14	9	16	0	1	1	1	1	0

Sequence Number	Base 1Dens 2Open	Bask1 DBI2	Topo-graphy	Curve	Bridge	Rec1 Reh2 Res3 Rep4	AADT	Truck Perc.	AADTT	Posted Speed	Num. Lane	Func Class
1300	1	.	2	0	0	3	15150	17.1	2591	65	2	10
1300	1	.	2	0	0	3	15150	17.1	2591	65	2	10
1300	1	.	2	0	0	3	15150	17.1	2591	65	2	10
1300	1	.	2	0	0	3	15150	17.1	2591	65	2	10
1300	1	.	2	0	0	3	15150	17.1	2591	65	2	10
1310	1	.	2	0	0	3	15150	17.1	2591	65	2	60
1310	1	.	2	0	0	3	15150	17.1	2591	65	2	60
1320	1	.	2	0	0	3	14330	6.6	946	65	2	10
1320	1	.	2	0	0	3	14330	6.6	946	65	2	10
1330	1	.	2	0	0	3	14330	6.6	946	65	2	10
1330	1	.	2	0	0	3	14330	6.6	946	65	2	10

Sequence Number	Age	Region	Crack Length ft	Seve-rity	Loca-tion	PCI	IRI Left Wheel	IRI Right Wheel	Section Length mile	Survey Direction N1S2E3W4
1300	11	1	50	1	2	100	60	66	1.01	4
1300	11	1	50	1	1	100	60	66	1.01	4
1300	11	1	100	1	2	100	60	66	1.01	4
1300	11	1	100	1	4	100	60	66	1.01	4
1300	11	1	100	1	3	100	60	66	1.01	4
1310	11	1	75	2	1	100	63	66	0.7	4
1310	11	1	75	2	1	100	63	66	0.7	4
1320	11	1	50	1	2	100	59	63	1.21	4
1320	11	1	50	1	3	100	59	63	1.21	4
1330	11	1	100	1	1	95	62	67	0.93	4
1330	11	1	50	1	2	95	62	67	0.93	4

Figure 3.1 Sample Portion of Constructed Database

Table 3.3 Potential Factors and Measures causing Longitudinal Cracking

Factor (1)	Measures or Values (2)	Rationale and Observations (3)
(a) Design		
Panel Width	12, 13, 14, 15 ft	Variable width slabs are of key interest in this study. Only the values shown were observed during data collection.
Thickness	7, 8, 9, 10, 11, 12 in., including ½-in increments	Pavement thickness is a key parameter in PCC pavement design. Thicknesses were not available for all Sequence Numbers.
Width-to-Thickness Ratio	Ratios vary from 1.0 to 2.0	Ratio of slab width to thickness is an important measure in this study. Accepted standard is joint spacing not to exceed twice the thickness (spacing expressed in feet, thickness expressed in inches). As-built thicknesses were not available for all Sequence Numbers.
Transverse Joint Spacing	15, 16 (short random), 18 (long random), 20 ft	Spacing of transverse joints may have an effect on contraction and tensile strength in the panel. Spacing of 16 or 18 denotes short or long random spacing, respectively. Short random spacing is 12'-15'-14'-13' and long spacing is 12'-18'-19'-13'.
Skewed Joints	Normal, Skewed	Orientation of joint may have an effect on contraction relief of panel width. Data were collected for all Sequence Numbers.
Parting Strips	Yes or No	Parting strips provide a mechanism for inducing a contraction crack and relief across adjoining slabs. Data were not available for all Sequence Numbers investigated.
Dowel bars	Not Investigated	Only Type-8 pavements of 25 years or less in age were investigated due to design policy change; all contained dowels.
Base thickness	Not Investigated	Thickness of base is a parameter in pavement design. Electronic data were unavailable for this factor.
Tie bars	Not Investigated	Bars that tie the adjacent lane or paved PCC shoulder may induce an effect. Specific data were unavailable.
Base type	Dense, Open	Drainability allows gravimetric flow of water away from base. Data were not available for all Sequence Numbers investigated.
Subbase	Not Investigated	Soil names are provided in PIF database but lacked classification data, such as clayey, silts, sands, etc.
Subgrade modulus	Not Investigated	Subgrade strength is an important parameter in pavement design; however, data were not available electronically.
Cross-slope	Not Investigated	Slope of the pavement (negative or positive) from the centerline on tangent sections, super-elevated curves. Data were not collected due to complexity of using plan-view photos.
Rumble Strip	Panel, Shoulder, None	Presence of a rumble strip in the concrete driving panel or shoulder may cause longitudinal cracking.
Shoulders	Unpaved, PCC, Asphalt	Tied PCC may have an effect on contraction relief in the longitudinal direction.
Shoulder sealant	Yes, No	Sealant applied between the driving panel and paved shoulder may have an effect (i.e., loss of edge support).

Table 3.3 (cont.) Potential Factors and Measures causing Longitudinal Cracking

Factor (1)	Measures or Values (2)	Rationale and Observations (3)
(b) Construction		
Dowel bar installation	Basket or Dowel Bar Inserter (DBI)	Installation method was not available for a majority of the sampled segments.
Mixture Design	Not Investigated	Detailed material constituents and properties such as flexural strength, compressive strength, etc.
Aggregate source	Not Investigated	Limestone, gravel, granite, basalt, etc., and fundamental properties of absorption, angularity, freeze thaw, etc. Data were not readily available.
Topography	Cut, Fill, Undefined	Fills have the potential for differential settlement. Severity and extent of cracking may be a function of earthwork.
Horizontal Curve	Tangent, Left Curve, Right Curve	In the direction of the survey, curvature increases or decreases the elevation with respect to the adjacent lane.
Gradient	0%, 3%, 5%	Gradient of roadway alignment in direction of travel. Data were not collected due to added complexity of using plan-view photos.
Pavement structures	Bridge above, bridge at grade, none.	Crack propagation in the vicinity of a bridge or manhole, and staging of construction among bridges and pavement presents the possibility of cracking.
Construction Scope	Recon., rehab., resurface, replace	The degree of construction activity to the structural layers may cause a certain level of cracking.
(c) Traffic		
AADT	Varies	Average annual daily traffic applied to the pavement.
Trucks	Percentage	Percentage of traffic that is comprised of trucks (FHWA classes 4 and greater).
AADTT	Varies	Average annual daily truck traffic counts.
Posted Speed	Varies	Velocity of vehicle movement across the concrete panels.
Number of Lanes	1, 2, 3, 4	Distribution of traffic across multiple lanes.
Functional Class	Variable Classes	Functional use of the highway segment such as Interstate, Expressway, Arterial, Collector, etc.
(d) Environmental		
Surface Year	Varies	Year the pavement was placed as a function of design policy at the time.
Age	Varies	Life of pavement having an effect on cracking.
Region	NW, NC, NE, SE, SW	Region of pavement having multiple effects from temperature, traffic, soil properties, etc.
(e) Performance		
Transverse Offset	Left Edge, Left Wheel Path, Between Wheel Paths, Right Wheel Path, Right Edge	Transverse location of longitudinal crack. Cracks that propagate across multiple transverse locations were recorded separately for each offset.
Length, ft	Varies	Lineal length of physical crack estimated between end points within a specific transverse offset.
Severity	Low ≤ 1/2 in, Medium > 1/2 in to ≤ 2 in, High > 2 in	Severity is classified using PCI levels.

3.5 Database Summary Statistics

The combined databases from Meta Manager, PIF, Ride Reports, and the observed cracking database created a single research database of 1,008 pavement segments (Sequence Numbers) representing 57% of doweled JPCP segments in the state (1,008/1,767). Table 3.4 summarizes the basic statistics associated with these 1,008 pavement segments. Factors were segregated into categories for pavement inventory, design effects, construction effects, traffic effects, and environmental effects.

Table 3.4 Basic Statistics for 1,008 Pavement Segments

Variable (1)	N (2)	Mean (3)	Standard Deviation (4)	Minimum(s) (5)	Maximum(s) (6)
(a) Pavement Inventory					
Sequence Number	1008	---	---	140	300580
Section Length, mi	1008	1.144	0.327	0.28	2.8
(b) Design					
Panel Width, ft	1008	13.88	0.56	12	15
Thickness, in	784	9.83	0.90	7	12.5
Width-to-Thickness	784	1.42	0.13	0.96	2.00
Joint Spacing, ft	978	16.77	1.69	15	20
Skewed Joints	1008	0.64	0.47	0 = Normal	1 = Skewed
Parting Strips	757	1.04	0.21	1 = Sawed	2 = Parting Strip
Tining	1008	1.20	0.44	0 = None 1= Transverse	2 = Longitudinal 3 = Diamond Grind
Rumble_Strip	1008	0.84	0.51	0 = None	1 =Asphalt 2 = PCC
Shoulder Type	1008	1.18	0.49	1 = Asphalt	2 = PCC 3 = CABC
Shoulder Crack Filler	1008	0.07	0.27	0 = No	1 = Yes
Base Gradation	715	1.41	0.49	1 = Dense	2 = Open

Table 3.4 (cont.) Basic Statistics for 1,008 Pavement Segments

Variable (1)	N (2)	Mean (3)	Standard Deviation (4)	Minimum (5)	Maximum (6)
(c) Construction					
Dowel Bar Installation	632	1.80	0.39	1 = Basket	2 = DBI Inserter
Topography	1008	0.72	0.87	0 = Flat	1 = Cut 2 = Fill
Curve	1008	0.19	0.56	0 = Tangent	1 = Left 2 = Right
Bridge	1008	0.04	0.27	0 = None	1 = Above grade 2 = At grade
Construction Scope	421	1.08	0.41	1 = Reconstruction 2 = Rehabilitation	3 = Resurface 4 = Replacement
(d) Traffic					
AADT	986	16348	15038.9	1310	134990
TRUCK %	986	11.82	5.52	2.6	22
AADTT	987	1874.23	1869.40	0	18073
Posted Speed, mph	968	58.52	8.11	25	65
Number of Lanes	972	2.03	0.19	1	4
Functional Class	902	---	---	9	90
(e) Environmental					
Age	994	12.74	5.90	2	26
Region	1008	2.77	1.60	1	5

There are several noteworthy observations in this table including panel width, ranging from 12 to 15 ft, and thickness ranging from 7 to 12.5 in. These combined dimensions yield a width-to-thickness ratio (w/t) ranging from 0.96 to 2.0. For example, a w/t = 1.0 is computed from a 12-ft wide panel 12 in thick, while a w/t = 2.0 is computed from a 14-ft wide panel 7 in thick. Missing observations were disclosed for several design factors such as thickness, parting strips, and aggregate base gradation. Missing observations for construction included method of dowel bar installation and construction scope. Traffic and environmental values were recorded for nearly every pavement segment. In all, a total of 1,008 concrete segments within the state, averaging 1.14 miles in length, were assembled for analysis.

Next, basic statistics are reported for observations of longitudinal cracking among the 1,008 segments. Of the 1,008 pavement segments, 599 segments had longitudinal cracking. The total number of cracks observed within the 599 segments totaled 3,065 resulting in an average of 5.12 cracks per 1.2-mile segment. Table 3.5 presents the mean, standard deviation, maximum, and minimum for values associated with each factor. Several variables had missing values resulting in values less than 3,065.

Table 3.5 Basic Statistics for Observed Longitudinal Cracking Segments

Variable (1)	N (2)	Mean (3)	Standard Deviation (4)	Minimum(s) (5)	Maximum(s) (6)
(a) Pavement Inventory					
Sequence Number	3065	---	---	140	300460
Section Length, mi	2956	1.217	0.357	0.28	2.8
Highway Number	3065	---	---	2	312
(b) Design					
Panel Width, ft	3065	13.881	0.638	12	15
Thickness, in	2600	9.788	1.095	7	12.5
Width-to-Thickness	2600	1.446	0.162	0.96	2
Joint Spacing, ft	2957	17.072	1.737	15	20
Skewed Joints	3065	0.695	0.460	0 = Normal	1 = Skewed
Parting Strips	2519	1.001	0.034	1 = Sawed	2 = Parting Strip
Tining	3065	1.116	0.393	0 = None 1= Transverse	2 = Longitudinal 3 = Diamond Grind
Rumble_Strip	3065	0.734	0.648	0 = None	1 = AC 2 = PCC
Shoulder Type	3065	1.349	0.676	1 = Asphalt	2 = PCC 3 = CABC
Shoulder Crack Filler	3065	0.133	0.340	0 = No	1 = Yes
Base Gradation	2357	1.533	0.498	1 = Dense	2 = Open
(c) Construction					
Dowel Bar Installation	1722	1.674	0.468	1 = Basket	2 = DBI Inserter
Topography	3065	1.260	0.835	0 = Flat	1 = Cut 2 = Fill
Curve	3065	0.278	0.637	0 = Tangent	1 = Left 2 = Right
Bridge	3065	0.046	0.257	0 = None	1 = Above grade 2 = At grade
Construction Scope	921	1.214	0.650	1 = Reconstruction 2 = Rehabilitation	3 = Resurface 4 = Replacement

Table 3.5 (cont.) Basic Statistics for Observed Longitudinal Cracking Segments

Variable (1)	N (2)	Mean (3)	Standard Deviation (4)	Minimum (5)	Maximum (6)
(d) Traffic					
AADT	2979	19421.2	17622.3	1310	134990
TRUCK %	2979	11.248	5.256	2.6	20.6
AADTT	2979	2037.01	1805.89	152	18073
Posted Speed, mph	2914	58.735	6.543	25	65
Number of Lanes	2920	2.032	0.190	1	4
Functional Class	2881	23.276	18.928	9	71
(e) Environmental					
Age	3028	16.138	5.195	2	26
Region	3065	3.467	1.642	1	5
(f) Performance					
Longitudinal Cracking	3065	1	0	0 = Not Present	1 = Present
Length, ft	3065	48.492	58.454	0	1000
Severity	3065	1.479	0.589	0 = None 1 = ≤ 1/2 in	2 = Medium > 1/2 in to ≤ 2 in, 3 = High > 2 in
Location of Crack	3065	3.441	1.054	0 = None 1 = Left Jt. 2 = Left Wheel Path	3 = Between WhP 4 = Right WhP 5 = Right Jt

CHAPTER 4 DATA ANALYSIS

4.1 Introduction

A comprehensive data analysis was performed to directly address the project objectives of statistically comparing the performance of wider concrete panels (14 and 15 ft) to standard width panels (12 and 13 ft), and determining the maximum allowable pavement width as a function of pavement thickness in order to achieve optimal concrete pavement performance. In the following sections, the analysis framework is described. Statistical models are assembled to screen factors that are significant or insignificant in explaining longitudinal cracking length (extent) and severity. Data plots accompany results of the statistical modeling to illustrate significant relationships. Significant factors are identified and reported to provide the basis for the development of guidelines.

4.2 Analysis Framework

The general framework for analysis was determining those factors, in addition to panel width and thickness, that produce longitudinal cracking in concrete pavements. Capturing a wider array of factors requires management of data across all phases of concrete pavement design, construction, and service life. As such, factors were assigned to design, construction, traffic, and environmental effect categories to manage the analysis. Equation 4.1 provides the conceptual framework for independent variables in relation to the dependent performance variable:

$$\begin{aligned}\text{Performance} = {} & \text{Design} + \text{Construction} + \text{Traffic} + \text{Environment} \\ & + \text{Unexplained Variability or Error} \end{aligned} \qquad (4.1)$$

Performance is treated as the dependent variable and modeled in three ways, as the: (1) presence or absence of longitudinal cracking in the pavement, (2) lineal length of longitudinal cracking, and (3) severity level of the longitudinal cracking. These performance variables were chosen since they are aligned with the project objectives and could be directly measured.

Design is a fundamental factor in the performance of any pavement. There are important elements of the design that have an effect, to varying degrees, on actual performance. Panel width, thickness, transverse joint spacing, and aggregate base gradation are just a few of many design elements that translate to in-service performance.

Construction is another key factor in the performance of any pavement. Construction means and methods have a direct effect on the long-term durability of the pavement, such as concrete mixture properties, base compaction, cut and fill sections, pavement structures, and staging of construction.

Traffic is an additional factor in pavement performance with frequency and magnitude of vehicle loading from a mix of cars and trucks. The functional class of the roadway may attract or deter a certain traffic mix, and thus, directly impact the magnitude of vehicle loading and performance.

Environmental factors have an impact on performance, namely, the exposure of the concrete and base to moisture, temperature, freeze-thaw cycles, and deicing salts. Of course, the concrete mixture is specifically designed for environmental effects, however, the environment poses a risk to performance.

Analysis of variance (ANOVA) methods were used to determine which factors caused longitudinal cracking and influenced changes in the extent and severity of longitudinal cracking. ANOVA is a statistical technique used to compare the means of two or more groups of observations or treatments. General Linear Models (GLM) specific to ANOVA methods were selected, where the mean of the data is first computed, then the variation of each independent variable in explaining deviations of the mean is computed. Regression modeling was considered, but ANOVA was chosen due to statistical efficiency in achieving the study objectives. The key distinction between ANOVA and regression is that the ANOVA procedure first finds the mean of the data, then the function, while the regression procedure first finds the function, then the mean.

A hypothesis test was used to determine if the mean level among any number of factor levels in longitudinal cracking presence, length, and severity were significantly different or not. The null hypothesis, H_O, hypothesized they were not different, while the alternative hypothesis, H_A, hypothesized they were different:

H_O: Mean of a given factor is not different (mean difference = 0).

H_A: Mean of a given factors is different (mean difference $\neq$ 0).

Two standard statistics were calculated and used to determine significance: (1) the F-ratio and (2) the p-value. The F-ratio calculated the ratio of mean variances in factors with error, and was then plotted on the F-distribution to determine a probability level of significance, or p-value. High F-ratios yielding p-values equal to or less 5% would indicate the null hypothesis should be rejected (i.e., 95% probability level). Equation 4.2 shows how the F-value is calculated using the mean squares (MS) of the factor divided by the MS of the unexplained error:

$$F_{Factor} = \frac{MS(Factor)}{MS(Error)} \qquad (4.2)$$

The output provided two estimates for the mean square: (1) Type I when the variable is entered first in the model, and (2) Type III when it is entered last. Type III Sum of Squares provide the most rigorous hypothesis test since it accounts for remaining unexplained variation when entered last in the model. This measurement technique provides a measure of variable robustness by the relative ability to accumulate sum of squares against the other previously-entered competing variables. A full model of variables was initially tried, then only significant variables were retained and further scrutinized.

In the following sections, ANOVA results are presented for design, construction, traffic, and environmental effects. Conclusions of formal statistical hypothesis tests at the 95% probability level along with data plots summarize findings for each data category.

4.3 Analysis of Segments with and without Longitudinal Cracking

A total of 1,008 concrete segments (Sequence Numbers) within the state, averaging 1.14 miles in length, were analyzed to determine which factors cause longitudinal cracking. Within these 1,008 segments, either longitudinal cracking was observed or not. Table 4.1 compares the frequency of pavement segments having cracking or not, among the 12, 13, 14, and 15 ft wide panels. Figure 4.1 illustrates the relative percentage of each panel width having or not having longitudinal cracking. As both the table and figure illustrate for each panel width, there is a greater percentage of pavement segments with longitudinal cracking than those without. All eight of the sampled 13-ft wide segments had cracking. Both the 12 and 15 ft panels had a greater percentage of segments with cracking than the 14 ft panels, a finding that is supported by the literature survey where the 12 and 15 ft panels were reported to have higher longitudinal cracking frequencies compared to 13 and 14 ft panels. From the sample of 1,008 segments, it can be concluded that about 60% (599/1,008) of 1.14-mile segments in the state have longitudinal cracking.

Table 4.1 Frequency of Pavement Segments with and without Longitudinal Cracking

Cracking observed in segment	Panel Width, ft				Total
	12	13	14	15	
No	14	0	389	6	409
Yes	58	8	502	31	599
Total	72	8	891	37	1008
Yes, %	81%	100%	56%	84%	---
1,008 of 1,767 pavement segments in state were sampled.					

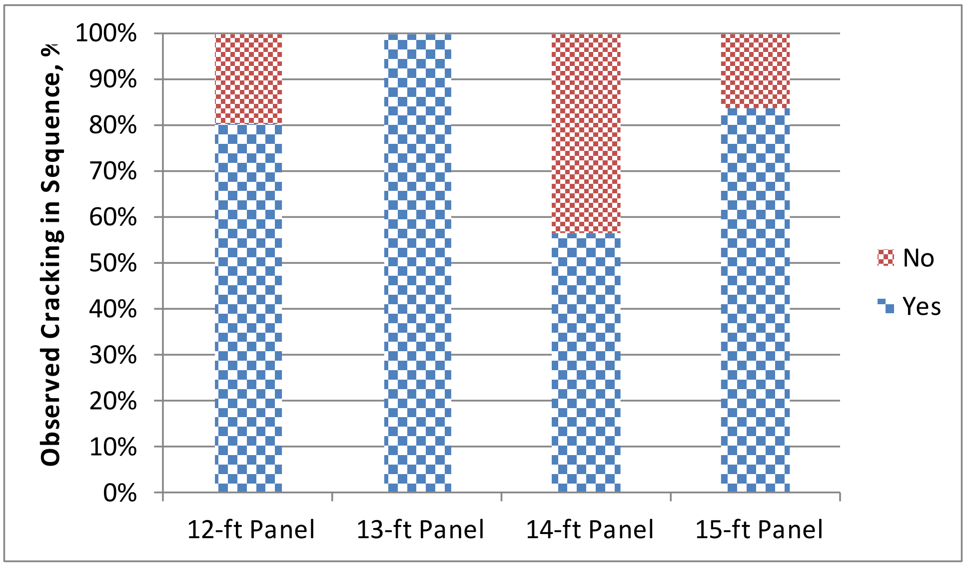


Figure 4.1 Relative Frequency of Observed Cracking among 1,008 Pavement Segments

The analysis framework equation was modified as Equation 4.3 to specifically designate the performance as cracking occurrence among the 1,008 segments (0 = No, 1 = Yes). Cracking (yes or no) was designated as a dependent variable that changes with independent variables associated with design, construction, traffic, and environmental effects.

$$\text{Cracking (Yes or No)} = \text{Design} + \text{Construction} + \text{Traffic} + \text{Environment} + \text{Unexplained Variability or Error} \quad (4.3)$$

The 13 ft panel width was dropped from the models due to small sample size (degrees of freedom) and difficulty of performing a robust hypothesis test. Due to a large number of variables and management of the data, ANOVA was performed separately for each analysis category. The following subsections present statistical hypothesis results and plots for design, construction, traffic, and environmental categories.

4.3.1 Design Factors

Table 4.2 summarizes the statistical hypothesis tests at the 95% probability level for design factors effecting the presence or absence of longitudinal cracking in the 1,008 pavement segments. Not all segments were analyzed due to missing values. The mean observation for 12 and 15 ft panels were identical (0.85) indicating that 85% of sampled segments had cracking, while the 14 ft panel had 57% of segments with cracking (these percentages approximate Figure 4.1). None of the design factors had an effect on cracking formation in 12 ft panels, and only shoulder type (CABC or asphalt) affected cracking in 15 ft panels. The 14 ft panel had seven design factors affecting the presence of cracking, including panel thickness, joint spacing, parting strips, tining, rumble strips, shoulder type, and shoulder crack filler. Those factors are further investigated in the following subsections.

Table 4.2 ANOVA Results for Design Factors

Variable	**Panel Width**		
	12 ft	14 ft	15 ft
Sample Size	27 of 72	632 of 891	27 of 37
Mean	0.85	0.57	0.85
Model R^2	54.8%	35.8%	49.7%
Thickness, in		x	
Width-to-Thickness			
Joint Spacing, ft		x	
Skewed Joints			
Parting Strips	Dropped	x	Dropped
Tining		x	
Rumble_Strip		x	
Shoulder Type		x	x
Shoulder Crack Filler		x	Dropped
Base Gradation			
x = Statistically significant at 95% probability level. Dropped = variable does not exist and was removed from the analysis.			

4.3.1.1 Width-to-Thickness Ratio

A key factor in this study, the width-to-thickness (w/t) ratio, was not statistically significant in explaining the ability of cracks to develop among the observed segments. Because of the importance of this variable, Figure 4.2 was prepared to illustrate the frequency of cracking by w/t ratios among the three panel widths. The largest w/t ratios for all panel widths had 100% segment cracking. The 12 ft panel had 100% cracking in 8 in (w/t = 1.5) and 12 in (w/t = 1.0) thick panels; the 14 ft panel had 100% cracking in 7 in (w/t = 2.0) and 12 in (w/t = 1.2) thick panels; the 15 ft panel had 100% cracking in 8 in (w/t = 1.9) and 9.5 in (w/t = 1.6) thick panels.

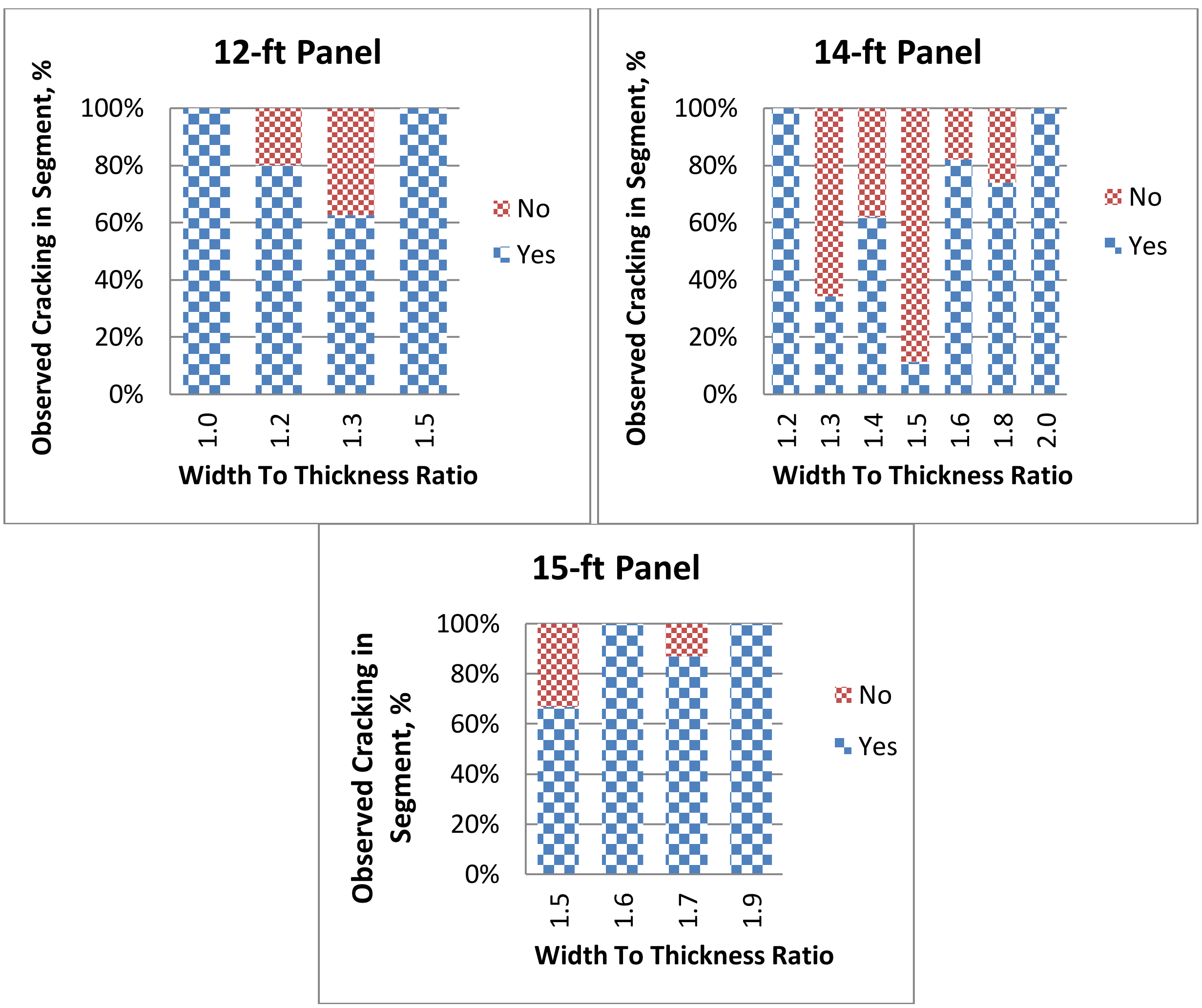


Figure 4.2 Width-to-Thickness Ratio and presence of Longitudinal Cracking by Panel Width

Further investigation of the w/t ratio is provided in Figure 4.3 with discrete w/t ratios and observed cracking (yes/no). Generally, there was a wider dispersion of w/t ratios in cracked segments than those without cracking. The 12-ft wide panel had no cracking with w/t ratios of 1.2 to 1.3, while cracking was observed in a wider range of 0.96 to 1.5. A similar relationship was also found for wider 14 ft and 15 ft slabs where cracking was observed across wider ranges, from 1.15 to 2.0 on 14 ft panels, and 1.5 to 1.9 on 15 ft panels. Despite the range differences, the median w/t values were similar with and without cracking, among all panel widths, confirming the statistical hypothesis test conclusions. However, the greatest w/t ratio for a given panel width always produced cracking (confirmed earlier with histogram frequencies).

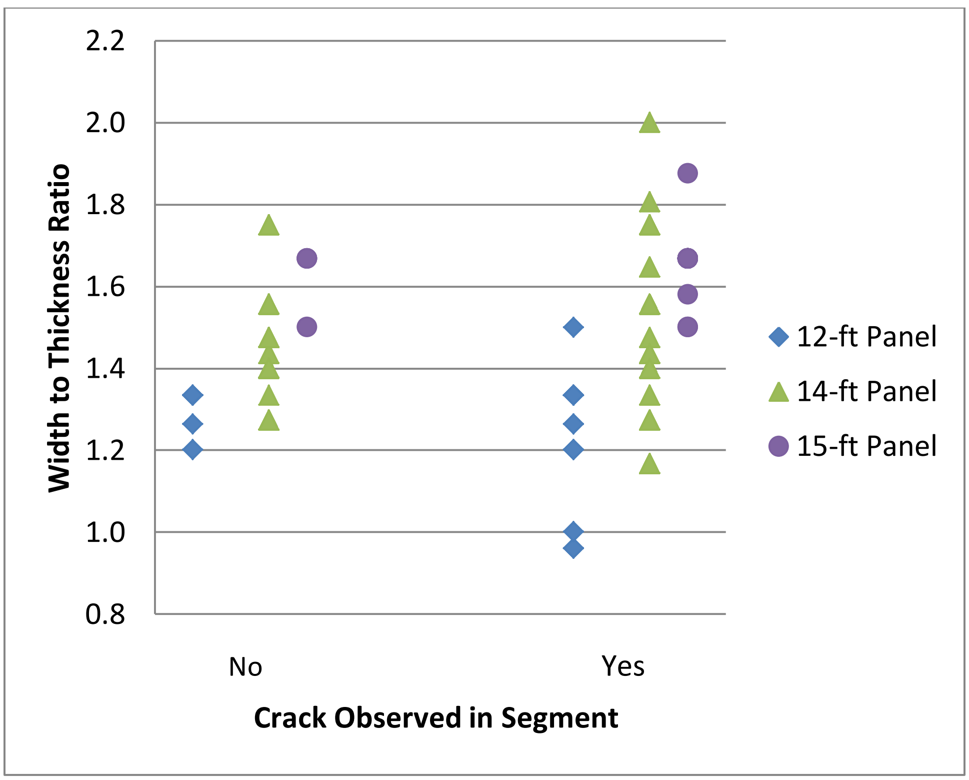
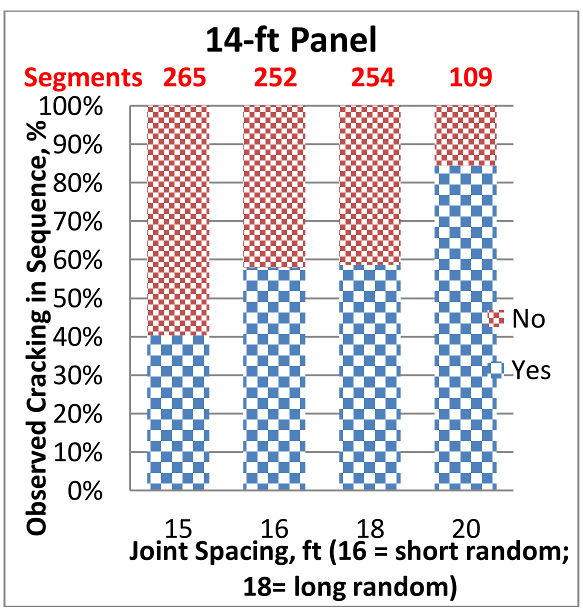


Figure 4.3 Width-to-Thickness Ratio Dispersion and Observed Cracking for Panel Widths

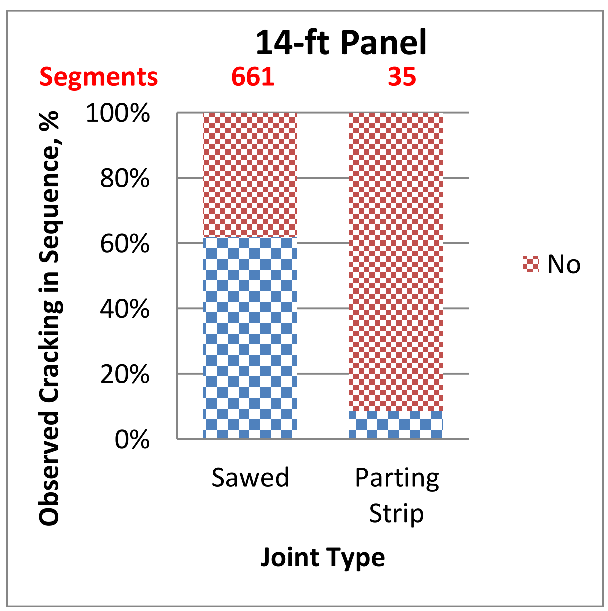
4.3.1.2 Transverse Joint Spacing and Longitudinal Jointing Method

For the 14 ft panel only, joint spacing and longitudinal jointing method (sawed or parting strips) were found to be statistically significant in changing the mean level of observed cracking. Figure 4.4 presents the histograms for joint spacing and longitudinal jointing method. The shorter 15-ft transverse spacing had a lower longitudinal cracking frequency of about 40% when compared the other spacing methods (short random, long random, and 20 ft). The 20-ft spacing had slightly over 80% of segments with observed cracking.

Longitudinal jointing method data indicate that about 10% of parting strip segments had cracking, while about 60% of segments with sawed joints had cracking. Although the sample size is skewed with sawed segments (n=661) and parting strip segments (n=35), there is a statistically lower mean in longitudinal cracking with parting strips. Based upon the statistical hypothesis test results and plots, a shorter 15-ft joint spacing and installation of longitudinal parting strips substantially reduced longitudinal cracking presence in 14 ft panels. However, a study by Lawrence et al. (1996) found improperly installed parting strips lead to spalling and secondary cracks parallel to the longitudinal joint.



(a) Joint Spacing



(b) Longitudinal Jointing Method

Figure 4.4 Joint Spacing and Longitudinal Jointing Method for 14 ft Panels

4.3.1.3 Tining Orientation

The frequency distribution of tining orientation on observed longitudinal cracking is shown in Figure 4.5 for the 14 ft panel. A statistical difference was concluded and is supported with lower observed cracking frequency of about 20% in longitudinally tined pavement. Slightly over 60% of segments with transverse jointing or diamond grinding had cracking. The reduced frequency percentage with longitudinal tining may be partially explained by age since those pavements are generally less than 6 years of age and both transverse and diamond grind pavements are generally older pavements.

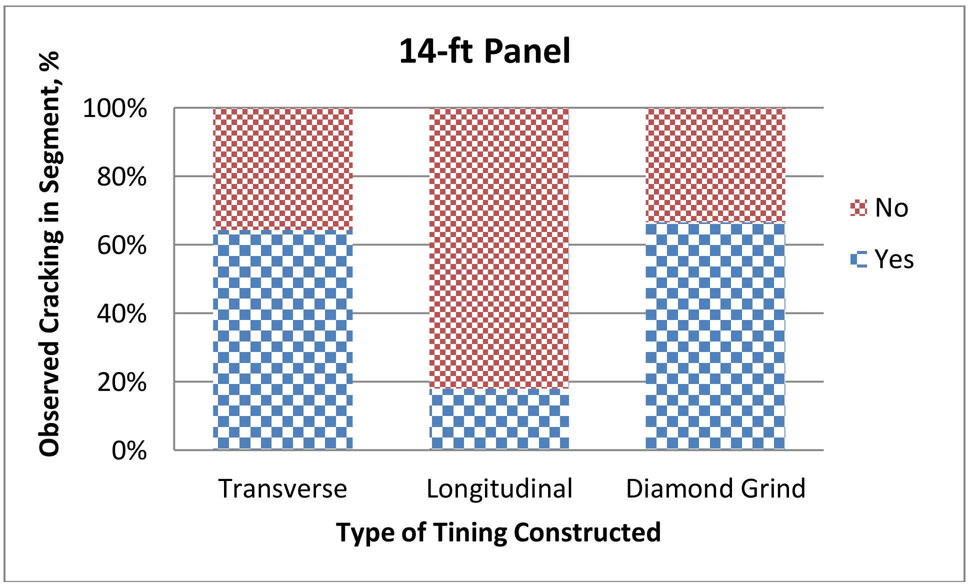


Figure 4.5 Tining and observed Longitudinal Cracking for 14 ft Panels

4.3.1.4 Shoulder Crack Filler

Shoulder crack filler between the right edge of the panel and paved shoulder was determined to be statistically significant in changing the observation of cracking among the 14-ft wide panel segments. Figure 4.6 illustrates the frequency histogram with and without cracking in a segment where no crack filler actually reduced the observed frequency. The presence of filler had a higher frequency of cracking, with about 50% of segments *without* filler having cracking, and about 80% of segments *with* filler having cracking. This finding may seem contrary to longitudinal crack filler preventing loss of edge support from moisture infiltration, but based upon the histograms, the null hypothesis is rejected and it can be concluded that no crack filler reduces cracking frequency.

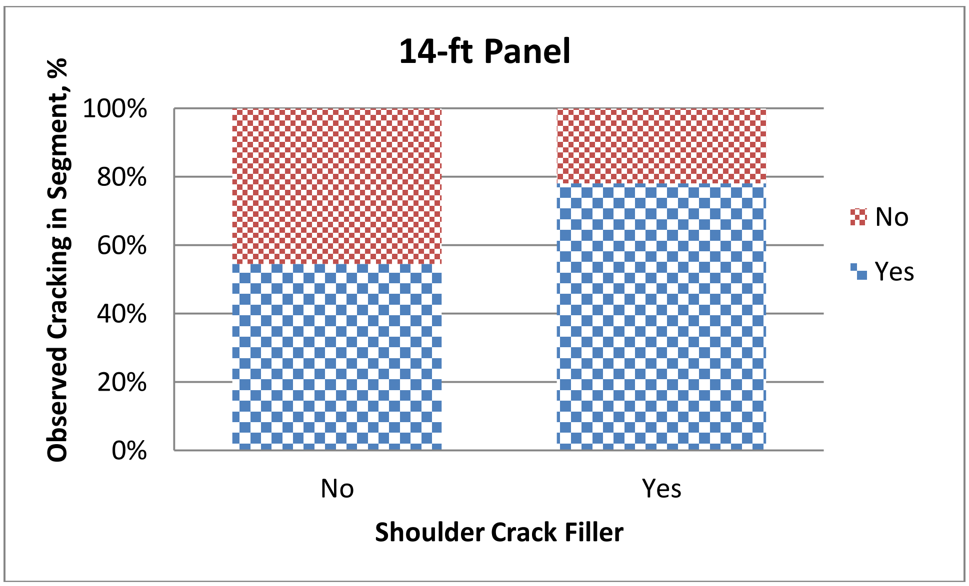


Figure 4.6 Shoulder Crack Filler and observed Longitudinal Cracking for 14 ft Panels

4.3.2 Construction Factors

Table 4.3 summarizes the hypothesis test results at the 95% probability level for two construction factors affecting the presence or absence of longitudinal cracking: dowel bar installation and construction scope. It was not possible to test construction scope (i.e., reconstruction, rehabilitation, resurfacing) for the 12 and 15 ft panels since both essentially contained segments classified as reconstruction projects (many segments had missing data). About a third of the sample size for dowel bar installation was analyzed due to missing values, and only the 14 ft panels were found to have statistical significance between method of dowel bar installation and whether cracking was observed within the segments.

Table 4.3 ANOVA Results for Construction Factors

Variable	Panel Width		
	12 ft	14 ft	15 ft
Sample Size	25 of 72	382 of 891	13 of 37
Mean	0.84	0.52	0.92
Model R^2	0.1%	5.7%	1.0%
Dowel Bar Installation		x	
Construction Scope	Dropped		Dropped
x = Statistically significant at 95% probability level. Dropped = variable does not exist and was removed from the analysis.			

Figure 4.7 illustrates the comparison of dowel bar basket and dowel bar inserter (DBI) segments with and without cracking. Dowel baskets had about double the frequency of cracking when compared to a mechanical DBI. Prior research by the Department has shown that dowel bars were more accurately placed with DBI's than baskets and the long term impact could be less cracking over time. The sample size for this histogram is the comparison was 105 segments having dowel baskets and 485 segments having mechanical DBI, exceeding the n=382 limitation from paving construction scope in the model. Despite the unbalanced sample sizes, the mean difference was significant where DBI has about half the observed segment cracking frequency as dowel baskets.

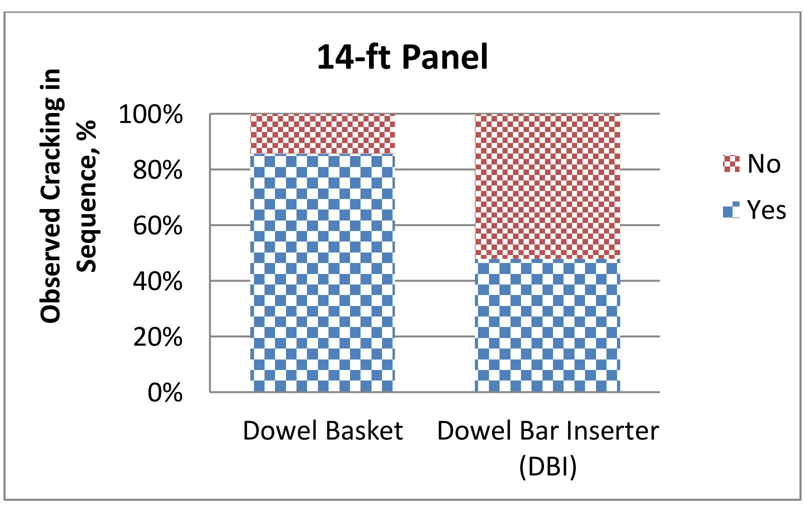


Figure 4.7 Dowel Bar Installation and presence of Longitudinal Cracking in 14 ft Panels

4.3.3 Traffic Factors

Table 4.4 summarizes the significant traffic factors causing changes in the observation of longitudinal cracking at the 95% probability level. Two factors affecting 12 ft panels were truck percentage and AADTT, and two factors influencing cracking in 14 ft panels were AADT and number of lanes. Analysis of traffic factors is presented in Section 4.4.

Table 4.4 ANOVA Results for Traffic Factors

Variable	Panel Width		
	12 ft	14 ft	15 ft
Sample Size	45 of 72	798 of 891	36 of 37
Mean	0.76	0.59	0.83
Model R^2	38.6%	6.1%	15.9%
AADT		x	
TRUCK %	x		
AADTT	x		
Posted Speed, mph			
Number of Lanes		x	Dropped
Functional Class			
x = Statistically significant at 95% probability level. Dropped = variable does not exist and was removed from the analysis.			

4.3.4 Environmental Factors

Table 4.5 summarizes the statistical hypothesis tests at the 95% probability level for two factors categorized as environmental: age and region. Age and region were significant in changing the observation of longitudinal cracking for 12 and 14 ft panels, but not with 15 ft panels. In this model, a majority of the 1,000 segments (1,008 minus eight 13-ft panels) were used for analysis.

Table 4.5 ANOVA Results for Environmental Factors

Variable	Panel Width		
	12 ft	14 ft	15 ft
Sample Size	63 of 72	887 of 891	33 of 37
Mean	0.83	0.56	0.84
Model R^2	30.3%	33.2%	18.9%
Age	x	x	
Region	x	x	

4.3.4.1 Age

Figure 4.8 plots the distribution of observed cracking by age in 5 year increments. The 12 and 14 ft panels had reverse trends, while the 15 ft panel had no discernible trend (confirming the hypothesis test conclusion). The newer 12 ft panels had a greater distribution of segments with cracking than older segments that could be explained in part with fewer 12 ft panels constructed in recent years. About 40% of 12 ft panels greater than 15 years of age did not have segments with longitudinal cracking. For the 14 ft panels, there was an increase in the observed cracking percentage with an increase in age, beginning with 20% of segment cracking at 5 years of age, and 95% of segment cracking over 20 years of age.

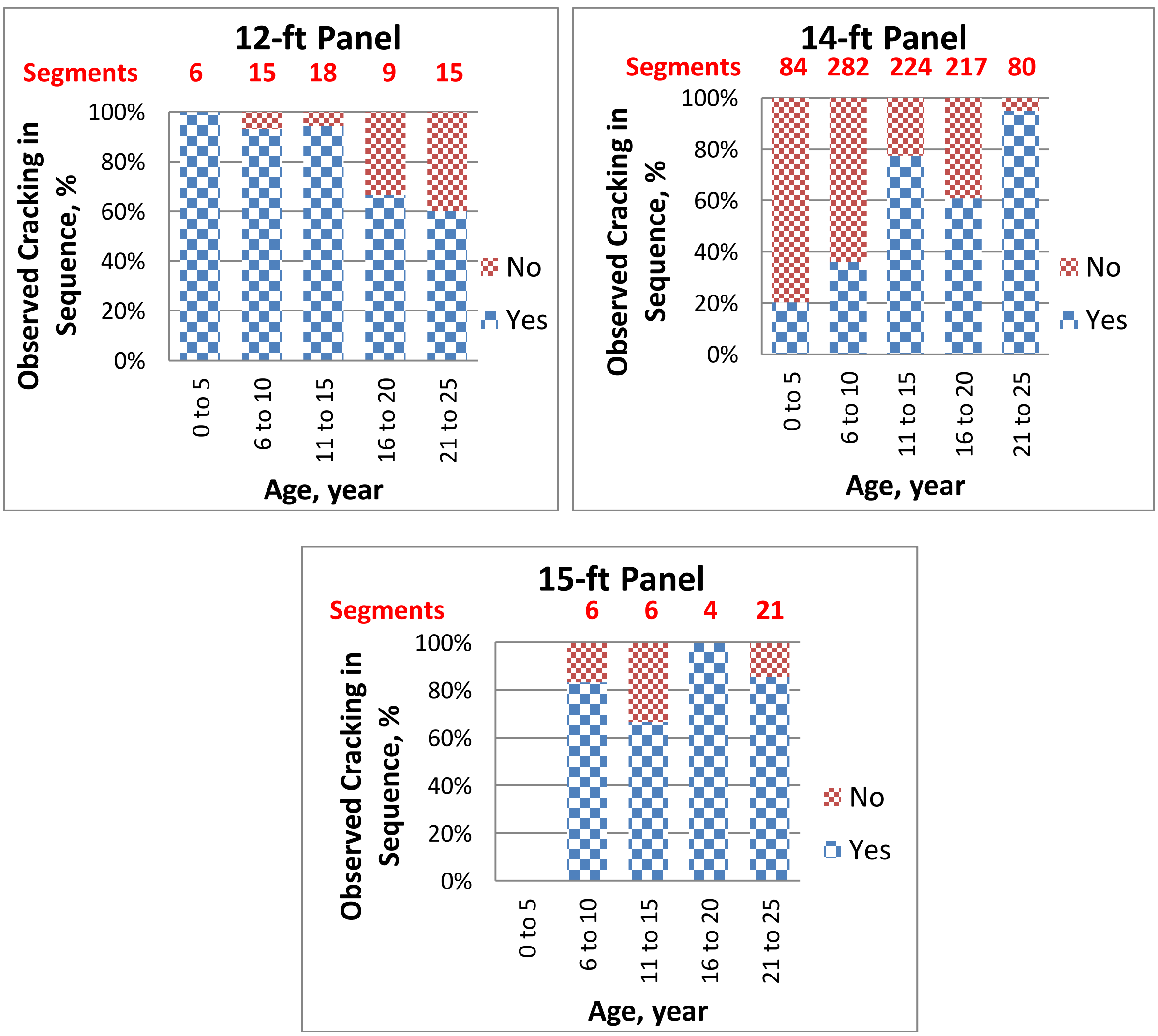


Figure 4.8 Age and presence of Longitudinal Cracking by Panel Width

4.3.4.2 Region

Figure 4.9 plots histograms for the distribution of cracking observations among the five WisDOT regions by panel width. Among the 12 and 15 ft panels, the NC and SE Regions had 100% cracking while the NW and SW Regions had approximately 70% to 80% cracking. No 12 ft panels were sampled in the NE Region. For the 14 ft panel, there was a fluctuation where the NW and NE Regions had less than 40% segment cracking, while the NC and SW Regions had about 80% segment cracking. In general, the NC and SE Regions had the highest frequency of observed cracking among sampled segments compared to the remainder of the state.

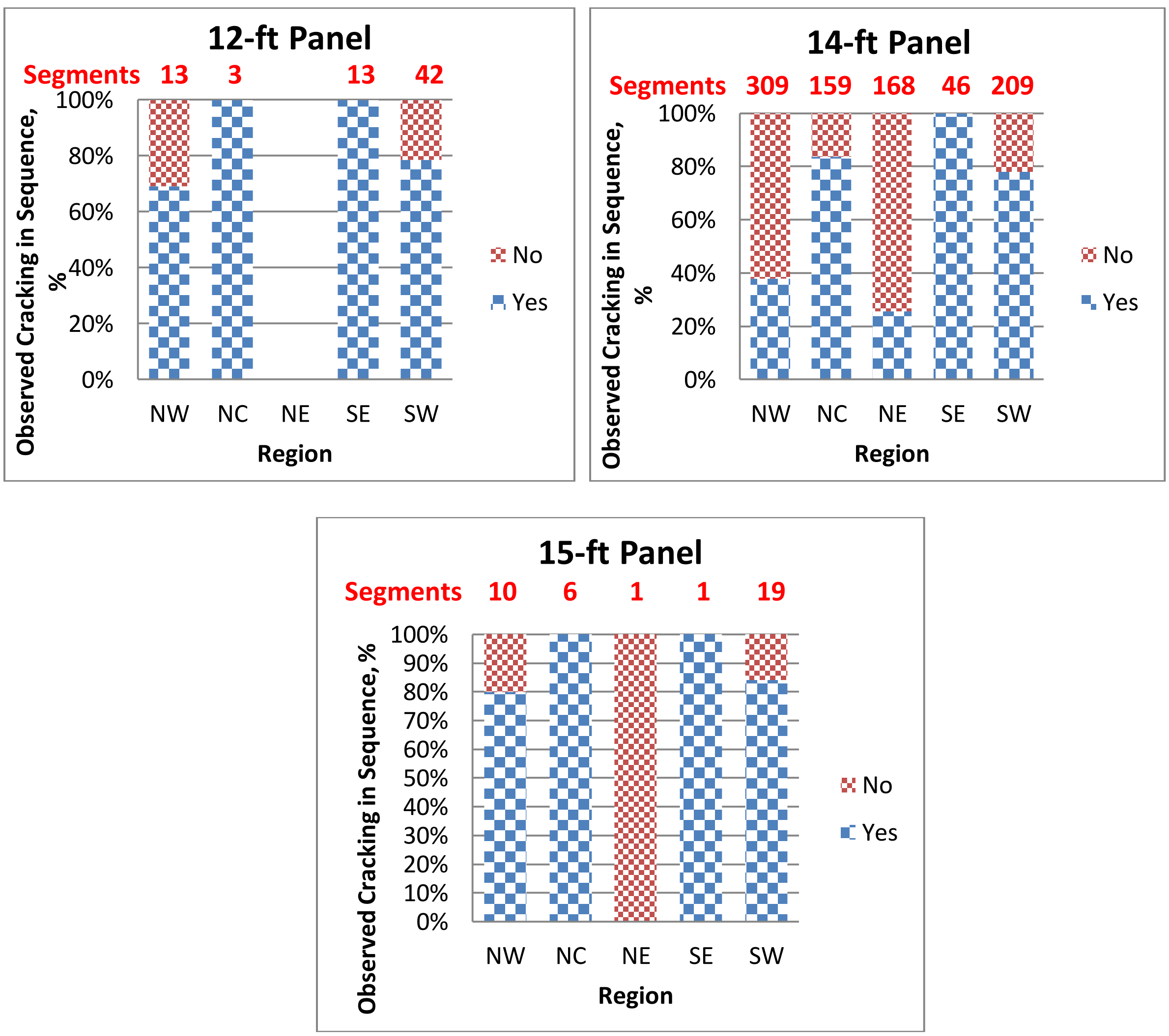


Figure 4.9 Region and presence of Longitudinal Cracking by Panel Width

4.3.5 Summary of Factors influencing Cracking Observation

A total of 1,008 concrete segments (Sequence Numbers) within the state, averaging 1.14 miles in length, were analyzed for the effects of performance, design, construction, traffic, and environment on observed cracking. Within these 1,008 segments, about 60% (599/1,008) of 1.14-mile segments in the state had longitudinal cracking while 40% did not (409/1,008). The percentage of segment cracking by panel width were 12 ft 81%, 13 ft 100%, 14 ft 56%, and 15 ft 84%. The wider 14 ft panels had 25% less segment cracking than narrower 12 ft and wider 15 ft panel widths.

An analysis of variance and frequency plots identified factors affecting longitudinal cracking for 12, 14, and 15 ft wide panels. The 13 ft panels were removed from the statistical analysis due to an insufficient sample size (n=8). The significant factors explaining the presence or absence of longitudinal cracking included width-to-thickness ratio, joint spacing, longitudinal jointing method, tining orientation, dowel bar installation, traffic level, age, and region. Table 4.6 summarizes significant factors and key findings from this initial data analysis.

Table 4.6 Significant Factors affecting the presence of Longitudinal Cracking in 1,008 Pavement Segments

Factor	Key Findings
Width-to-Thickness Ratio	The largest w/t ratios for each panel width had segment cracking: 12 ft w/t = 1.5 14 ft w/t = 2.0 15 ft w/t = 1.9 The next smallest w/t ratio had a smaller percentage of segments without cracking and fluctuations thereafter. There was a wider range of w/t ratios with segment cracking than those without.
Joint Spacing (14 ft only)	Only the 14 ft panel was significant, where shorter 15-ft transverse spacing had a lower longitudinal cracking frequency of 40% compared the other spacing (random, 18 ft, and 20 ft).
Longitudinal Jointing Method (14 ft only)	Parting strips had 10% segment cracking. Sawed joints had 60% segment cracking.
Tining Method (14 ft only)	Longitudinal tining had 20% segment cracking. Transverse jointing or diamond grinding had slightly over 60% segment cracking.
Shoulder Crack Filler (14 ft only)	The presence of shoulder crack filler had 80% segment cracking, while no filler had about 50% segment cracking.
Dowel Bar Installation (14 ft only)	Dowel baskets had about double the frequency of segment cracking when compared to a dowel bar inserter (DBI).
AADT and AADTT	Two factors affecting 12 ft panels were truck percentage and AADTT, and two factors influencing segment cracking in 14 ft panels were AADT and number of lanes.
Age	Newer 12 ft panels less than 10 years of age had nearly all segment cracking than older segments. Older 12 ft panels greater than 15 years of age had about 60% segment cracking. The 14 ft panels had an increase in the observed cracking percentage with an increase in age; 20% segment cracking at 5 years of age, and 95% segment cracking at 20 years of age. The 15 ft panels had 70% to 100% segment cracking with no discernible trend.
Region	Among the 12 and 15 ft panels, the NC and SE Regions had 100% segment cracking while the NW and SW Regions had nearly 70% segment cracking. The 14 ft panel had fluctuations where the NW and NE Regions had less than 40% segment cracking, while the NC and SW Regions had about 80% segment cracking. For all panels, the NC and SE Regions had the highest cracking frequency compared to the remainder of the state.

4.4 Analysis of Factors affecting Extent and Severity of Longitudinal Cracking

The previous section determined multiple factors producing longitudinal cracking in 12, 14, and 15 ft wide panels. Those factors included width-to-thickness ration, joint spacing, longitudinal jointing method, tining orientation, dowel bar installation, traffic level, age, and region. In this section, all measurable factors hypothesized to affect the length (extent) and severity of longitudinal cracking are investigated. The fundamental analysis framework equation was modified for cracking length and severity as Equations 4.4 and 4.5.

$$\text{Length of Cracking (ft)} = \text{Design} + \text{Construction} + \text{Traffic} + \text{Environment} + \text{Unexplained Variability or Error} \qquad (4.4)$$

$$\text{Severity of Cracking (1 Low, 2 Medium, 3 High)} = \text{Design} + \text{Construction} + \text{Traffic} + \text{Environment} + \text{Unexplained Variability or Error} \qquad (4.5)$$

Where,

Low = $\leq 1/2$ in

Medium = $> 1/2$ in to ≤ 2 in

High = > 2 in

To better manage the analysis and screen numerous factors, an analysis of variance (ANOVA) was conducted separately for design, construction, traffic, and environmental categories. Additionally, a separate analysis was performed for the relationship of crack offset with length and severity. The following sections present statistical hypothesis test results and data plots for factors within these categories.

4.4.1 Crack Offset

Table 4.7 summarizes the significance tests for cracking offset changing the mean length (extent) and severity of longitudinal cracking. As discussed in the previous chapter, observed longitudinal cracking was classified into five offset locations: left edge, left wheel path, between wheel paths, right wheel path, and right edge. For the three panel widths, crack offset affected severity levels with an average of 1.5 to 1.6 between low and medium levels.

Table 4.7 ANOVA Results for Crack Offset

Variable	Panel Width					
	12 ft		14 ft		15 ft	
Sample Size	262 of 278		2553 of 2964		201 of 207	
Longitudinal Crack	Length	Severity	Length	Severity	Length	Severity
Mean	26 ft	1.6	49 ft	1.5	75 ft	1.6
Model R^2	2.2%	3.6%	2.8%	1.7%	5.4%	4.4%
Offset of Crack		x	x	x	x	x
'x' denotes factor significant at 95% probability level.						

The observed numbers of longitudinal cracks by offset are summarized in Figure 4.10 for panel widths of 12, 13, 14, and 15 ft. For the 12 ft panel, a majority of cracks are in the middle of the panel between the wheel paths, followed closely by the right wheel path. As the panel width is widened to 13 and 14 ft, the greatest occurrence of cracking shifts to the right wheel path closer to panel center, followed by between wheel paths. The 15 ft panel had a majority of cracking between wheel paths (about 40% the panel width from the left edge), followed closely by the right wheel path. Based upon these frequency histograms, it can be concluded that a majority of longitudinal cracking across all panel widths is between wheel paths or in the right wheel path. The 12, 13, and 14 ft panels had a majority of longitudinal cracking closer to the middle of the panel, while the 15 ft panel had a majority of cracking 40% of the transverse distance from the left edge. Among all panel widths, there is less cracking occurrence adjacent to the longitudinal joints and in the left wheel path.

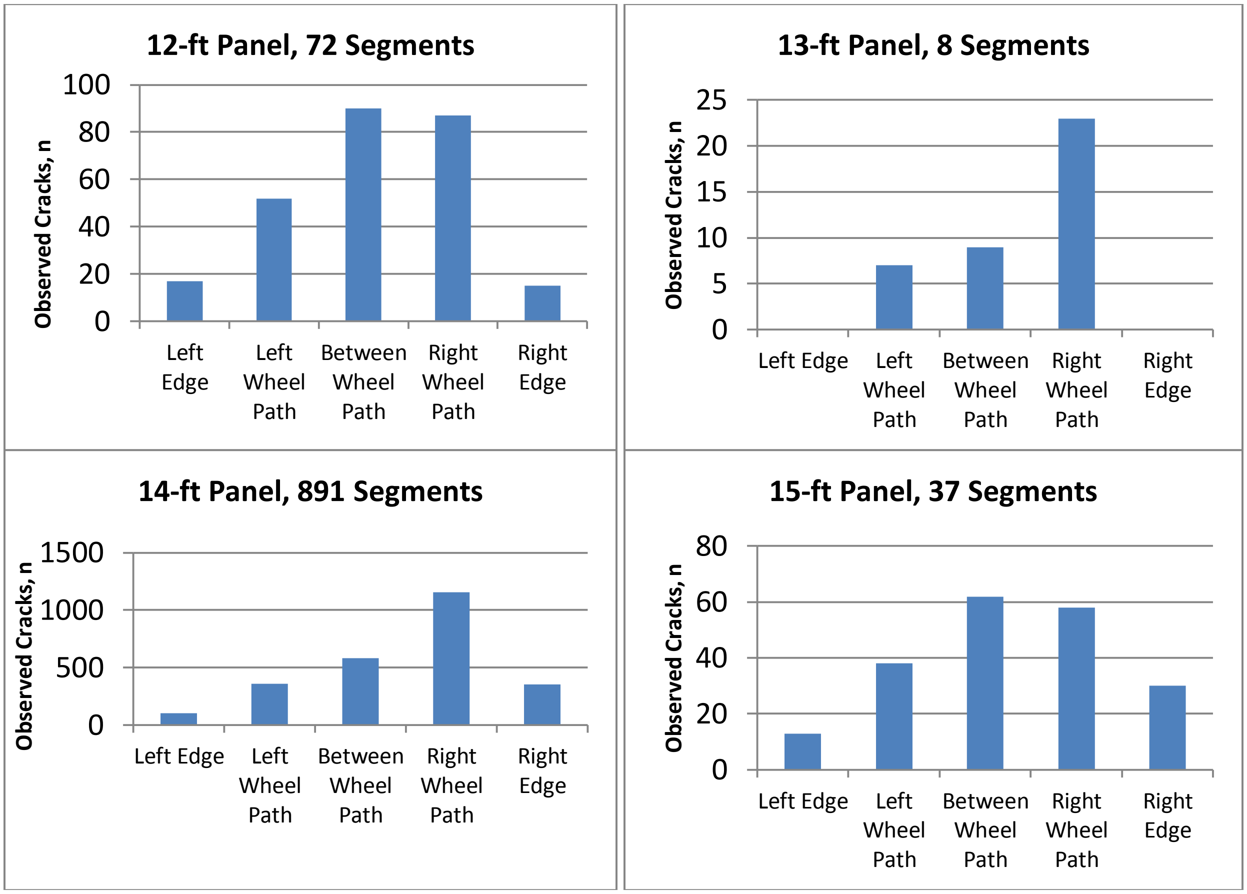


Figure 4.10 Frequency of Longitudinal Cracking and Offset by Panel Width

Next, the cumulative length and severity of longitudinal cracking by offset are summarized by histogram plots in Figure 4.11 for the 12, 14, and 15 ft panels. These histograms support the earlier frequency histograms where a greater cumulative length of cracking is found between wheel paths or in the right wheel path. Low and medium severity levels at these locations were nearly equal for the 12 ft panel, while the 14 ft panel had greater abundance of low severity cracking and the 15 ft panel more medium severity cracking.

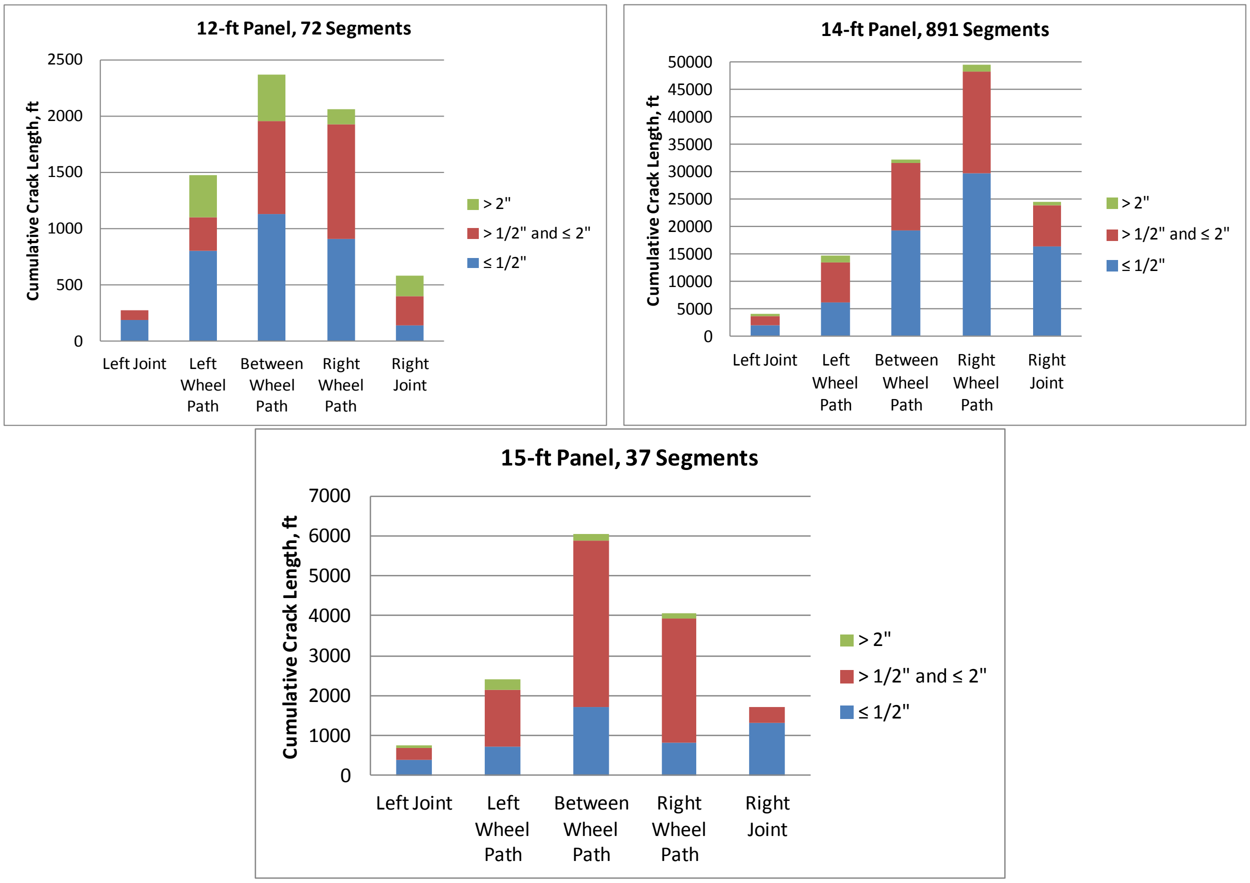


Figure 4.11 Cumulative length of Longitudinal Cracking by offset for Panel Width

With the finding that a majority of cracking occurs mid panel for 12 and 14 ft panels, and about 40% from the left edge in 15 ft panels, a comparison of cracking distribution by offset and panel width is summarized by Figure 4.12. On a percentage basis, between-wheel-path cracking is greater on the 12 and 15 ft panels, while right-wheel-path cracking is greater on 13 and 14 ft panels.

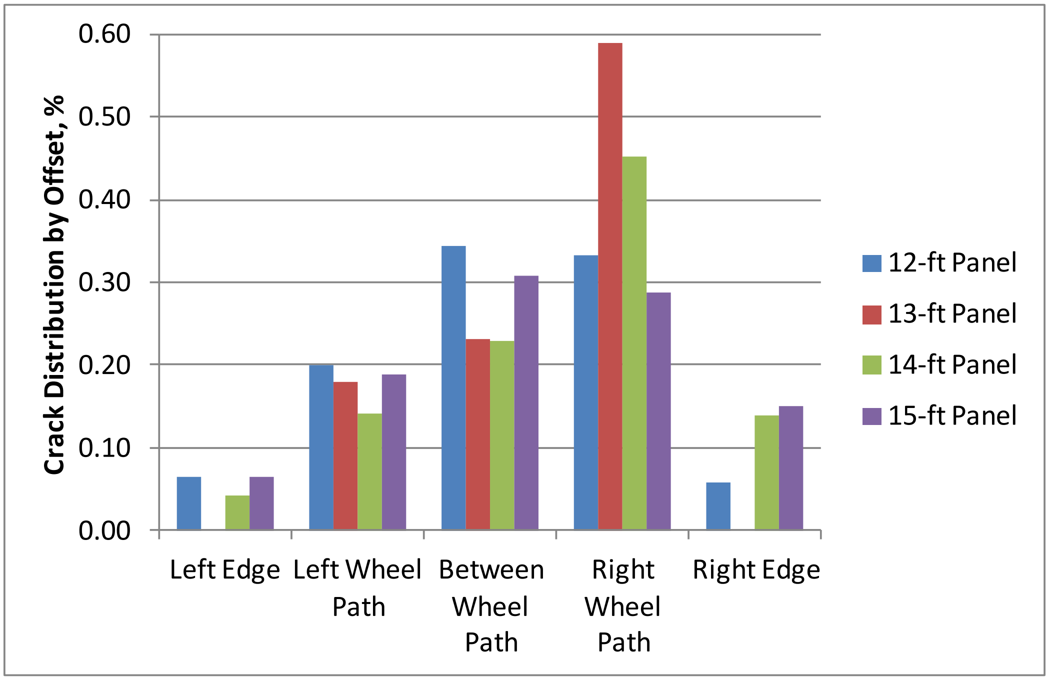


Figure 4.12 Comparison of Longitudinal Cracking distribution by Offset and Panel Width

4.4.2 Design Factors

Table 4.8 summarizes the statistical hypothesis tests at the 95% probability level for design factors changing the length (extent) and severity of longitudinal cracking. Pavement thickness and the width-to-thickness ratio affected the severity of cracking with ratings for the three panel widths between low and medium (1.3 to 1.5). In the wider 14 and 15 ft panels, the joint spacing and orientation (normal or skewed) affected both the length and severity. Parting strips installed only in the 14 ft panels were found to be statistically significant in affecting length and severity of cracking. Tining and rumble strip placement influenced crack length and severity for all panel widths. Shoulder type for the 15 ft panel (asphalt or crushed aggregate) had an effect on severity and length of cracking. Filling of the joint between the concrete panel and asphalt shoulder also had an effect on cracking length in the 14 ft panels. Finally, the dense and open graded base affected the length of longitudinal cracking on the 14 ft panel. Plots and analysis in the following subsections further investigate these significant factors.

Table 4.8 ANOVA Results for Design Factors

Variable	Panel Width					
	12 ft		14 ft		15 ft	
Sample Size	93 of 278		2260 of 2964		155 of 207	
Longitudinal Crack	Length	Severity	Length	Severity	Length	Severity
Mean	25 ft	1.5	44 ft	1.3	46 ft	1.5
Model R^2	9.7%	34.0%	11.9%	21.3%	28.7%	30.6%
Thickness, in		x	x	x		x
Width-to-Thickness		x		x	x	x
Joint Spacing, ft			x	x	x	x
Skewed Joints			x	x	x	x
Parting Strips	Dropped	Dropped	x	x	Dropped	Dropped
Tining		x	x	x		x
Rumble_Strip		x	x	x		x
Shoulder Type				x	x	x
Shoulder Crack Filler			x		Dropped	Dropped
Base Gradation			x			
x = Statistically significant at 95% probability level. Dropped = variable does not exist and was removed from the analysis.						

4.4.2.1 Thickness

Figure 4.13 provides frequency histograms of observed crack severity for pavement thickness among 12, 14, and 15 ft panels. Sample sizes of observed 1.14-mile average length segments are reported above each frequency to understand the relative effect. Among all panel widths, the 9-in thick pavement had the predominant number of sampled segments and observed cracks with 12 and 14 ft panels having a majority at the low severity level, and nearly equal low and medium severity for 15 ft panels. As the thickness increases above 9 in for all widths, the frequency of cracking dropped. An important finding is that for an equivalent number of 14-ft wide panel segments, there were more observed cracks at 9 in (821) than at 10 in (602), representing a 25% decrease. Thus, a 1 in thickness increase from 9 to 10 in among 14 ft panels reduced the number of cracks by 25%. Severity levels for 12 ft panels decreased, while 15 ft panels increased, as the pavement thickness increased, confirming statistical significance in the hypothesis test. In general, thinner pavements had a greater frequency of cracking than thicker pavements.

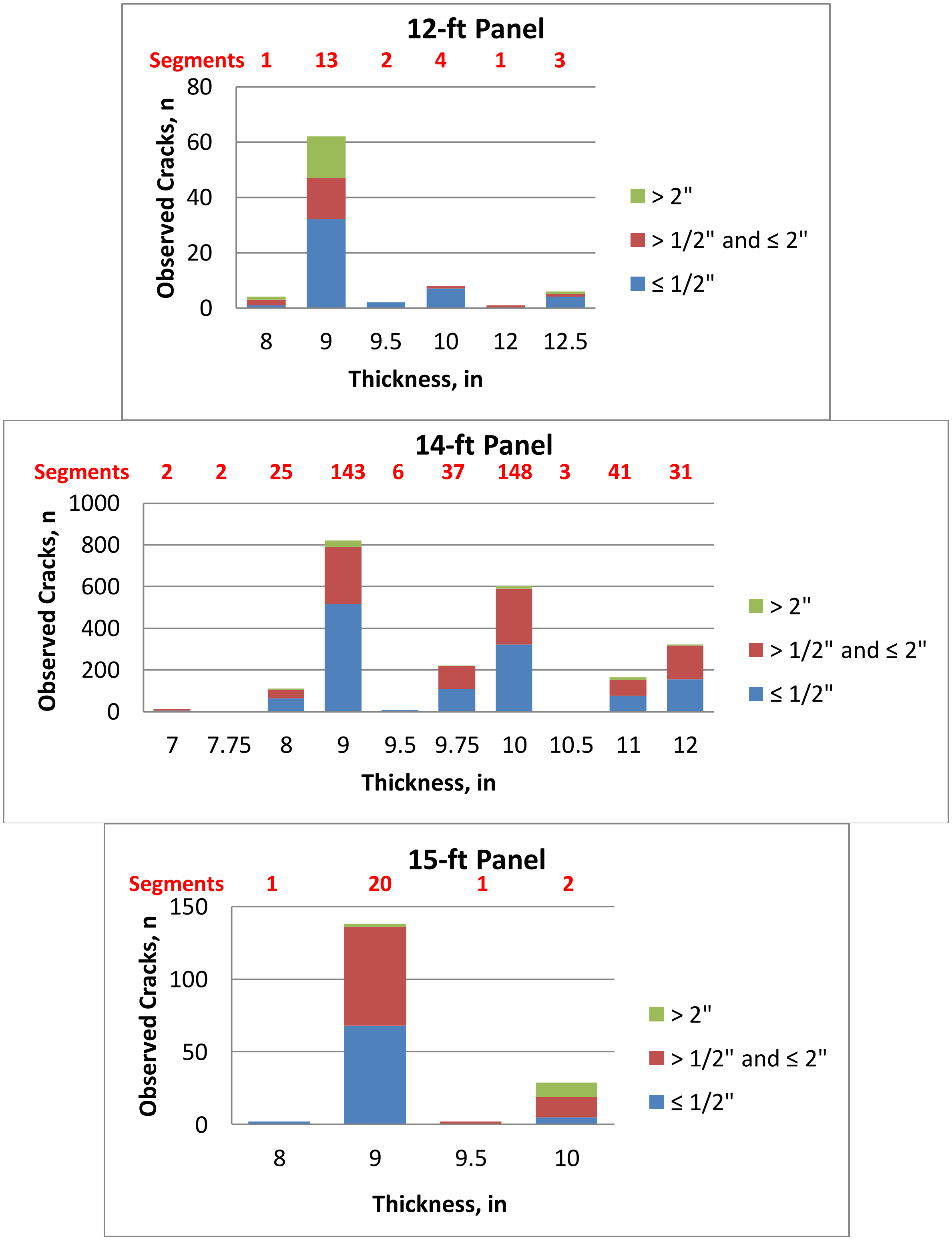


Figure 4.13 Pavement Thickness and severity frequency of Longitudinal Cracking

4.4.2.2 Width-to-Thickness Ratio

The width-to-thickness ratio (w/t) was statistically significant in explaining changes in the severity of longitudinal cracks for all panel widths, and the cracking length in 15 ft panels. Figure 4.14 reports the cumulative cracking length and severity for the w/t ratio among the 12, 14, and 15 ft panels. The statistically significant severity levels for all panel widths had varying results. For 12 ft panels, a higher severity with greater w/t ratio, while 15 ft panels had more relative high severity with w/t ratio = 1.5, and more medium severity with w/t ratio = 1.7. The 14 ft panels had no trend in severity level; more relative medium severity with w/t ratio = 1.2 and 1.4, and more low severity with w/t ratio = 1.3 and 1.5.

For the narrower 12 ft panels, the w/t ratio of 1.3 had 2,100 ft of cracking among 21 pavement segments averaging 100 ft per segment, while the lower w/t ratio of 1.0 and 1.2 had about 200 ft of combined cracking among 12 panel segments, averaging 20 ft per segment. About 100 ft of cracking in one segment was observed for the w/t ratio of 1.5.

For the wider 14 ft panel, there were a greater number of segments evaluated having a w/t ratio ≤ 1.5. In a comparison of the two largest sample sizes, 260 segments at w/t = 1.4 and 173 segments at w/t = 1.6, there was a near equal length of cumulative cracking. The average cracking length for w/t = 1.4 was 164 ft (42528 ft / 260), and w/t = 1.6 was 238 ft (41,113 ft / 173). This indicates that when the w/t ratio is raised from 1.4 to 1.6 in 14 ft panels, the average cracking length within a pavement segment increases by about 45%. This relationship of crack length increase with w/t ratio increase provides an estimate for the development in guidelines in the next chapter.

The 15 ft panel had only two w/t ratios with enough segments for a meaningful comparison. The average cracking length for w/t = 1.5 was 362 ft (1085 ft / 3), and w/t = 1.7 was 430 ft (9,883 ft / 23). Although this a small number of segments, this estimates that when the w/t ratio is raised from 1.5 to 1.7 in 15 ft panels, the average cracking length within a pavement segment increases by 18%. This relationship of crack length increase with w/t ratio increase also provides an estimate for the development in guidelines.

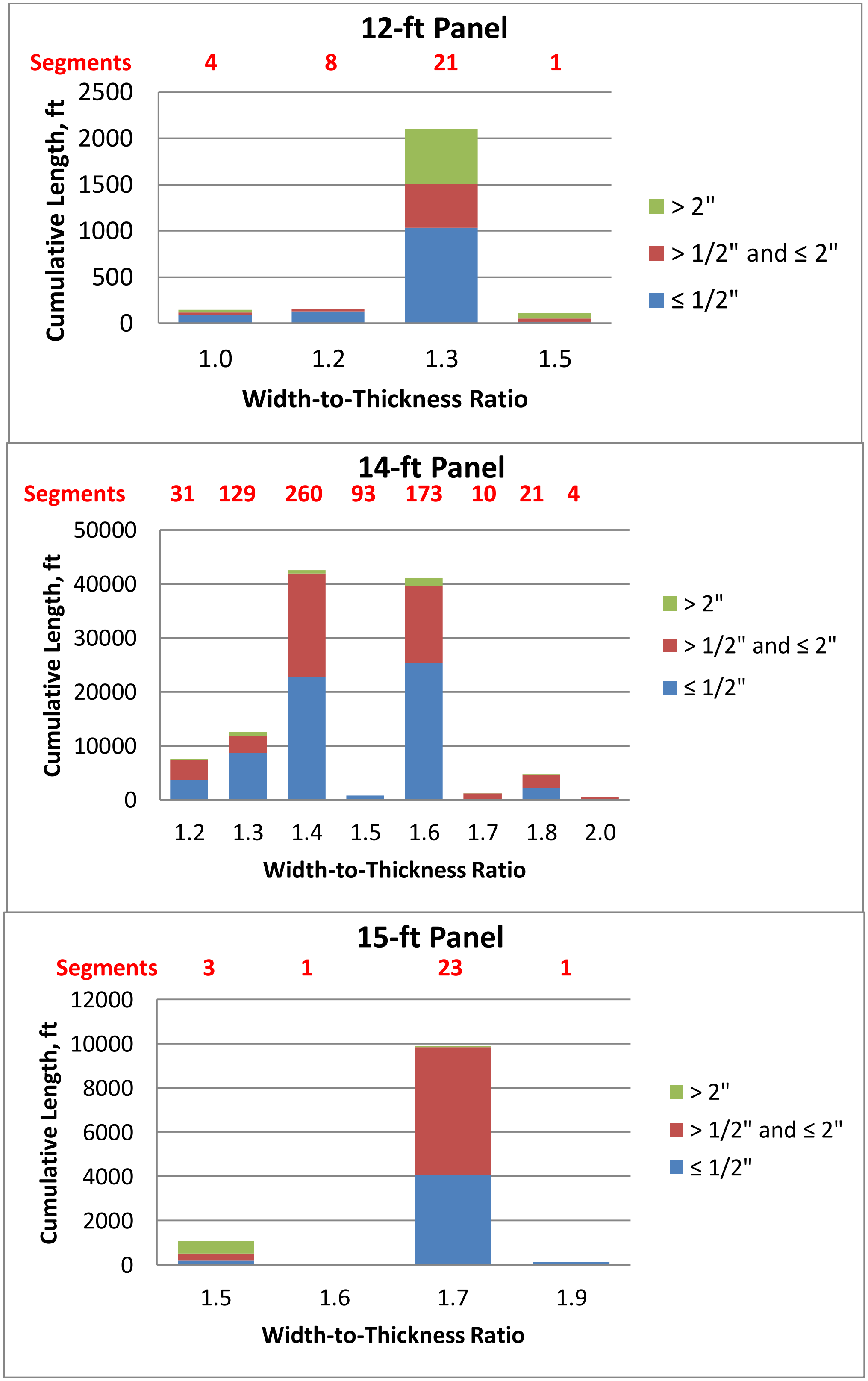


Figure 4.14 Width-to-Thickness Ratio and Cumulative Length and Severity of Longitudinal Cracking

4.4.2.3 Joint Spacing

Joint spacing and average length by severity of cracking are illustrated in Figure 4.15. For the 12 ft panel, the 20-ft spacing had the greatest average cracking length per segment followed by the 15 ft and short random spacing. The long random spacing had less average cracking and severity. The 14 ft panel highest average cracking with 20-ft spacing followed by long random spacing. The least amount of cracking was the 15-ft joint spacing. For the 15 ft panel, the short random spacing had the greatest average length of cracking per segment, followed by 18-ft spacing and short random spacing. Based upon these histograms, the least amount of cracking for the 12 ft panel was long random joint spacing, 14 ft panel was 15-ft joint spacing, and 15 ft panel was 20-ft spacing.

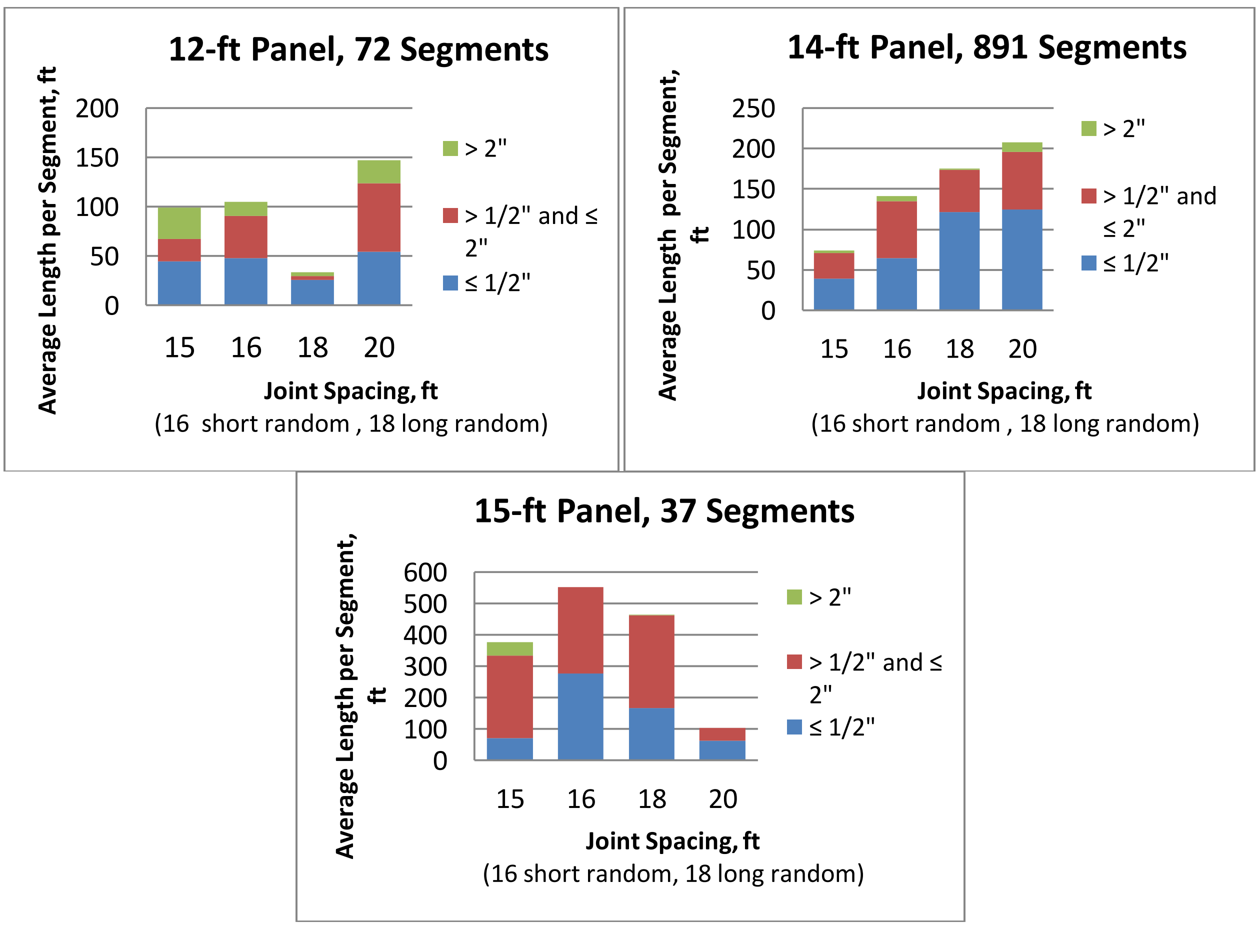


Figure 4.15 Joint Spacing and Cracking length and severity by Panel Width

4.4.2.4 Skewed and Normal Joints

Orientation of transverse joints was found to be statistically significant in changing average length and severity of longitudinal cracking. Figure 4.16 compares the cracking distribution by joint orientation and panel width, and whether cracking was observed. Overall, a greater percentage of longitudinal cracking was observed in skewed joints when compared to normal joints. The 12 ft panel had similar cracking in normal joints (42%) and skewed joints (53%), supporting the hypothesis test conclusion. The panel width of 14 ft had 60% of cracking with skewed joints and 26% with normal joints; the remaining 14% of segments had no cracking. The 15 ft panel was similar to the 14 ft panel where there was a majority of cracking in the skewed joints; 80% of cracking with skewed joints and 17% with normal joints; the remaining 3% of segments had no cracking. Skewed joints were specified in a majority of older pavements, thus, age and exposure to more traffic and the environment may also be contributing factors (investigated in later section). Severity levels were not statistically different for the 12 ft panel, but both the 14 and 15 ft panels were statistically different with medium severity with skewed joints than normal joints. Based upon statistical hypothesis test conclusions and frequency histograms, a greater distribution of longitudinal cracks are in pavements with skewed joints.

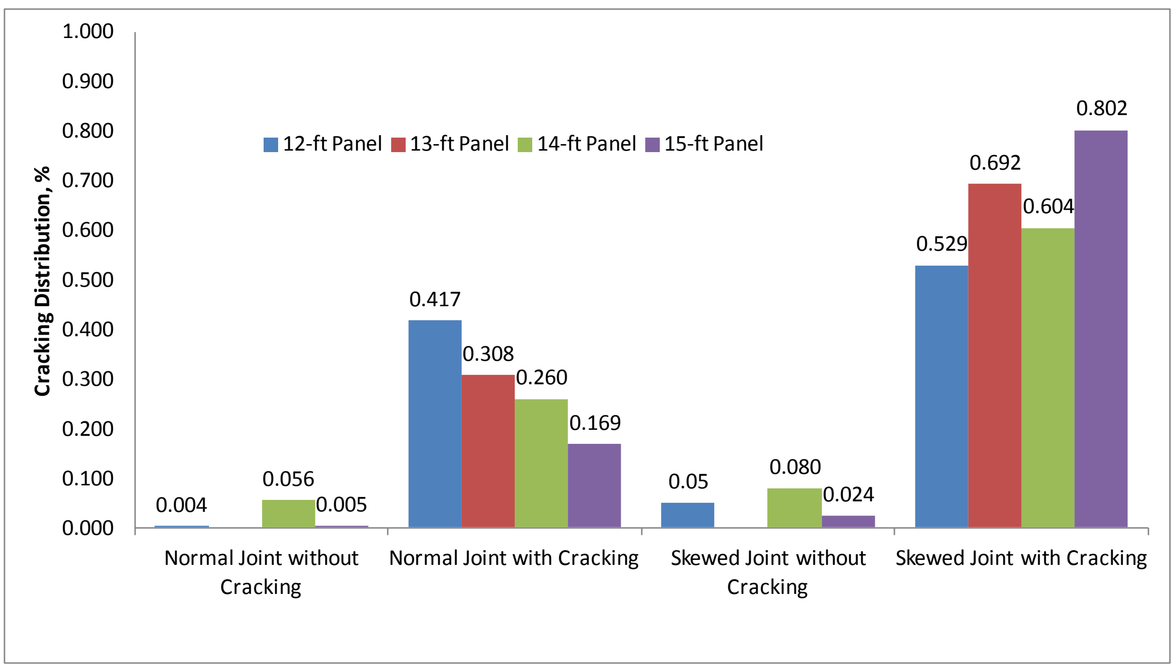


Figure 4.16 Transverse Joint orientation and Cracking distribution by Panel Width

4.4.2.5 Rumble Strips

Location of the rumble strip in the PCC panel, asphalt shoulder, or no installed rumble strip were found to be significant in affecting the severity of longitudinal cracking for all panel widths, and the length in 14 ft panels. Figure 4.17 illustrates the average segment length and severity for three rumble strip design options. For the 12 ft panels, no rumble strip had the highest average extent and severity, and a much less extent and severity for placement in the asphalt shoulder or PCC panel. The 14 ft panel had a slightly greater average cracking length per segment with no rumble strip than that in the shoulder. A greatest average cracking in 15 ft panels was associated with the PCC panel, less in the CABC shoulder, and little average cracking in the asphalt shoulder. The 15 ft panel had higher severity with no rumble strip (CABC shoulder) and lower severity with rumble strips in the PCC panel.

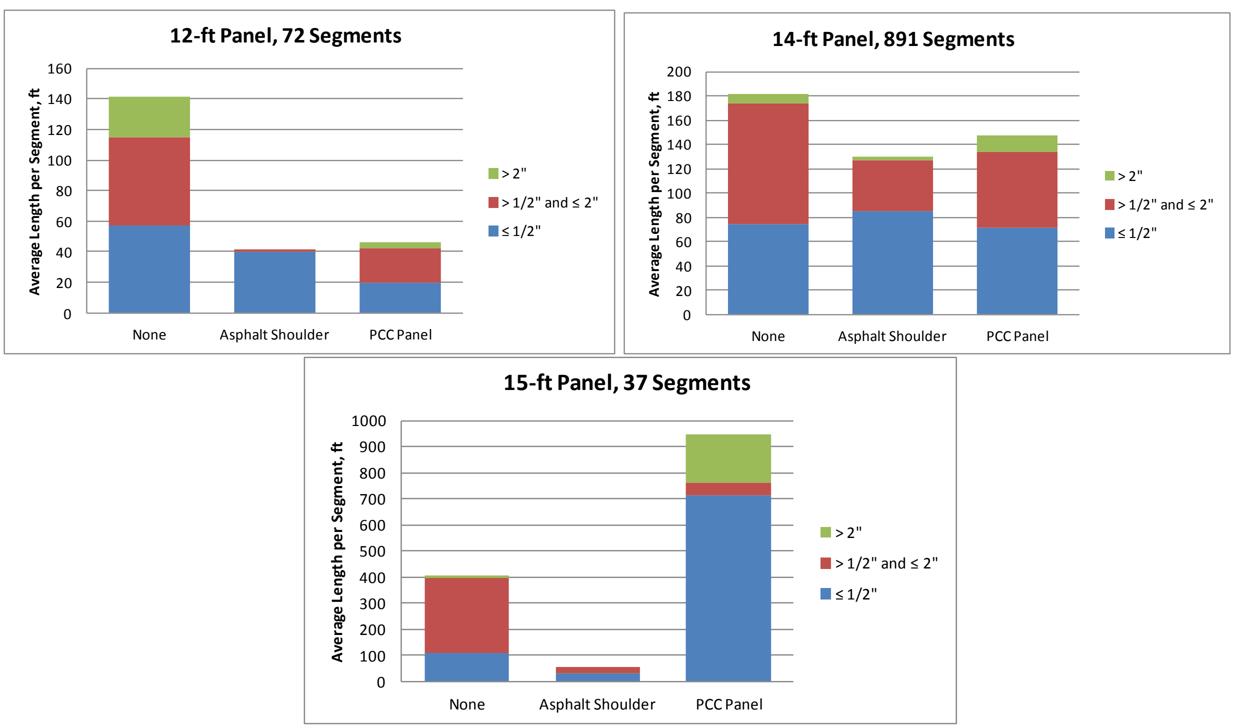


Figure 4.17 Rumble Strip placement and Cracking length and severity by Panel Width

4.4.2.6 Base Gradation

The gradation of the pavement base only affected the length of longitudinal cracking in the 14 ft panels, as shown by Figure 4.18. With 30% more dense graded sections included in the analysis (371 vs. 285), the open and dense graded bases had similar cumulative length and severity of cracking. In other words, the 14 ft panels had 28% greater length of individual crack lengths per segment in open graded bases at 180 ft (51,290 ft / 285) compared to dense graded bases at 140 ft (51,676 ft / 371). Data for the 12 and 15 ft panels are also reported where no statistical significance was concluded from the hypothesis test. Insignificance with the 15 ft panel can be explained by the low sample size (n=2) which has diminished ability to yield an estimate of variance for the statistical F-test.

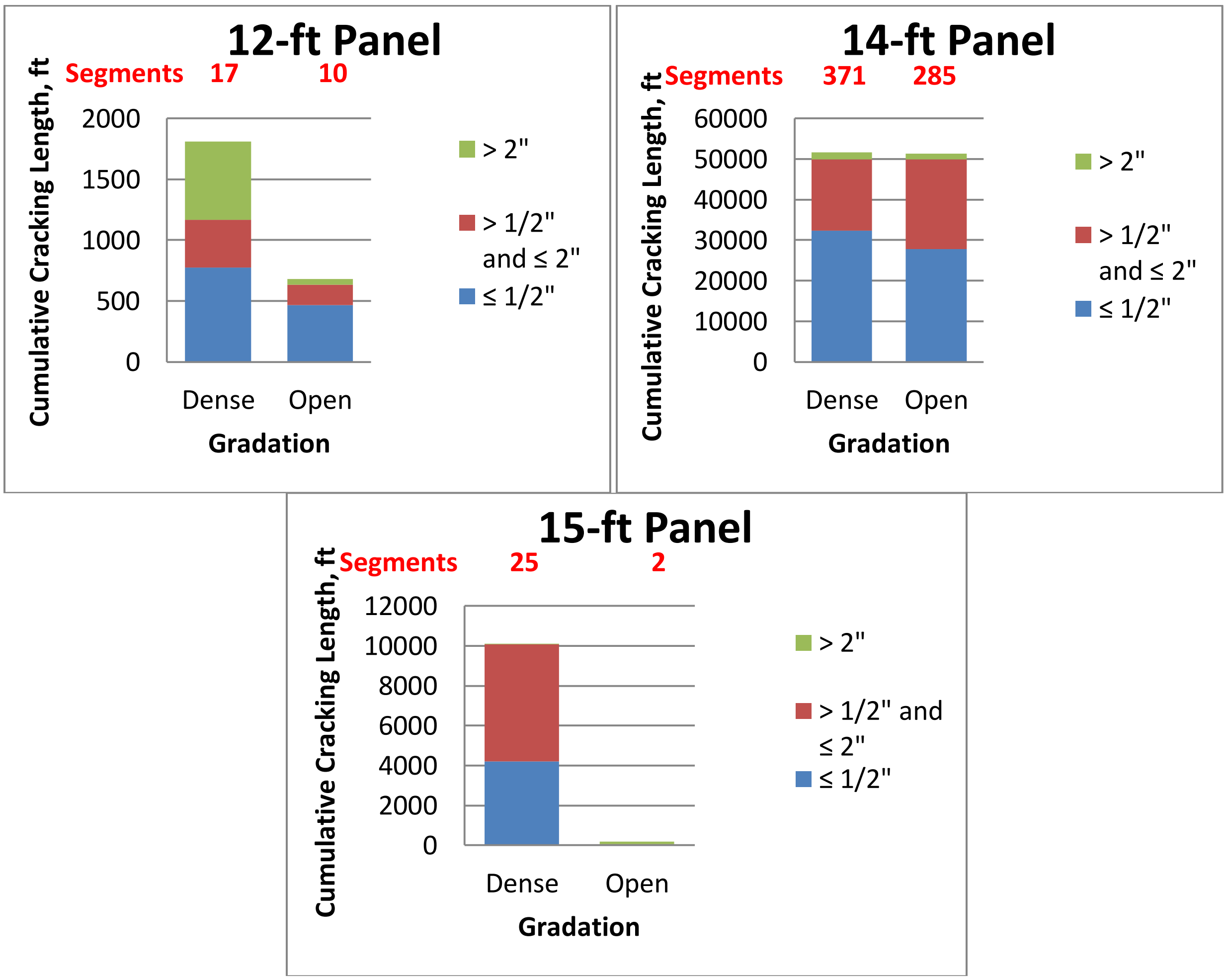


Figure 4.18 Base Gradation and Cracking length and severity by Panel Width

4.4.3 Construction Factors

Table 4.9 summarizes the significant construction factors in changing the mean length and severity of longitudinal cracking. Only about a third of the sample size for 12 and 15 ft panels were analyzed because of missing values for dowel bar installation. The average severity level among the panel widths was lowest (1.2) for 14 ft and highest (1.7) for 12 ft. Topography (cut and fill) had a significant effect on cracking severity for all panel widths, and on cracking length for 14 and 15 ft panels. Curvature of the roadway had an effect on 14 ft panel cracking length and severity. The vicinity of cracking to bridges had no effect on length and severity. The degree of construction scope was dropped from all models since there was either no change in the factor (12 and 15 ft) or it aided in the analysis by increasing the degrees of freedom for the hypothesis test (14 ft).

Table 4.9 ANOVA Results for Construction Factors

Variable	Panel Width					
	12 ft		14 ft		15 ft	
Sample Size	67 of 278		1801 of 2964		80 of 207	
Longitudinal Crack	Length	Severity	Length	Severity	Length	Severity
Mean	29 ft	1.7	41 ft	1.2	52 ft	1.5
Model R^2	7.1%	24.4%	2.0%	16.6%	36.0%	15.1%
Dowel Bar Installation		x				
Topography	x	x	x	x	x	x
Curve			x	x	x	
Bridge						
Construction Scope	Dropped[2]	Dropped[2]	Dropped[1]	Dropped[1]	Dropped[2]	Dropped[2]
x = Statistically significant at 95% probability level. Dropped[1] = dropped to increase degrees of freedom Dropped[2] = dropped with no variation in scope; Reconstruction only						

4.4.3.1 Dowel Bar Installation

The average cracking length by method of inserting dowel bars are summarized in Figure 4.19 for panel widths of 12, 14, and 15 ft. Dowel baskets in 12 ft panels had about double the length of cracking when compared to the dowel bar inserter (DBI) for all severity levels. The opposite occurred on the 14 and 15 ft panels where the DBI had a greater average length of cracking, with a near-even distribution among low and medium severity levels in the 14 ft panel. Dowel baskets only had medium severity level observed in the 15 ft panel, and all severity levels with the DBI.

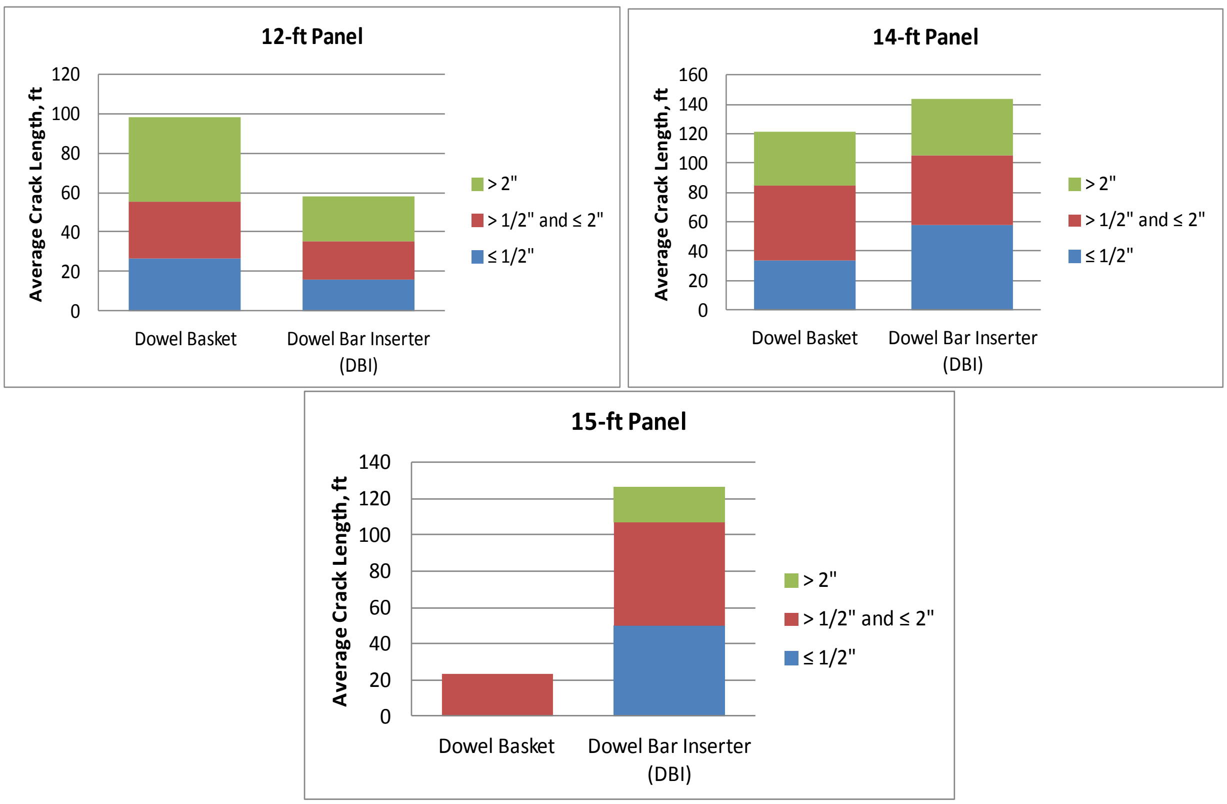


Figure 4.19 Dowel Bar Installation and Cracking Length and Severity in Panel Widths

4.4.3.2 Topography

Topography was determined to be statistically significant in changing the mean extent and severity of cracking among all panel widths. Undefined sections were not classified as either cut or fill. Figure 4.20 for the 12, 14, and 15 ft panels show about double the length of cracking in cut and fill sections for 12 ft panels, and half of undefined cut/fill sections for 14 and 15 ft panels. Cut and fill sections had near-equal severity levels.

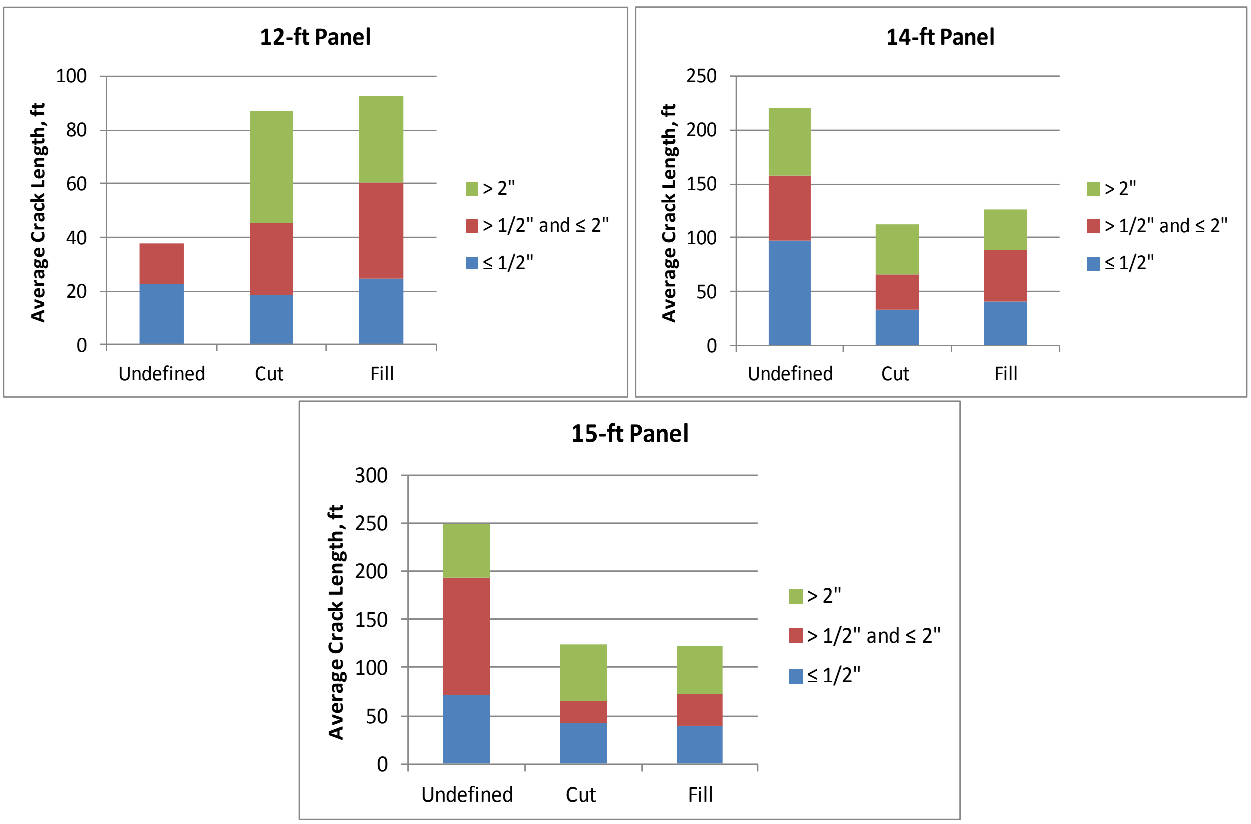


Figure 4.20 Topography effect on Cracking Length and Severity by Panel Width

4.4.4 Traffic Factors

Table 4.10 summarizes the statistical hypothesis tests at the 95% probability level for traffic factors changing the average length and severity of longitudinal cracking. AADT changed the mean level of cracking length and severity in the 15 ft panel. For all panel widths, the truck percentage and AADTT affected the length or severity of cracking. AADTT affected cracking length in 12 and 15 ft panels, and severity in wider 14 and 15 ft panels. Posted speed, number of lanes, and functional class all had an effect on the mean length or severity of cracking in the 12 and 14 ft panels. Plots and analysis in the following subsections further investigate AADTT and posted speed.

Table 4.10 ANOVA Results for Traffic Factors

Variable	Panel Width					
	12 ft		14 ft		15 ft	
Sample Size	141 of 278		2804 of 2964		194 of 207	
Longitudinal Crack	Length	Severity	Length	Severity	Length	Severity
Mean	83 ft	1.4	43 ft	1.3	76 ft	1.6
Model R^2	12.4%	14.1%	4.2%	6.1%	27.1%	17.0%
AADT					x	x
TRUCK %	x		x	x	x	x
AADTT	x			x	x	x
Posted Speed, mph		x	x	x		
Number of Lanes				x	Dropped	Dropped
Functional Class		x	x			
x = Statistically significant at 95% probability level. Dropped = variable does not exist and was removed from the analysis.						

4.4.4.1 AADTT

Truck traffic levels as measured by the AADTT impacted the length of cracking on the 12 and 15 ft panels, and the severity on the wider 14 and 15 ft panels. Figure 4.21 detects a downward trend where higher truck traffic levels had lower cracking length, that may be explained in part by enhanced pavement design and thickness for heavier truck trafficked roadways. [Note that this trend line only serves as a visual tool; specific models must be checked for important assumptions]. In summary, lower truck traffic volumes tend to have greater extent and severity of cracking.

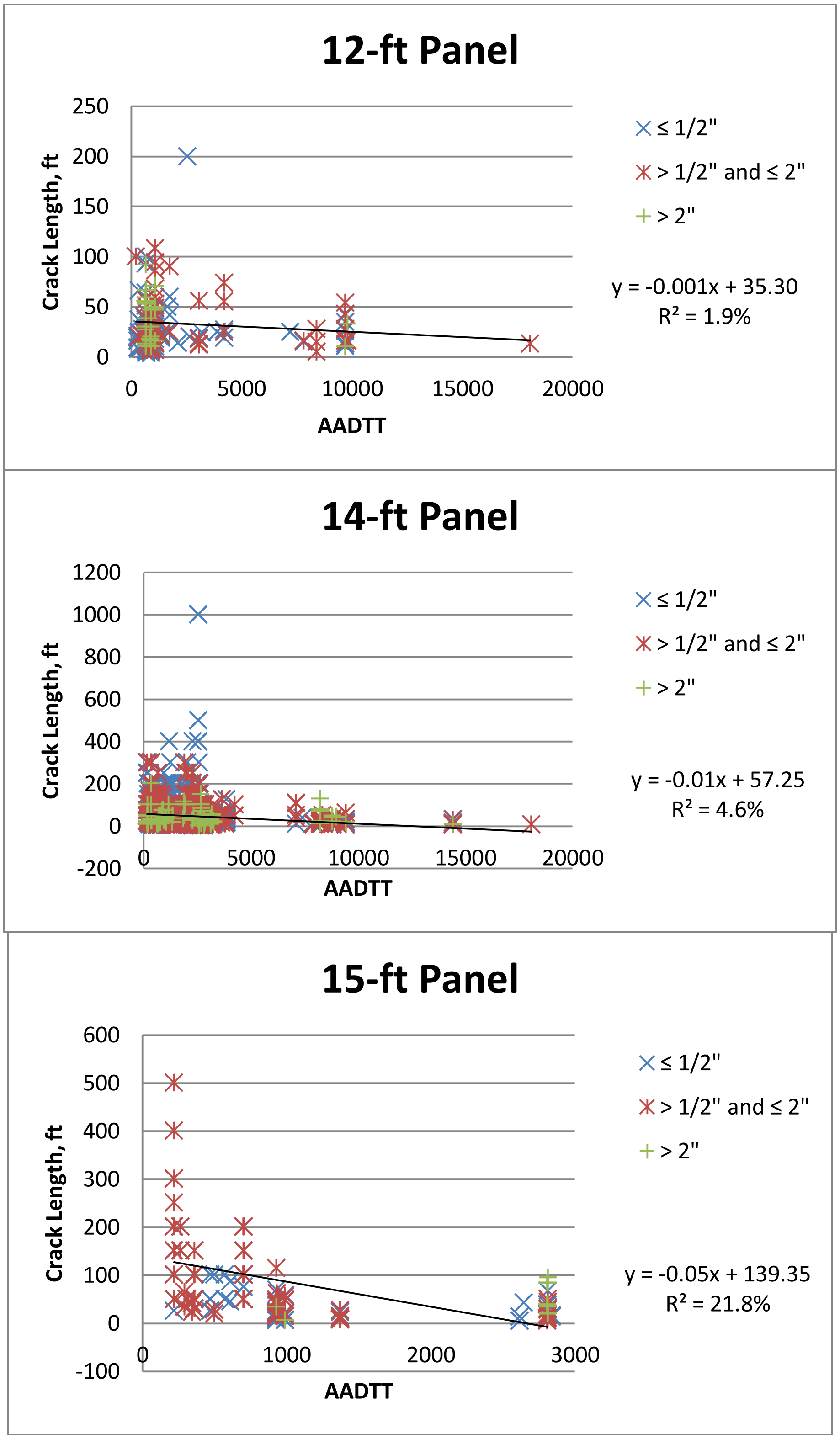


Figure 4.21 AADTT and Cracking Length and Severity by Panel Width

4.4.4.2 Posted Speed

Figure 4.22 plots the average length and severity of cracking in three posted speed ranges among the panel widths. Greater average longitudinal cracking length was observed on 55 to 65 mph posted speed highways for the 12 and 15 ft panels, and 40 to 50 mph for the 14 ft panel. Severity of cracks in 12 and 14 ft panels had a near equal length, except for no high severity in the 14 ft panel. The 15 ft panel had no high severity levels for lower speeds.

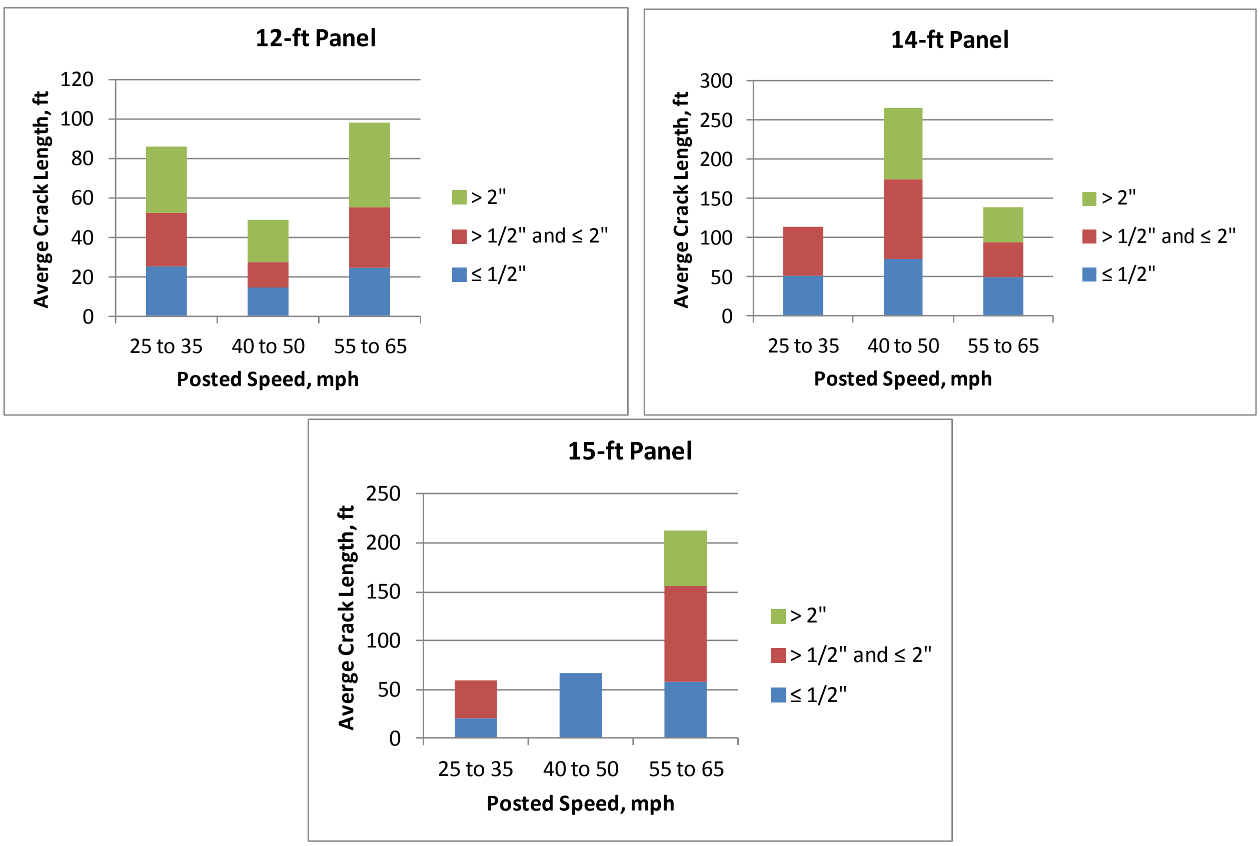


Figure 4.22 Posted Speed with Average crack length and severity by Panel Widths

4.4.5 Environmental Factors

Table 4.11 summarizes the statistical hypothesis tests at the 95% probability level for the two environmental factors (age and region) tested for changing the average length and severity of longitudinal cracking. Age had a significant effect on the length and severity of 12 and 14 ft panels, where newer pavements had shorter length and severity of cracking. Region impacted the severity of 12 and 14 ft panels, and the crack length of 14 and 15 ft panels. Plots of these two factors are illustrated in the following subsections to investigate their relative effect.

Table 4.11 ANOVA Results for Environmental Factors

Variable	Panel Width					
	12 ft		14 ft		15 ft	
Sample Size	240 of 278		2960 of 2964		207 of 207	
Longitudinal Crack	Length	Severity	Length	Severity	Length	Severity
Mean	25 ft	1.4	42 ft	1.3	72 ft	1.6
Model R^2	11.5%	8.6%	8.5%	22.5%	29.7%	5.0%
Age	x	x	X	x		
Region		x	X	x	x	
x = Statistically significant at 95% probability level.						

4.4.5.1 Age

Histograms are reported in Figure 4.23 to illustrate the average cracking length by severity and age. There was no consistent trend or change in length of crack by panel width. As the age of the 12 ft panels increased, the low severity length of 120 ft at 1 to 5 years of age dropped to an average length of 20 or less. Greater average length of cracking was observed in the 14 ft panel for ages 11 to 20, but shorter lengths for ages less than 11 years and greater than 20 years.

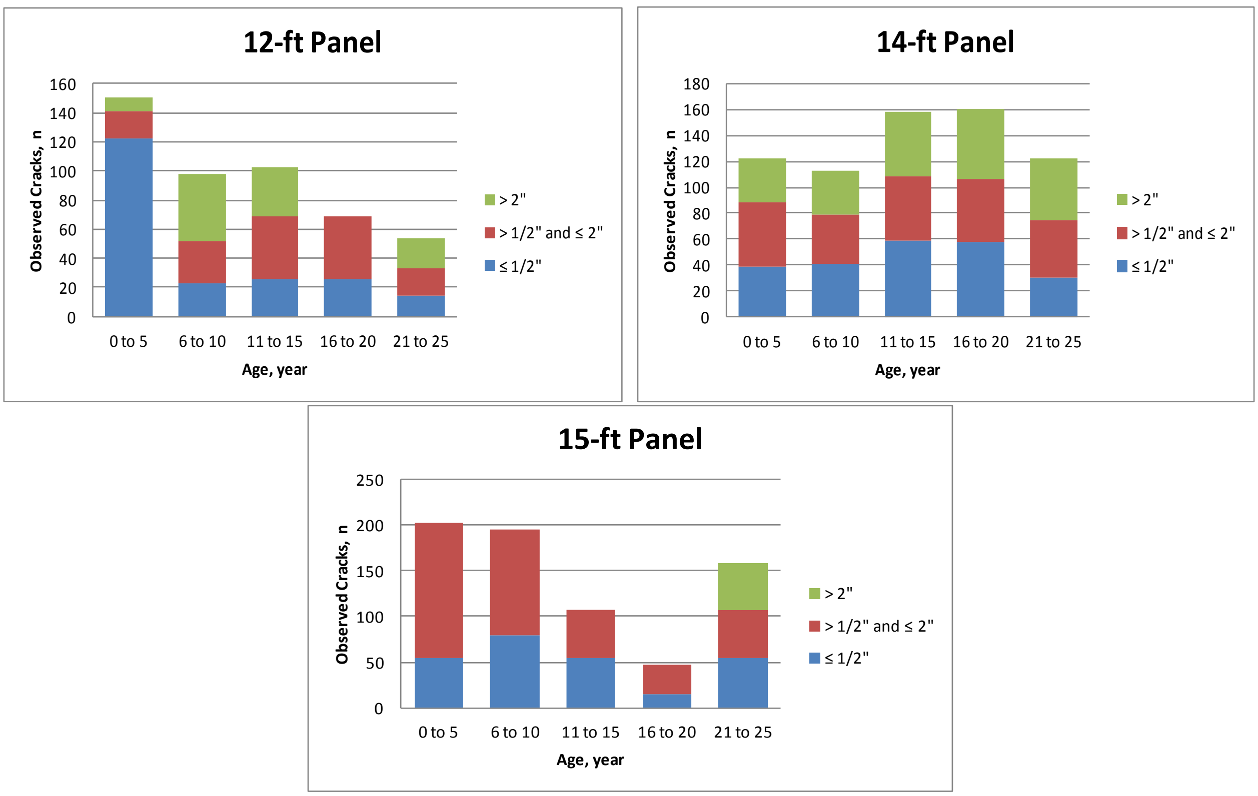


Figure 4.23 Age and severity of Longitudinal Cracking for Panel Wdith

4.4.5.2 Region

The five regions within the state were found to have statistical differences in terms of cracking length and severity. The distribution of average length and severity levels by region for the 12, 14, and 15 ft panel widths are illustrated in Figure 4.24. Among the 12 ft panels, cracks in the NW and NC Regions were low and medium severity levels, while the SE and SW Regions had a similar lengths of cracking for low and medium severity, while the SW Region had greater length of high severity. Distribution of lengths among 14 ft panels had greater lengths in the NW and NC Regions than the other three regions. A similar finding was also observed for the 15 ft panels where the NW and NC Regions had greater cracking length, while all SE and SW Regions had shorter crack lengths.

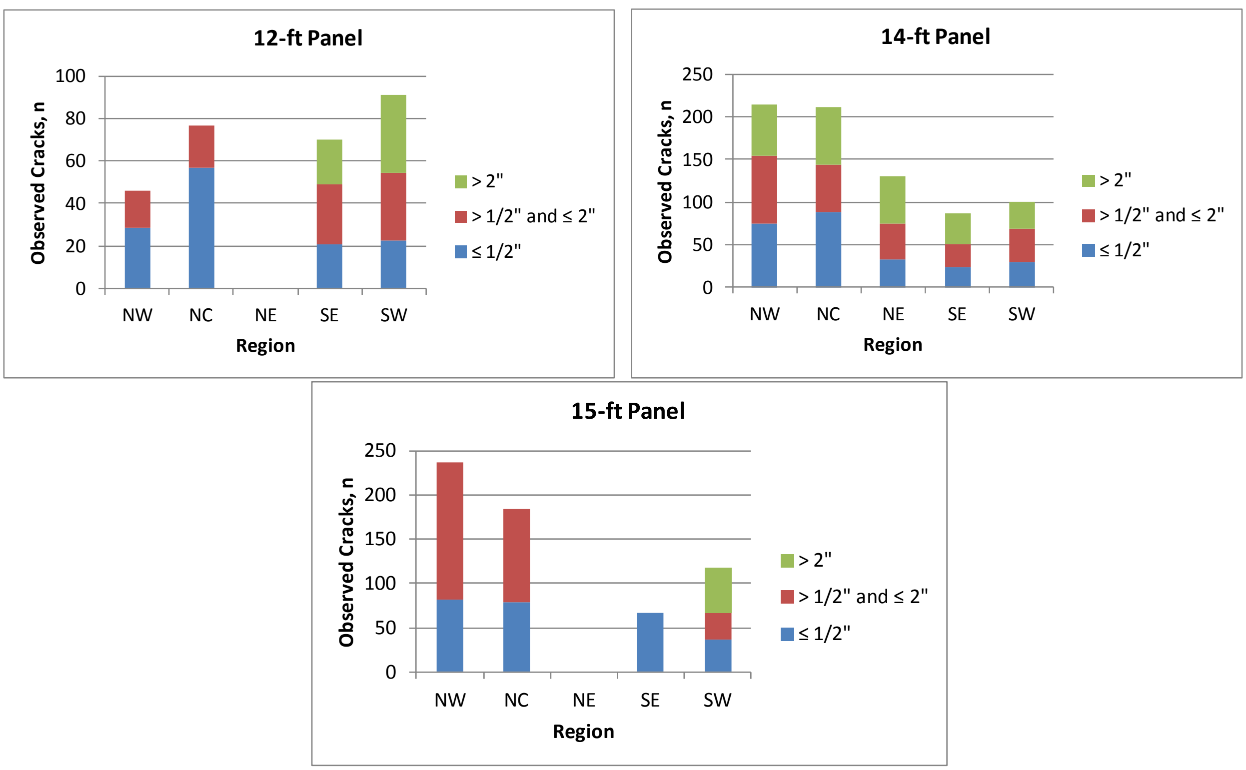


Figure 4.24 Region and Average Cracking length and severity by Panel Width

4.4.6 Summary of Factors affecting Length and Severity of Cracking

Among the 1,008 sampled segments in this study, 60% (599/1,008) of the average 1.14-mile long segments had some degree of longitudinal cracking. Cracking within those 599 segments were investigated in detail for the effects of performance, design, construction, traffic, and environment on the length and severity of observed cracking. The significant factors explaining the length and/or severity of longitudinal cracking included offset of crack, pavement thickness, width-to-thickness ratio, joint spacing, transverse joint orientation (skewed or normal), rumble strips, base gradation (dense or open), dowel bar installation, AADTT, age, and region. Table 4.12 summarizes significant factors and key findings from this portion of the data analysis.

Table 4.12 Factors affecting the Length and Severity of Longitudinal Cracking

Factor	Key Findings for Panel Width
Offset	Length: • All panels: Greatest cumulative length is between wheel paths or in the right wheel path. Less cracking occurs adjacent to the left or right longitudinal edge and in the left wheel path. • 12, 13, and 14 ft panels had a majority of cracking length closer to the middle of the panel. • 13 ft panel was removed from statistical analysis since only 8 segments were sampled. • 15 ft panel had a majority of cumulative cracking length 40% of the distance from the left edge. Severity: • 12 ft panel: low and medium severity levels were nearly equal. • 14 ft panel: more low severity cracking. • 15 ft panel: more medium severity cracking.
Thickness	Length: • 14 ft panel was only statistically significant width with a decrease in crack length with thickness. Frequency: • In general, thinner pavements had a greater frequency of cracking than thicker pavements. • The 9-in thick pavement had the predominant number of sampled segments and cracks for all panel widths. As the thickness increases above 9 in for all panel widths, the frequency of cracking dropped. • 14 ft panel with a 1 in thickness increase from 9 to 10 in reduced the number of cracks by 25%. Severity: • 12 ft panels have majority at low severity level; severity decreased as the pavement thickness increased. • 14 ft panels have majority at low severity level. • 15 ft panels have nearly equal low and medium severity level; severity increased as the pavement thickness increased.

Table 4.12 (cont.) Factors affecting the length and severity of Longitudinal Cracking

Factor	Key Findings for Panel Width
Width-to-Thickness Ratio	Length: • 15 ft panels were only statistical significant width with increase in crack length with w/t ratio. • 12 ft panels: 100% cracking in 8 in (w/t = 1.5) and 12 in (w/t = 1.0) thick panels w/t ratio = 1.3 averaged 100 ft per segment w/t ratio = 1.0 and 1.2 averaged 20 ft per segment. w/t ratio = 1.5 had 100 ft per segment (one segment) • 14 ft panels in comparison n=260 segments at w/t = 1.4 and n=173 segments at w/t = 1.6, there was a near equal length of cumulative cracking. 100% cracking in 7 in (w/t = 2.0) and 12 in (w/t = 1.2) thick panels w/t = 1.4 averaged 164 ft per segment. w/t = 1.6 averaged 238 ft per segment. w/t ratio is raised from 1.4 to 1.6, the average cracking length within a pavement segment increases by 45%. • 15 ft panels 100% cracking in 8 in (w/t = 1.9) and 9.5 in (w/t = 1.6) thick panels w/t = 1.5 averaged 362 ft per segment. w/t = 1.7 averaged 430 ft per segment. w/t ratio is raised from 1.5 to 1.7, the average cracking length within a pavement segment increases by 18%. Severity: • 12 ft panels: higher severity with greater w/t ratio. • 14 ft panels: no trend; more relative medium severity with w/t ratio = 1.2 and 1.4, and more low severity with w/t ratio = 1.3 and 1.5. • 15 ft panels: more relative high severity with w/t ratio = 1.5, and more medium severity with w/t ratio = 1.7.
Joint Spacing	Length: • The minimal of longitudinal cracking occurs by panel width when: 12 ft panel = 18-ft joint spacing 14 ft panel = 15-ft joint spacing 15 ft panel = random spacing Severity: • 14 and 15 ft panels were statistical significant, while 12 ft panel was not. • 14 ft panels: greater medium severity with random spacing. • 15 ft panels: greater medium severity with 15-ft and 18-ft joint spacing.

Table 4.12 (cont.) Factors affecting the Length and Severity of Longitudinal Cracking

<table>
<tr><th>Factor</th><th>Key Findings for Panel Width</th></tr>
<tr><td>Skewed and Normal Joints</td><td><u>Length:</u>
12 ft panel not statistically different, 14 and 15 ft statistically different.
12 ft panel: skewed joints 53% cracking, normal joints 42% cracking.
14 ft panel: skewed joints 60% cracking, normal joints 26% cracking; 14% no cracking.
15 ft panel, skewed joints 80% cracking, normal joints 17% cracking; 3% no cracking.
<u>Severity:</u>
12 ft panel not statistically different, 14 and 15 ft statistically different.
14 ft panel: greater medium severity with skewed joints.
15 ft panel: greater medium severity with skewed joints.</td></tr>
<tr><td>Rumble Strips</td><td><u>Length:</u>
14 ft panel was only statistically significant width with greater average length per segment with no rumble strip than in the asphalt shoulder.
Average lineal length of cracking per segment in 14 ft panels was:
130 ft asphalt shoulder.
143 ft PCC panel.
183 ft no rumble strip.
15 ft panels had the greatest average cracking with PCC panels.
<u>Severity:</u>
Rumble strips were statistically significant for all panel widths.
12 ft panels: no rumble strip had the highest relative severity, and much lower average severity for placement in asphalt shoulder or PCC panel.
14 ft panel had higher severity with no rumble strips and lower severity with rumble strips in the asphalt shoulder.
15 ft panel had higher severity with no rumble strip (CABC shoulder) and lower severity with rumble strips in the PCC panel.</td></tr>
<tr><td>Base Gradation</td><td><u>Length:</u>
14 ft panel was only statistically significant width with greater length of cracking in open-graded sections compared to dense-graded sections.
Average length of cracking per pavement segment by base type:
Dense graded base = 140 ft per segment.
Open graded base = 180 ft per segment.
<u>Severity:</u>
There was no statistical difference in severity with the two base gradations for all panel widths.</td></tr>
<tr><td>Dowel Bar Installation</td><td><u>Length:</u>
12 ft panels were statistically significant with double the length of cracking with dowel baskets compared to the dowel bar inserter (DBI) for all severity levels.
The opposite occurred on the 14 and 15 ft panels where the DBI had a greater average length of cracking.
<u>Severity:</u>
The DBI had a near-even distribution among low and medium severity levels in the 14 ft panel.
Dowel baskets only had medium severity level observed in the 15 ft panel,</td></tr>
</table>

	and all severity levels with the DBI.

Table 4.12 (cont.) Factors affecting the length and severity of Longitudinal Cracking

Factor	Key Findings for Panel Width
Topo-graphy	Length: • Double the length of cracking in cut and fill sections for 12 ft panels, and half of undefined cut/fill sections for 14 and 15 ft panels Severity: • Cut and fill sections had near-equal severity levels.
AADTT	Length: • AADTT was statistically significant in cracking length in 12 and 15 ft panels. • Higher truck traffic levels had lower cracking length; explained by enhanced pavement design and thickness for heavier truck trafficked roadways. • Lower truck traffic volumes had greater length of cracking. Severity: • AADTT was statistically significant in severity in wider 14 and 15 ft panels. • Lower truck traffic volumes tend to had higher severity of cracking.
Age	Length: • Age had a statistically significant effect on length of cracking for 12 and 14 ft panels, but not with 15 ft panels. • With a statistical mean difference in length by age, there was no consistent trend. • Greater average length of cracking was observed in the 14 ft panel for ages 11 to 20, but shorter lengths for ages less than 11 years and greater than 20 years. Severity: • As the age of the 12 ft panels increased, the low severity length of 120 ft at 1 to 5 years of age dropped to an average length of 20 or less.
Region	Length: • Five regions were found to have statistical differences in terms of cracking length. • 12 ft panels in SE and SW Regions had similar lengths of cracking. • 14 ft panels had greater lengths in the NW and NC Regions than the other three regions. A similar finding was also observed for the 15 ft panels where the NW and NC Regions had greater cracking length, while all SE and SW Regions had shorter crack lengths. . Severity: • Five regions within the state had statistically significant differences in cracking severity. • 12 ft panels in the SE and SW Regions had similar low and medium severity, while the SW Region had greater length of high severity.

4.6 Summary of Hypothesis Test for Factors affecting Longitudinal Cracking

Two separate analysis of variance investigations were conducted to determine factors influential in affecting longitudinal cracking. In each analysis, performance, design, construction, traffic, and environmental effects were investigated. The first analysis evaluated 1,008 concrete segments within the state, averaging 1.14 miles in length, to determine factors explaining the presence or absence of cracking. The second analysis investigated 599 segments having cracking to determine those factors affecting the length and severity of longitudinal cracking. Table 4.13 summarizes significant factors from both analyses for presence or absence of cracking, length of cracking, and severity of cracking.

Table 4.13 Results of ANOVA for Presence, Length, and Severity of Cracking

Variable	Panel Width								
	12 ft			14 ft			15 ft		
Longitudinal Crack	Present	Length	Severity	Present	Length	Severity	Length	Extent	Severity
Offset of Crack	N/A		x	N/A	x	x	N/A		x
Thickness, in			x	x	x	x			x
Width-to-Thickness			x			x		x	x
Joint Spacing, ft				x	x	x		x	x
Skewed Joints					x	x		x	x
Parting Strips	Drop		Drop	x	x	x	Drop	Drop	Drop
Tining			x	x	x	x			x
Rumble Strip			x	x	x	x			x
Shoulder Type				x		x	x	x	x
Shoulder Crack Filler				x	x		Drop	Drop	Drop
Base Gradation					x				
Dowel Bar Installation			x	x					
Topography			x		x	x		x	x
Curve					x	x		x	
Bridge									
Construction Scope	Drop	Drop	Drop		Drop	Drop	Drop	Drop	Drop
AADT				x				x	x
TRUCK %	x	x			x	x		x	x
AADTT	x	x				x		x	x
Posted Speed, mph			x		x	x			
Number of Lanes				x		x	Drop	Drop	Drop
Functional Class			x		x				
Age	x	x	x	x	x	x			
Region	x		x	x	x	x		x	

Among the 1,008 concrete pavement segments, the significant factors explaining the presence or absence of longitudinal cracking included width-to-thickness ratio, joint spacing, longitudinal jointing method, tining orientation, dowel bar installation, traffic level, age, and region. Within these 1,008 segments, about 60% (599/1,008) of 1.14-mile segments in the state had longitudinal cracking while 40% did not (409/1,008).

The significant factors explaining the length and/or severity of longitudinal cracking included offset of crack, pavement thickness, width-to-thickness ratio, joint spacing, transverse joint orientation (skewed or normal), rumble strips, base gradation (dense or open), dowel bar installation, AADTT, age, and region.

CHAPTER 5 GUIDELINES TO OPTIMIZE JPCP PERFORMANCE THROUGH PANEL WIDTH SELECTION

5.1 Introduction

This chapter provides guidance on determining the maximum allowable pavement width as a function of pavement thickness in order to achieve optimal concrete pavement performance. The guidelines development process is depicted in Figure 5.1 and derived from literature findings, survey of professional engineers from six Midwest states, online discussion of case studies from various states, analysis of in-service performance, and life cycle cost analyses involving concrete pavement panels ranging in width from 12 ft to 15ft. The literature findings and surveys of professionals from the Midwest provide a basis for identifying best practices with potential applicability to Wisconsin because of similarities in climate and traffic patterns. It is also recognized that existing WisDOT design practice, as well as recommended changes to existing practice, must be made in the context of life-cycle costs. For that purpose, a life-cycle cost was performed to examine the cost and benefits associated with panels in use in Wisconsin.

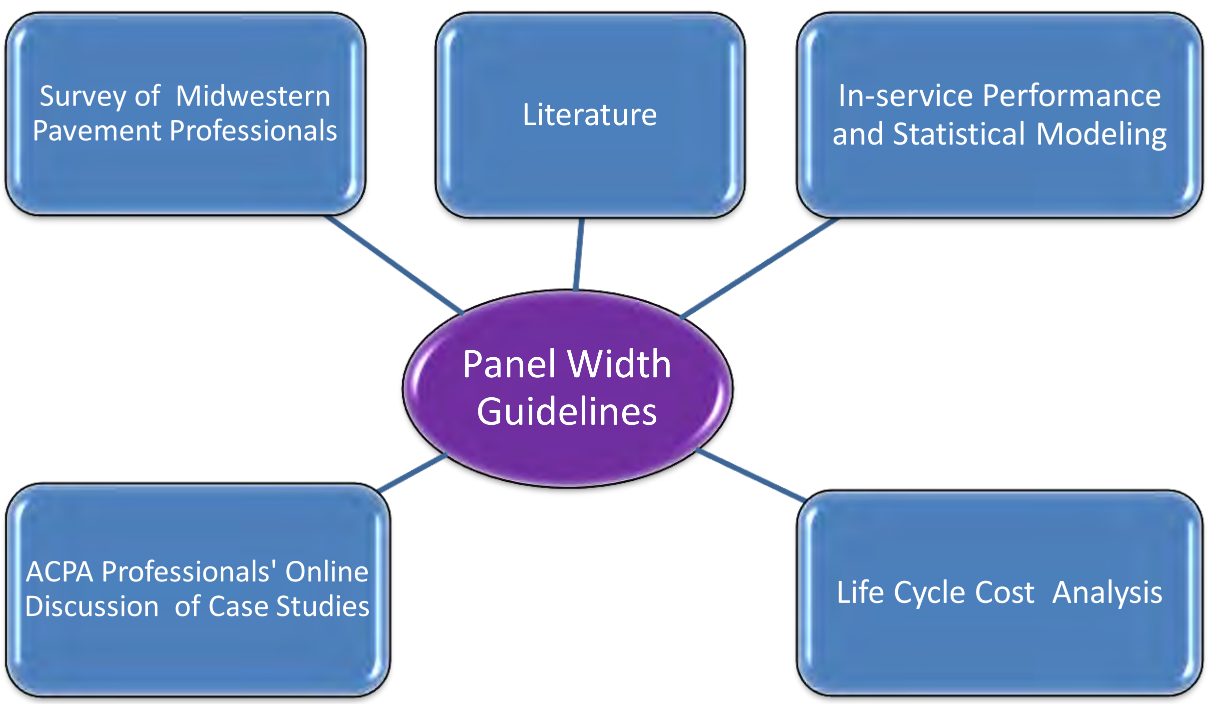


Figure 5.1 Panel Width Guidelines Development Framework

The guide is developed with a series of sections. The first section provides an abbreviated understanding regarding the phenomena of cracking in concrete pavements pertaining to causes, time of occurrence, and traditional treatment methods synthesized from the literature. The second section synthesizes results from a questionnaire survey of six Midwestern states regarding JPCP practices and how those practices impact longitudinal cracking development in JPCP. The third section summarizes the results of a statistical analysis of Wisconsin JPCP segments as it relates to longitudinal cracking presence, extent, and severity. The fourth section arranges Wisconsin practices, the literature review, Midwestern survey, and statistical analysis in matrix form to recommend specific modifications regarding current WisDOT panel width practice. The fifth section presents statistical models to manage longitudinal cracking by transverse offset location. Finally, the sixth section performs a life-cycle cost analysis to quantify the design and treatment option costs.

5.2 Understanding Longitudinal Cracking from Literature Review

The phenomena of cracking in concrete pavements including causes, time of occurrence, and treatment methods (besides panel width options) have been widely discussed in the literature. Since previous work plays an important role in creating these guidelines, a brief synthesis from Chapter 2 findings is captured. The consensus is that cracking of concrete slabs occur when internal tensile stresses exceed tensile strength. The internal stresses have been attributed to initial moisture loss during curing, base restraint or subbase friction during longitudinal expansion and contraction from temperature changes, as well as thermal/moisture gradients between the top and bottom of the slabs (Halm et al. 1985; Richardson and Armaghani 1987; Voigt 1992; Voigt 1994; Okamoto et al. 1994; Weiss 1999; Corley-Lay and Morrison 2002; Ardani et al. 2003).

The majority of longitudinal cracking tends to be random or uncontrolled in nature and has been reported to occur in some new pavements within the first two months of construction, initially appearing at large intervals (30 to 150 ft) and forming at similar intervals over time. In situations where random cracking initially occurs and continue to develop well after paving and sawing, slab movement from grade settlement/frost heave or slab restraint from the use of stabilized subbases such as cement-treated, asphalt-treated, permeable asphalt-treated, and econocrete have been found to be the causes (Halm et al. 1985; Voigt 1992; Voigt 1994). A study in North Carolina reported the occurrence of longitudinal cracking on 80% of slabs placed on cement-treated bases compared to 7% for sections placed on crushed aggregate bases (Corley-Lay and Morrison 2002).

5.2.1 Approaches to Limiting Cracking Impact from Induced Stresses

The traditional approach to minimizing the effect of induced stresses in concrete slabs is to apply proper jointing techniques to create transverse and longitudinal saw cut joints, which in turn induce a plane of weakness that can allow the crack to initiate and propagate to the bottom of the slab. The jointing process is influenced by a number of factors including when to saw, the sawing process, saw cut depth, and saw blade properties. Sawing too early outside an optimum time window is known to induce raveling of the concrete from the saw blade, while sawing too late may result in pop-off cracks. The desired optimum window is reported to begin when concrete strength is acceptable to saw without excessive raveling along the cut and ends when the concrete volume reduces significantly due to drying shrinkage or contraction (Okamoto et al. 1994; FHWA 2005). Raoufi et al. (2008) concluded that the latest age a saw cut should be based on a comparison of the predicted residual stress of an uncut pavement with the product of the pavement strength values and a strength reduction factor. Early-age saw cut depths of 1/4 times the slab thickness is found to produce better crack control than larger depths (Zollinger 1994). Shallower saw depth cuts (< 1/4 times the slab thickness) is reported to increase stress to 50% of the tensile strength of the slab leading to micro-cracking development and reduction in long-term performance (Raoufi et al. 2008).

Despite the application of proper jointing techniques to limiting induced stress impact, it is highly recognized that substantial changes in weather during and after construction can induce random cracking. Hence, the paving window is found to be critical. Field observations indicate that concrete paved in early morning under warm, sunny summer conditions exhibit more instances of random cracking than concrete paved during the late morning or afternoon. The FHWA developed the High PERformance Concrete PAVing (HIPERPAVE)® software to address such temperature gradients during construction. The software provides guidance on timelines to saw cut pavement based on project input data such as ambient air temperature, wind speed, and strength development rate of concrete.

5.2.2 Panel Width Considerations in Limiting Cracking Impacts on JPCP

The concept of panel width consideration in limiting cracking on pavements is fairly new. One of the earliest studies that linked panel width with premature longitudinal cracking was conducted by Ardani et al. (2003) for IH-70 and USH-287 in Colorado. The study concluded that 14-ft wide slabs did not contribute to longitudinal cracking on rural highways. Other factors including poor construction and jointing practices, and the presence of untreated native soil with high swelling potential were the main factors that caused cracking on the pavements studied.

In 2011, the Iowa Concrete Pavement Association reported the sudden appearance of significant amount of longitudinal cracking within 2-3ft of the edge of 10-15 year old 14-ft widened concrete pavements in Iowa (Smith 2011). The subject pavements were reported to be 10 to 12 in thick with 20-ft joint spacing and placed over 8 to 9 in of granular subbase in the outer wheel area. This observation from Iowa generated an online discussion among professionals in the ACPA network looking for answers. Experiences varied considerably among the professionals. Temple (2011) reported that Louisiana has 20-year old 15-ft widened lanes with no cracking and suggested that Iowa's pavement problem could be a combination of load transfer device issue and truck tire loading since all the cracks appeared to occur in the wheel path. Experience from South Dakota revealed initial longitudinal cracking problems with 15-ft widened non-doweled panels but no problems have been encountered for 20-years after a switch to 14-ft wide doweled pavements having 20-ft transverse joints (Engbrecht 2011). In addition, South Dakota has used 13-ft panels on the interstates for more than 20 years with no problems. The 13-ft panels are used in conjunction with 20-ft transverse joints for thicker pavements (≥10 in), while 15-ft transverse joints are used with thinner pavements (<10 in). Voigt (2011) suggested that the degree of support either from settlement or heaving would be a probable cause for the Iowa pavements since the cracking occurred 2 to 3 ft from the edge many years after construction. Voigt called for an investigation of the subbase widening constructed to accommodate the widened lane from the previous lane configuration.

5.3 Survey of JPCP Panel Width Practices in Selected Midwestern States

Six Midwest states including Iowa, Ohio, Michigan, Wisconsin, Illinois, and Minnesota were invited to participate in an online survey that pertain to practices involving doweled JPC panel width usage on two- and multilane rural highways. The objective was to determine how these practices impacted longitudinal cracking development on JPCP. Thirty seven professionals participating in the online survey indicated the following:

a. Pavement thickness is the dominant factor considered in the selection of JPCP panel width on rural highways. Other factors include traffic volume, percent trucks, ease of construction, and construction & maintenance costs.
b. The most commonly used panel width on 2-lane 2-way rural pavements is 12 ft followed by the 15-ft panel. On multi-lane highways, the 12-ft panel is commonly used.
c. The 12-ft and 15-ft wide panels were reported to have higher longitudinal cracking frequencies compared to 13-ft and 14-ft wide panels. The cracking generally occurs more near panel edge and at mid-panel locations compared to the vicinity of sawn longitudinal joints.
d. Premature longitudinal cracking initiation time varies from less than a month to as high 60 months with an average initiation time of 24 months.
e. Thicker pavements (≥11 in) do not tend to exhibit longitudinal cracking compared to more vulnerable thinner pavements.
f. Pavements with shorter joint spacing tend to experience more longitudinal cracking.
g. Higher longitudinal cracking frequencies tend to be associated with inadequate subbase compaction, poor joint saw-cut timing, misaligned dowel bars, and faulty vibrators. In addition, 12-ft panels are prone to more construction related longitudinal cracking compared to all other panels.
h. The main methods for fixing premature or normal longitudinal cracking include rout and seal, cross-stitching, and partial or full panel replacement. The cost would vary depending on the treatment type.

5.4 Statistical Analysis of Wisconsin JPCP Panel Widths

Wisconsin experience with panel widths was captured through an analysis of the in-service performance of a sample of 1,008 JPCP segments averaging 1.14 miles in length. The distribution of sampled pavement segments with and without cracking is shown in Table 5.1 for various panel widths. A higher proportion of cracking occurred on all panels; all 13 ft panels exhibited longitudinal cracking. The wider 14 ft panels had 25% less segment cracking than narrower 12 ft and wider 15 ft panel widths.

Table 5.1 Proportion of Pavement Segments with and without Longitudinal Cracking

Cracking observed in segment	Panel Width, ft				Total
	12	13	14	15	
No	14	0	389	6	409
Yes	58	8	502	31	599
Total	72	8	891	37	1008
Yes, %	81%	100%	56%	84%	---
1,008 of 1,767 pavement segments in state were sampled.					

The performance measures used were defined in terms of the presence or absence of cracking (Eq. 5.1), the length of cracking (Eq. 5.2) and severity of cracking (Eq. 5.3).

$$\text{Cracking (Yes or No)} = \text{Design} + \text{Construction} + \text{Traffic} + \text{Environment} + \text{Unexplained Variability or Error} \quad (5.1)$$

$$\text{Length of Cracking (ft)} = \text{Design} + \text{Construction} + \text{Traffic} + \text{Environment} + \text{Unexplained Variability or Error} \quad (5.2)$$

$$\text{Severity of Cracking (1 Low, 2 Medium, 3 High)} = \text{Design} + \text{Construction} + \text{Traffic} + \text{Environment} + \text{Unexplained Variability or Error} \quad (5.3)$$

Where,

Low = $\leq 1/2$ in

Medium = $> 1/2$ in to ≤ 2 in

High = > 2 in

Through modeling of Equations 5.1 through 5.3, the main factors that impact the presence, length, and severity of longitudinal cracking are summarized in Table 5.2 for various panel widths in use in Wisconsin. The table suggests that panel width cannot be treated in isolation without consideration to design, construction, traffic, and environmental factors.

Table 5.2 Results of ANOVA for Presence, Length, and Severity of Cracking

Variable	**Panel Width**								
	12 ft			**14 ft**			**15 ft**		
Longitudinal Crack	Present	Length	Severity	Present	Length	Severity	Length	Extent	Severity
Offset of Crack	N/A		x	N/A	x	X	N/A		x
Thickness, in			x	x	x	X			x
Width-to-Thickness			x			X		x	x
Joint Spacing, ft				x	x	X		x	x
Skewed Joints					x	X		x	x
Parting Strips	Drop		Drop	x	x	X	Drop	Drop	Drop
Tining			x	x	x	X			x
Rumble Strip			x	x	x	X			x
Shoulder Type				x		X	x	x	x
Shoulder Crack Filler				x	x		Drop	Drop	Drop
Base Gradation					x				
Dowel Bar Installation			x	x					
Topography			x		x	X		x	x
Curve					x	X		x	
Bridge									
Construction Scope	Drop	Drop	Drop		Drop	Drop	Drop	Drop	Drop
AADT				x				x	x
TRUCK %	x	x			x	X		x	x
AADTT	x	x				X		x	x
Posted Speed, mph			x		x	X			
Number of Lanes				x		X	Drop	Drop	Drop
Functional Class			x		x				
Age	x	x	x	x	x	X			
Region	x		x	x	x	X		x	
x = Statistically significant at 95% probability level. Drop = Independent variable does not apply to width, or insufficient sample size for hypothesis test.									

5.5 Recommended Practices for JPCP Panel Width

Coupling the field in-service performance with findings from the literature review and surveys, a guidance on panel width usage is provided in Table 5.3. The last column of Table 5.3 provides specific recommended modifications to be made regarding current WisDOT panel width practice.

Table 5.3 indicates that WisDOT panel characteristics consistent with the literature and survey findings include: the use of the standard panel width of 14-ft (which is reported to have least cracking frequency), transverse joint spacing in the range of 12 to 20 ft, and the use of untreated aggregate bases as opposed to stabilized bases. Major differences, however, exist regarding other panel characteristics including: width-to-thickness ratio, saw-cut depth, and filling of the panel/shoulder interface with a filler. WisDOT width-to-thickness ratio for JPCP is in the range of 1.0 to 2.0, compared to 1.2 to 1.5 encountered in the literature. While the literature recommends a saw-depth cut 1/4 times the slab thickness for better cracking control, WisDOT practice is based on 1/3 times the slab thickness, a standard put in place in 2003. WisDOT policy on filling of the panel/shoulder interface appears not to be clearly defined. While some departments fill the interface, others do not. The literature suggests that filling of the interface can delay deterioration of the joint by 6 years. However, results of this study suggests that cracking frequency on the panel is reduced when the shoulder interface is not filled.

Modifications for consideration in current practice include:

a) Use of the standard panel width of 14-ft based on its field performance in exhibiting the lowest cracking frequency compared to all other panels.
b) Applying a width-to-thickness ratio between 1.2 to 1.5 for 14-ft panels to minimize cracking severity and extent. This translates to concrete pavement thickness in the range of 9.5 to 12 in.
c) It was statistically determined that several interrelated factors influence cracking severity and extent for specific panels. For the recommended panel width of 14 ft, better performance is expected when used in conjunction with untreated aggregate base, dowel basket installation, longitudinal tining, and the current WisDOT standard of normal transverse joint orientation with 15 ft transverse spacing.

Table 5.3 Recommended Practices for JPCP Panel Width Usage

Panel Charac-teristic (1)	Existing WisDOT Practice (2)	Literature Recommendation and Survey Inputs from Midwestern States (3)	Wisconsin JPCP In-service Performance Analysis Results (4)	Recommended Changes to WisDOT Practice (5)
Width	12, 13, 14, and 15 ft, however, 14 ft is new standard	• 14-ft not linked with longitudinal cracking on rural highways (Ardani et al. 2003) • 13 and 14-ft panels experience less longitudinal cracking compared to 12- and 15-ft	• 100% of 13-ft panels experienced cracking • Lowest proportion (56%) of 14 ft panels experienced longitudinal cracking compared to 81% for 12-ft panels and 84% for 15-ft panels	Retain current 14-ft standard
Width-to-thickness (w/t) ratio	Varies: • 1.0-1.5 for 12-ft panels • 1.2-2.0 for 14-ft panels • 1.5-1.9 for 15-ft panels	• 1.4-1.5 for US 287, I-70 (Ardani et al., 2003) • 1.2-1.4 for Iowa PCC case study (Smith 2011) • 1.3 South Dakota Interstates (Engbrecht 2011)	• Large w/t ratios are associated with cracking • Increasing w/t ratio from 1.4 to 1.6 can increase average crack length by 45% for 14-ft panel. The increase is 18% for 15-ft panels when w/t ratio goes from 1.5 to 1.7. • w/t ratio of 1.0 and 1.2 result in an average crack length of 20 ft per segment for 12-ft panel	Specify w/t ratio to minimize cracking severity and extent as follows: • 1.2 (12" thickness) to 1.5 (9.5") if 14-ft panels are used; 1.4 (10 in) will limit cracking severity and extent. A 1-in thickness increase from 9 to 10-in reduced number of cracks by 25% and average crack length by 45%%. • 1.0-1.3 if 12-ft panels are used (Fig. 4.2, 4.3, 4.14)
Transverse Joint spacing	12, 15, 16 (random), 18, and 20 ft	• 12, 15, 18, 20 ft; high cracking frequency linked with 20-ft spacing	• Minimal cracking linked with 15-ft spacing for 14 ft panel; 18-ft spacing for 12-ft panel, and random spacing for 15-ft panel	Maintain current 15-ft joint spacing standard on rural highways
Base material type	Dense, Open	• Stabilized bases linked with high incidence of cracking (Halm et al. 1985; Voigt 1992; Voigt 1994) • Low cracking linked with crushed aggregate base course (Corley-Lay and Morrison 2002)	• 14-ft panels had 28% greater length of cracking per segment in open graded bases than in dense graded bases.	Untreated aggregate recommended over stabilized bases; dense graded may be preferred to minimize average crack length.

Table 5.3 (cont.) Recommended Practices for JPCP Panel Width Usage

Panel Charac-teristic (1)	Existing WisDOT Practice (2)	Literature Recommendation and Survey Inputs from Midwestern States (3)	Wisconsin JPCP In-service Performance Analysis Results (4)	Recommended Changes to WisDOT Practice (5)
Joint type	Skewed, Normal	N/A	Skewed joints exhibited higher levels of cracking compared to normal joints in all panels (Fig. 4.16)	Retain current normal joint orientation to improve performance
Dowel Bar Installation	Basket, Dowel bar inserter	N/A	• Dowel baskets had about double the frequency of segment cracking at all severity levels compared to dowel bar inserters for 12-ft panels (Fig 4.19) • For 14 and 15-ft panels, dowel bar inserters had double the frequency of cracking (Fig 4.19)	Consider basket installation to improve performance of 14-ft standard panel
Saw-cut depth	1/3 of slab thickness	• 1/4 of slab thickness depth produces better longitudinal crack control with 98% reliability in mixtures with crushed limestone aggregate; reliability is 86% for river gravel mixtures (Saraf and McCollough 1985) • Depth < 1/4 * slab thickness can increase stress to 50% of slab tensile strength leading to micro-cracking (Raoufi et al. 2008)	N/A	Current WisDOT standard of 1/3 slab depth may be studied and compared with literature findings that advocate 1/4 slab depth for better cracking control
Rumble strip placement	AC shoulder, PCC panel, None	N/A	The presence of rumble strips minimized cracking severity and extent (Fig. 4.17)	Specify rumble strips on paved asphalt shoulders or in the PCC panel

Table 5.3 (cont.) Recommended Practices for JPCP Panel Width Usage

Panel Charac-teristic (1)	Existing WisDOT Practice (2)	Literature Recommendation and Survey Inputs from Midwestern States (3)	Wisconsin JPCP In-service Performance Analysis Results (4)	Recommended Changes to WisDOT Practice (5)
Shoulder type	PCC, asphalt, unpaved	N/A	N/A	N/A
Longitu-dinal jointing	Sawed, Parting strip	When parting strip is properly installed, pavements exhibit less longitudinal joint distress than pavements constructed by sawing longitudinal joint (Lawrence et al., 1996)	Parting strip substantially reduced longitudinal cracking in 14-ft panels (Fig. 4.4)	Consider parting strip for standard 14-ft panel
Shoulder crack filler	Filler, No filler	For asphalt shoulders, filler can delay the occurrence of longitudinal joint deterioration by as much as 6 years (Owusu-Ababio and Schmitt; 2003)	No filler reduced cracking frequency (Fig. 4.6)	For cracking control , panel and shoulder interface should be left open
Tining Orientation	Transverse, Longitudinal, Diamond Grind	Longitudinally tined PCC pavements may be preferred over transversely tined ones, since they generate lower levels of tire-pavement noise (Drakopoulos and Kuemmel; 2007)	Significantly lower cracking frequency in 14-ft panels with longitudinal tining compared to transverse and diamond grind tining (Fig. 4.5)	Specify longitudinal tining. It has the additional benefit of providing quieter ride than transverse.
Cut or Fill Section	N/A	Slab movement from grade settlement/frost heave (Halm et al. 1985; Voigt 1992; Voigt 1994).	• Double the occurrence of cracking in fill sections when compared to cut sections. • Cut sections had near-equal severity level of low and medium, while fill sections had a greater occurrence of low severity level compared to medium level.	No change, however, recommend investigating base densification of cut versus fill sections.

5.6 Design Practice to Minimize Cracking Severity and Extent at Pavement Cross-section Locations

One of the critical factors identified to impact cracking extent and/or severity is the crack offset (i.e., transverse location of the crack across the pavement cross-section). Loaded wheel paths, for example, will be expected to show more deterioration compared to non-loaded locations. The crack length and severity by location across the pavement cross-section for the various panels are summarized in Figure 5.2, which show the majority of cracking occurring in wheel paths and at mid-panels compared to edges.

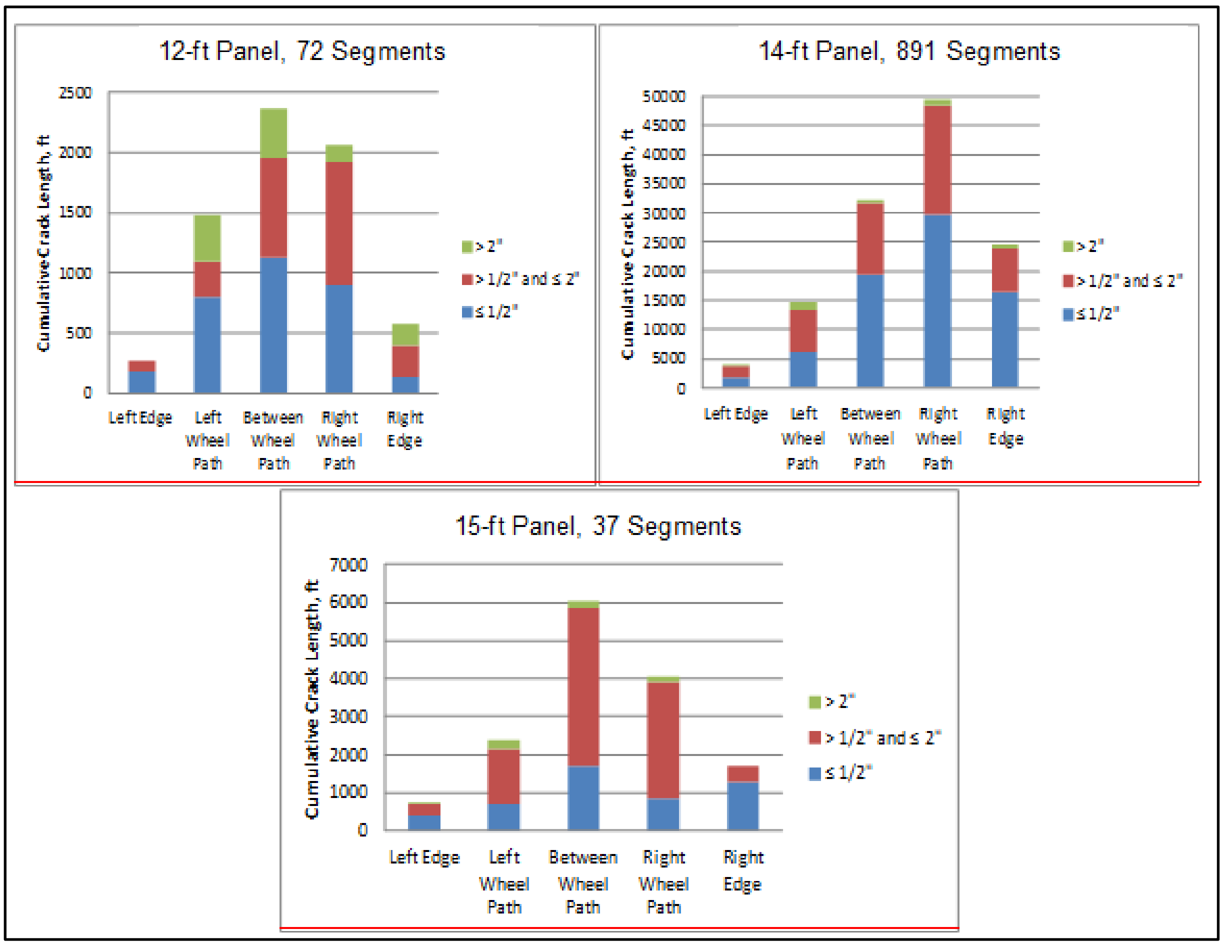


Figure 5.2 Cumulative Length of Longitudinal cracking by location and Panel Width

An understanding of the causes of the cracking at such locations provides a basis for improving design methods to alleviate their impact. This research study was initiated because of the appearance of longitudinal cracking occurring at specific locations including wheel paths and panel edges. Hence, the analysis was extended to examine parameters that need to be controlled for the design objective of minimizing cracking occurrence and/or severity at any of these locations for specific panel widths. Tables 5.4 and 5.5 respectively show summaries of parameters at the 95% significance level that impact crack length and severity for 14-ft and 15-ft panels for various potential crack locations across the pavement.

Table 5.4 Design Factors for 14-ft Wide Panels to Control Cracking by Offset

Variable	Crack Length					Crack Severity				
Potential Crack Location	LE	LWP	BWP	RWP	RE	LE	LWP	BWP	RWP	RE
Sample size, n	84	277	458	955	285	84	277	458	955	285
Mean	42 ft	40 ft	57 ft	42 ft	73 ft	1.7	1.6	1.5	1.5	1.4
Model R^2, %	27%	21%	15%	18%	15%	42%	16%	9%	14%	6%
Thickness, in			x							
Width-to-Thickness			x							
Joint Spacing, ft				x	x		x		x	
Skewed Joints		x		x		x	x	x	x	
Tining										
Rumble Strip	X	x	x	x	x			x	x	
Shoulder Type										
Shoulder Crack Filler		x	x	x			x		x	
Base Gradation		x	x	x					x	
LE = Left Edge; LWP = Left Wheel Path; BWP = Between Wheel Path; RWP = Right Wheel Path; RE = Right Edge.										

Table 5.5 Design Factors for 15-ft Wide Panels to Control Cracking by Offset

Variable	Crack Length					Crack Severity				
Offset Location	LE	LWP	BWP	RWP	RE	LE	LWP	BWP	RWP	RE
Sample size, n	92	310	498	995	315	92	310	498	995	315
Mean	44 ft	43 ft	58 ft	43 ft	71 ft	1.7	1.6	1.5	1.5	1.4
Model R^2, %	33%	22%	14%	20%	15%	39%	14%	8%	14%	6%
Thickness, in									x	
Width-to-Thickness										
Joint Spacing, ft		x	X	X	X		X	X	X	
Skewed Joints		x	X	X	X	x	X		X	
Tining										
Rumble Strip	X	x	X	X	X			X	X	
Shoulder Type							X	X		
Shoulder Crack Filler			X	X			X		X	
Base Gradation		x	X	X					X	
LE = Left Edge; LWP = Left Wheel Path; BWP = Between Wheel Path; RWP = Right Wheel Path; RE = Right Edge.										

The model parameter estimates for the 14-ft and 15-ft panels are shown respectively in Tables 5.6 and 5.7. The model R-squares appear relatively low for both the 14-ft and 15-ft panels. They range from 8-17% for crack length estimates and 3-10% for crack severity for the 14-ft.panel. The 15-ft panel R-squares range from 22-36% for crack length estimates and 19-33% for crack severity estimates. It must, however, be recognized that the focus of the models is on design variables only, which are a component of several factors (traffic, environment, construction, material properties, and maintenance practices) that together can explain overall pavement deterioration.

The models suggest that although relationships exist between crack length or crack severity and the various panel elements, these relationships are less than ideal. They however, validate some standards currently in use by WisDOT. For example, for 14-ft panels, the higher crack extent and severity in the right wheel path (RWP) can potentially be minimized in design by determining the appropriate joint spacing, base material type, the type of rumble strip to install, the type joint (skewed or normal), and whether to install a crack filler at the panel/shoulder interface. Using Table 5.6, the design parameters to potentially yield the minimum crack length and severity will include the use of a 15-ft transverse joint spacing, a normal joint orientation, PCC rumble strip, and open graded base course. The 15-ft transverse spacing and the normal joint orientation are current standards in use by WisDOT.

Table 5.6 Model Parameters for 14-ft Wide Panels

Offset (1)	Parameters (2)	R-squared (3)
Left Edge	Length (ft) = 20.05 + 6.21 (1 None; 0 otherwise) + 27.21 (1 Asphalt Rumble Strip; 0 otherwise) + 0.00 (1 PCC Rumble Strip; 0 otherwise)	13%
	Severity (lower is less) = 1.73 - 0.53 (1 Normal Joint; 0 otherwise) + 0.017 (1 Skewed Joint 1; 0 otherwise)	5%
Left Wheel Path	Length (ft) = 10.55 - 15.43 (1 Normal Joint; 0 otherwise) + 0.00 (1 Skewed Joint 1; 0 otherwise) + 5.65 (1 No Rumble Strip; 0 Otherwise) + 25.12 (1 Asphalt Rumble Strip; 0 Otherwise) + 0.00 (PCC Rumble Strip; 0 Otherwise) + 16.09 (1 No Crack Filler; 0 Otherwise) + 0.00 (1 Yes Crack Filler; 0 Otherwise) + 13.38 (1 Dense Graded Base; 0 Otherwise) + 0.00 (1 Open Graded; 0 Otherwise)	17%
	Severity (lower is less) = 1.53 -0.13 (1 15-ft Joint Spacing; 0 Otherwise) -0.31 (1 Random Joint Spacing; 0 Otherwise) -0.33 (1 18-ft Joint Spacing; 0 Otherwise) +0.00 (1 20-ft Joint Spacing; 0 Otherwise) - 0.23 (1 Normal Joint; 0 otherwise) + 0.00 (1 Skewed Joint 1; 0 otherwise) + 0.39 (1 No Crack Filler; 0 Otherwise) + 0.00 (1 Yes Crack Filler; 0 Otherwise)	10%

Table 5.6 (cont.) Model Parameters for 14-ft Wide Panels

Offset (1)	Parameters (2)	R-squared (3)
Between Wheel Path	Length (ft) = 1395 + 15.22 (1 No Rumble Strip; 0 Otherwise) + 41.78 (1 Asphalt Rumble Strip; 0 Otherwise) + 0.00 (1 PCC Rumble Strip; 0 Otherwise) + 28.14 (1 No Crack Filler; 0 Otherwise) + 0.00 (1 Yes Crack Filler; 0 Otherwise) -69.77 (Thickness in inches) -503.82 (Width-to-Thickness ratio) + 30.16 (1 Dense Graded Base; 0 Otherwise) + 0.00 (1 Open Graded Base; 0 Otherwise)	14%
	Severity (lower is less) = 1.65 - 0.12 (1 Normal Joint; 0 otherwise) + 0.00 (1 Skewed Joint 1; 0 otherwise) - 0.13 (1 No Rumble Strip; 0 Otherwise) - 0.25 (1 Asphalt Rumble Strip; 0 Otherwise) + 0.00 (1 PCC Rumble Strip; 0 Otherwise)	3%
Right Wheel Path	Length (ft) = 12.91 -7.28 (1 15-ft Joint Spacing; 0 Otherwise) +2.94 (1 Random Joint Spacing; 0 Otherwise) +7.09 (1 18-ft Joint Spacing; 0 Otherwise) +0.00 (1 20-ft Joint Spacing; 0 Otherwise) - 18.72 (1 Normal Joint; 0 otherwise) + 0.00 (1 Skewed Joint 1; 0 otherwise) + 10.52 (1 No Rumble Strip; 0 Otherwise) + 28.45 (1 Asphalt Rumble Strip; 0 Otherwise) + 0.00 (1 PCC Rumble Strip; 0 Otherwise) + 10.14 (1 No Crack Filler; 0 Otherwise) + 0.00 (1 Yes Crack Filler; 0 Otherwise) + 19.34 (1 Dense Graded Base; 0 Otherwise) + 0.00 (1 Open Graded Base; 0 Otherwise)	14%

Table 5.6 (cont.) Model Parameters for 14-ft Wide Panels

Offset (1)	Parameters (2)	R-squared (3)
Right Wheel Path	Severity (lower is less) = 1.41 -0.23 (1 15-ft Joint Spacing; 0 Otherwise) +0.02 (1 Random Joint Spacing; 0 Otherwise) -0.24 (1 18-ft Joint Spacing; 0 Otherwise) +0.00 (1 20-ft Joint Spacing; 0 Otherwise) - 0.13 (1 Normal Joint; 0 otherwise) + 0.00 (1 Skewed Joint 1; 0 otherwise) + 0.16 (1 No Rumble Strip; 0 Otherwise) + 0.03 (1 Asphalt Rumble Strip; 0 Otherwise) + 0.00 (1 PCC Rumble Strip; 0 Otherwise) + 0.19 (1 No Crack Filler; 0 Otherwise) + 0.00 (1 Yes Crack Filler; 0 Otherwise) + 0.05 (1 Dense Graded Base; 0 Otherwise) + 0.00 (1 Open Graded Base; 0 Otherwise)	10%
Right Edge	Length (ft) = 60.38 -42.21 (1 15-ft Joint Spacing; 0 Otherwise) -35.25 (1 Random Joint Spacing; 0 Otherwise) -14.96 (1 18-ft Joint Spacing; 0 Otherwise) +0.00 (1 20-ft Joint Spacing; 0 Otherwise) + 15.52 (1 No Rumble Strip; 0 Otherwise) + 50.43 (1 Asphalt Rumble Strip; 0 Otherwise) + 0.00 (1 PCC Rumble Strip; 0 Otherwise)	8%

Table 5.7 Model Parameters for 15-ft Wide Panels

Offset (1)	Parameters (2)	R-squared (3)
Left Edge	Length (ft) = 27.0 + 40.1 (1 None; 0 otherwise) + 0.00 (1 Asphalt Rumble Strip; 0 otherwise) + 0.00 (1 PCC Rumble Strip; 0 otherwise) Severity (lower is less) = 1.58 + 1.42 (1 Normal Joint; 0 otherwise) + 0.00 (1 Skewed Joint 1; 0 otherwise)	30% 27%
Left Wheel Path	Length (ft) = 76.92 -37.92 (1 15-ft Joint Spacing; 0 Otherwise) +43.25 (1 Random Joint Spacing; 0 Otherwise) +0.00 (1 18-ft Joint Spacing; 0 Otherwise) - 29.43 (1 Normal Joint; 0 otherwise) + 0.00 (1 Skewed Joint 1; 0 otherwise) + 8.33 (1 No Rumble Strip; 0 Otherwise) + 0.00 (1 PCC Rumble Strip; 0 Otherwise) - 3.50 (1 Dense Graded Base; 0 Otherwise) + 0.00 (1 Open Graded; 0 Otherwise) Severity (lower is less) = 1.69 -0.77 (1 15-ft Joint Spacing; 0 Otherwise) -0.67 (1 Random Joint Spacing; 0 Otherwise) +0.00 (1 18-ft Joint Spacing; 0 Otherwise) + 0.20 (1 Normal Joint; 0 otherwise) + 0.00 (1 Skewed Joint 1; 0 otherwise) + 0.89 (1 Asphalt Shoulder; 0 Otherwise) + 0.94 (1 PCC Shoulder; 0 Otherwise) + 0.00 (1 CABC Shoulder; 0 Otherwise)	36% 19%
Between Wheel Path	Length (ft) = 104 -20.74 (1 15-ft Joint Spacing; 0 Otherwise) +60.00 (1 Random Joint Spacing; 0 Otherwise) +25.29 (1 18-ft Joint Spacing; 0 Otherwise) +0.00 (1 20-ft Joint Spacing; 0 Otherwise) - 45.77 (1 Normal Joint; 0 otherwise) + 0.00 (1 Skewed Joint 1; 0 otherwise) + 22.50 (1 No Rumble Strip; 0 Otherwise) + 8.24 (Asphalt Rumble Strip; 0 Otherwise) + 0.00 (PCC Rumble Strip; 0 Otherwise) - 76.24 (1 Dense Graded Base; 0 Otherwise) + 0.00 (1 Open Graded Base; 0 Otherwise)	27%

Table 5.7 (cont.) Model Parameters for 15-ft Wide Panels

Offset (1)	Parameters (2)	R-squared (3)
Between Wheel Path	Severity (lower is less) = 0.89 +0.46 (1 15-ft Joint Spacing; 0 Otherwise) +0.36 (1 Random Joint Spacing; 0 Otherwise) +0.51 (1 18-ft Joint Spacing; 0 Otherwise) +0.00 (1 20-ft Joint Spacing; 0 Otherwise) + 0.25 (1 No Rumble Strip; 0 Otherwise) - 0.99 (1 Asphalt Rumble Strip; 0 Otherwise) + 0.00 (PCC Rumble Strip; 0 Otherwise) + 0.64 (1 Asphalt Shoulder; 0 Otherwise) - 0.15 (1 PCC Shoulder; 0 Otherwise) + 0.00 (1 CABC Shoulder; 0 Otherwise)	27%
Right Wheel Path	Length (ft) = 8.67 + 2.33 (1 15-ft Joint Spacing; 0 Otherwise) +36.49 (1 Random Joint Spacing; 0 Otherwise) +53.16 (1 18-ft Joint Spacing; 0 Otherwise) +0.00 (1 20-ft Joint Spacing; 0 Otherwise) - 52.77 (1 Normal Joint; 0 otherwise) + 0.00 (1 Skewed Joint 1; 0 otherwise) + 10.71 (1 No Rumble Strip; 0 Otherwise) - 3.73 (1 Asphalt Rumble Strip; 0 Otherwise) + 0.00 (1 PCC Rumble Strip; 0 Otherwise) + 19.84 (1 Dense Graded Base; 0 Otherwise) + 0.00 (1 Open Graded Base; 0 Otherwise)	22%
	Severity (lower is less) = 2.13 -0.13 (1 15-ft Joint Spacing; 0 Otherwise) +0.09 (1 Random Joint Spacing; 0 Otherwise) -0.26 (1 18-ft Joint Spacing; 0 Otherwise) +0.00 (1 20-ft Joint Spacing; 0 Otherwise) - 0.70 (1 Normal Joint; 0 otherwise) + 0.00 (1 Skewed Joint 1; 0 otherwise) + 1.00 (1 No Rumble Strip; 0 Otherwise) + 1.17 (1 Asphalt Rumble Strip; 0 Otherwise) + 0.00 (1 PCC Rumble Strip; 0 Otherwise) - 1.22 (1 Dense Graded Base; 0 Otherwise) + 0.00 (1 Open Graded Base; 0 Otherwise)	33%

Table 5.7 (cont.) Model Parameters for 15-ft Wide Panels

Offset (1)	Parameters (2)	R-squared (3)
Right Edge	Length (ft) = 75.0 -31.91 (1 15-ft Joint Spacing; 0 Otherwise) -25.00 (1 Random Joint Spacing; 0 Otherwise) -10.01 (1 18-ft Joint Spacing; 0 Otherwise) +0.00 (1 20-ft Joint Spacing; 0 Otherwise) - 37.72 (1 Normal Joint; 0 otherwise) + 0.00 (1 Skewed Joint 1; 0 otherwise) + 15.52 (1 No Rumble Strip; 0 Otherwise) + 50.43 (1 Asphalt Rumble Strip; 0 Otherwise) + 0.00 (1 PCC Rumble Strip; 0 Otherwise)	31%

Tables 5.8 and 5.9 provide respective summaries of recommended potential design factors that can be implemented to reduce cracking extent and/or severity for 14-ft and 15-ft panels at all cross-section locations. With the exception of the left edge (LE), cracking extent at all transverse locations for the 14-ft panel can be reduced through the use of 15-ft joint spacing in conjunction with normal joint application, PCC rumble strip installation, and open graded base. However, for mid-panel cracking, the width-to-thickness ratio is another factor to consider. Normal joint application will minimize severity at LWP, BWP, and RWP locations for 14-ft panels.

For 15-ft panels (Table 5.9), crack extent reduction at LWP, BWP, RWP, and RE locations can be achieved through the use of 15-ft joint spacing in conjunction with normal joint application, and PCC rumble installation. Dense-graded bases will be beneficial to control cracking extent at LWP and BWP locations. If RWP cracking is of concern, then the use of open-graded base may be more appropriate.

Table 5.8 Recommended Design Parameters for 14-ft Panels to Address Cracking Occurrence at Targeted Pavement Cross-section Locations

Potential Crack Location (1)	Potential design factors to minimize *crack length* at location (2)	Basis for recommendation (3)	Potential design factors to minimize *crack severity* at location (4)	Basis for recommendation (5)
Left Edge (LE)	No significant model parameters	N/A	No significant model parameters	N/A
Left Wheel Path (LWP)	• Normal joint • PCC rumble strip installation • Open graded base	Tables 5.4, 5.6	• Normal joint	Tables 5.4, 5.6
Between Wheel Paths (BWP)	• Width-to-thickness ratio • PCC rumble strip install • Open graded base	Tables 5.4, 5.6	• Normal joint • PCC shoulder and rumble strip	Tables 5.4, 5.6
Right Wheel Path (RWP)	• 15-ft transverse joint spacing • Normal joint • PCC rumble strip • Open graded base course	Tables 5.4, 5.6	• 15-ft transverse joint spacing • Normal joint • PCC rumble strip • Open graded base course	Tables 5.4, 5.6
Right Edge (RE)	• 15-ft transverse joint spacing PCC rumble strip installation	Tables 5.4, 5.6	No significant model parameters	N/A

Table 5.9 Recommended Design Parameters for 15-ft Panels to Address Cracking Occurrence at Targeted Pavement Cross-section Locations

Potential Crack Location (1)	Potential design factors to minimize crack length at location (2)	Basis for recommendation (3)	Potential design factors to minimize crack severity at location (4)	Basis for recommendation (5)
Left Edge (LE)	No significant model parameters	N/A	No significant model parameters	N/A
Left Wheel Path (LWP)	• Normal joint • 15-ft joint spacing • PCC rumble strip install • Dense graded base	Tables 5.5, 5.7	• 15-ft joint spacing	Tables 5.5, 5.7
Between Wheel Paths (BWP)	• Normal joint • 15-ft joint spacing • PCC rumble strip installation • Dense graded base	Tables 5.5, 5.7	• Random joint spacing • PCC rumble strip installation • PCC shoulders	Tables 5.5, 5.7
Right Wheel Path (RWP)	• 15-ft transverse joint spacing • Normal joint • PCC rumble strip • Open graded base course	Tables 5.5, 5.7	• 15-ft transverse joint spacing • Normal joint • PCC rumble strip • Dense graded base course	Tables 5.5, 5.7
Right Edge (RE)	• 15-ft transverse joint spacing • PCC rumble strip • Normal joint	Tables 5.5, 5.7	No significant model parameters	N/A

5.7 Life Cycle Cost Analysis

Existing WisDOT design practice, as well as recommended changes to existing practices, must be made in the context of life cycle cost. For that purpose, a life cycle cost analysis (LCCA) was performed to quantify the costs and benefits associated with each panel width over its life cycle.

5.7.1 Pavement Cross-Section for LCCA

For any given JPCP structural thickness determined from design, the LCCA comparative analysis will be dictated by costs associated with the panel widths. The developed database showed pavement thicknesses of 9 in and 10 in to be associated with both the 12-ft and 15-ft panels, while thickness in the range of 9 to 12 in dominated the 14-ft panel. Hence, the analysis evaluated the prescribed thickness values in terms of width-to-thickness (w/t) ratio and related costs. The three panel alternatives are shown in Figure 5.3. Each mainline is assumed to be paved over 6-in of 3/4-in dense aggregate base per WisDOT minimum base standard under concrete pavement. Adjoining paved shoulders consist of minimum 3.5-in HMA thickness consistent with WisDOT minimum design thickness for HMA shoulders.

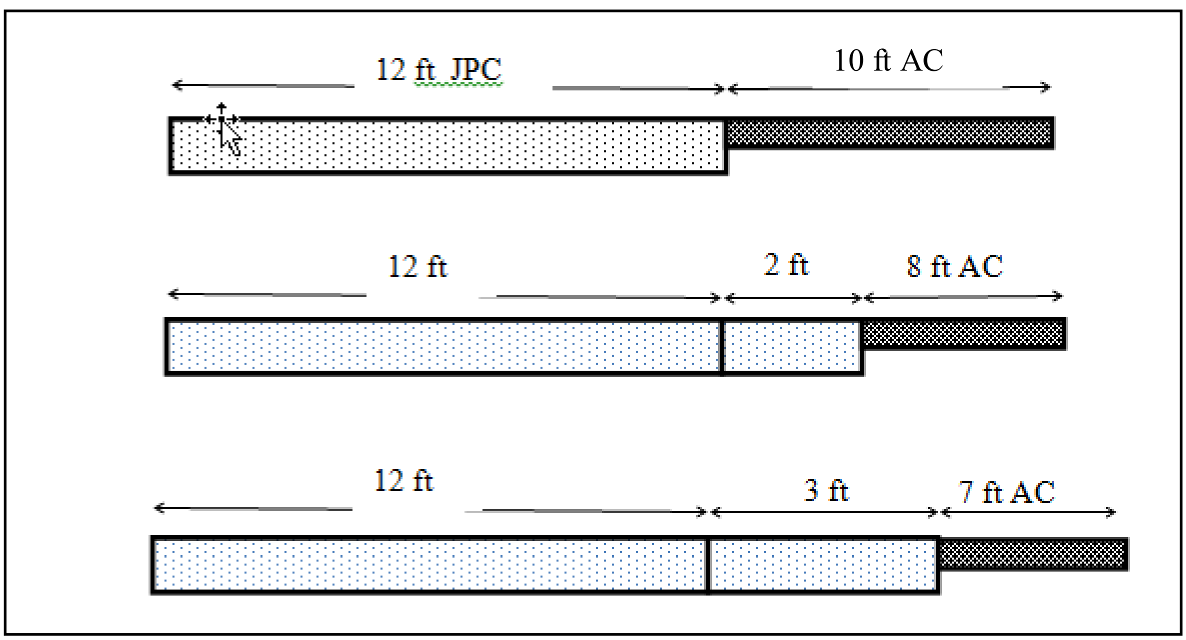


Figure 5.3 Panel Width Cross-section Alternatives for Life Cycle Cost

5.7.2 Life Cycle Sequence for Panel Width Alternatives

LCCA requires knowledge of the timing for maintenance and rehabilitation intervention for each pavement option. A series of simplified time and traffic dependent models focusing on severity were examined to determine the time/traffic element for the LCCA. The assumption was that for the average segment length of 1.14 mi analyzed in this study, crack severity will be the determining factor for maintenance and/or rehabilitation intervention. The models were tailored to the location of the crack with respect to the pavement cross-section. Only the critical models based on adjusted coefficient of determination are reported in Table 5.10 for the various panel widths and assumed in the LCCA. The 15-ft panel model makes use of two steps, first determining the truck traffic level to reach one of three crack severity levels (1, 2, 3) and then using the truck traffic information to estimate the time when that severity level will be reached. The limitation to this model is that it can be applied to severity levels 2 and 3 only. In addition, it appears to be the weakest model when compared to the 12-ft and 14-ft panel models on the basis of the coefficient of determination (R^2).

Table 5.10 Life Cycle Cost Related Models

Panel Width	Location Modeled	Applicable Severity Model	Model Statistics	Age to reach Severity Level, years		
				Level 1	Level 2	Level 3
12 ft	Left Edge	Severity = 0.799747 + 0.00179218*Age^2	R^2=43.1%; p=0.0047; n=15	11	26	35
14 ft	Left Edge	$Severity = \left(0.393908 * \sqrt{T}\right)^2$ $T = 1 + \left(\frac{Age^{2.258} - 1}{79.2584}\right)$	R^2=93.4%; p=0.0001; n=106	15	21	25
15 ft	Between Wheel Paths	$AADTT = \frac{1}{-0.0008540 + \frac{0.057929}{Age}}$ $Severity = \sqrt{2.45563 + 3.39075 * 10^{-7} * AADTT^2}$	R^2=40.4%; p=0.0000; n=60 R^2=17.5%; p=0.0008; n=60	-	44	54

In addition to Table 5.10, existing WisDOT guidelines for PCC maintenance and rehabilitation were reviewed to develop a life cycle sequence for each alternative. Table 5.11 shows initial and rehabilitation service lives for concrete pavements as reported in Chapter 14 of the WisDOT Facilities Development Manual (FDM). The FDM suggests that the initial service lives for drained pavement structures are estimates that add 25 percent more life onto like undrained pavement structures.

The model service life estimates for severity level 2 for the 12-ft panel and severity level 3 for the 14-ft panel in Table 5.10 appear to coincide with the WisDOT service life value of 25 years for non-drained concrete, while estimates for the 15-ft panel appear significantly higher (1.8-2.4 times the WisDOT value for non-drained concrete). It requires 11 and 15 years for low severity cracks (≤1/2 in wide) to develop in the 12-ft and 14-ft panels, respectively.

To build a uniform, consistent, repeatable and defensible LCCA, the FDM provides the most probable sequence of rehabilitation scenarios and standard sequences based upon the best knowledge to-date. The scenarios and sequences are shown in Table 5.12. In addition, a one-time maintenance cost guide is provided by WisDOT and reported in Table 5.13.

Table 5.11 Initial and Rehabilitation Service Lives (Adapted from WisDOT 2012a)

	Initial Construction	Service life (years)
Initial Service Life	Concrete	25
	Concrete (drained)	31
	Concrete over Rubblized Concrete	31
Rehabilitation Service Life	HMA over JPCP	15
	Concrete Grind	8
	Concrete pavement repair and grind	8

Table 5.12 Rehabilitation Sequence Options (Adapted from WisDOT 2012a)

Scenario (1)	Rehabilitation Options (2)
Initial Construction (Concrete Pavement over granular base)	
First Rehabilitation (Functional Repair)	Concrete Pavement Repair and Grind or Concrete Partial Depth Repair or Concrete Pavement Repair and HMA Overlay
Second Rehabilitation (Functional or Structural Repair)	Concrete Pavement Repair and Grind or Concrete Pavement Repair and HMA Overlay
Third Rehabilitation (Functional or Structural Repair)	Concrete Pavement Repair and HMA Overlay or HMA Mill, Concrete Pavement Repair and HMA Overlay or Concrete Pavement Repair and Concrete Overlay
Reconstruction	Pavement Removal and Pavement Reconstruction or Concrete Rubblization and Pavement Reconstruction

Table 5.13 Maintenance Cost (Adapted from WisDOT 2012a)

Pavement Surface Type	Pavement Surface Age (yrs)	One time cost per lane mile
Concrete	10-15	\$2,000
Concrete	15-Surface Rehab	\$4,000
HMA	3-5	\$1,000
HMA	5-Surface Rehab	\$1,250

The life cycle sequences for all panel alternatives are summarized in Figures 5.4 through 5.6 for an analysis period of 50 years, which is the standard used by WisDOT for mainline pavements. The 12-ft panel will experience two major rehabilitation activities involving concrete repair and diamond grind in year 26 and repair plus a 2-in overlay in year 35. Overlay thickness is generally determined as part of design based on traffic loading, subgrade, and performance inputs. It was assumed in this analysis that the overlay would be used to correct surface deterioration or functional deficiency and therefore requires minimum thickness. The 2-in overlay on the mainline pavement will require a 2-in HMA overlay of the shoulder to compensate for the elevation change between the newly surfaced mainline and the existing shoulder. Four maintenance events will occur at years 11, 18, 39, and 45.

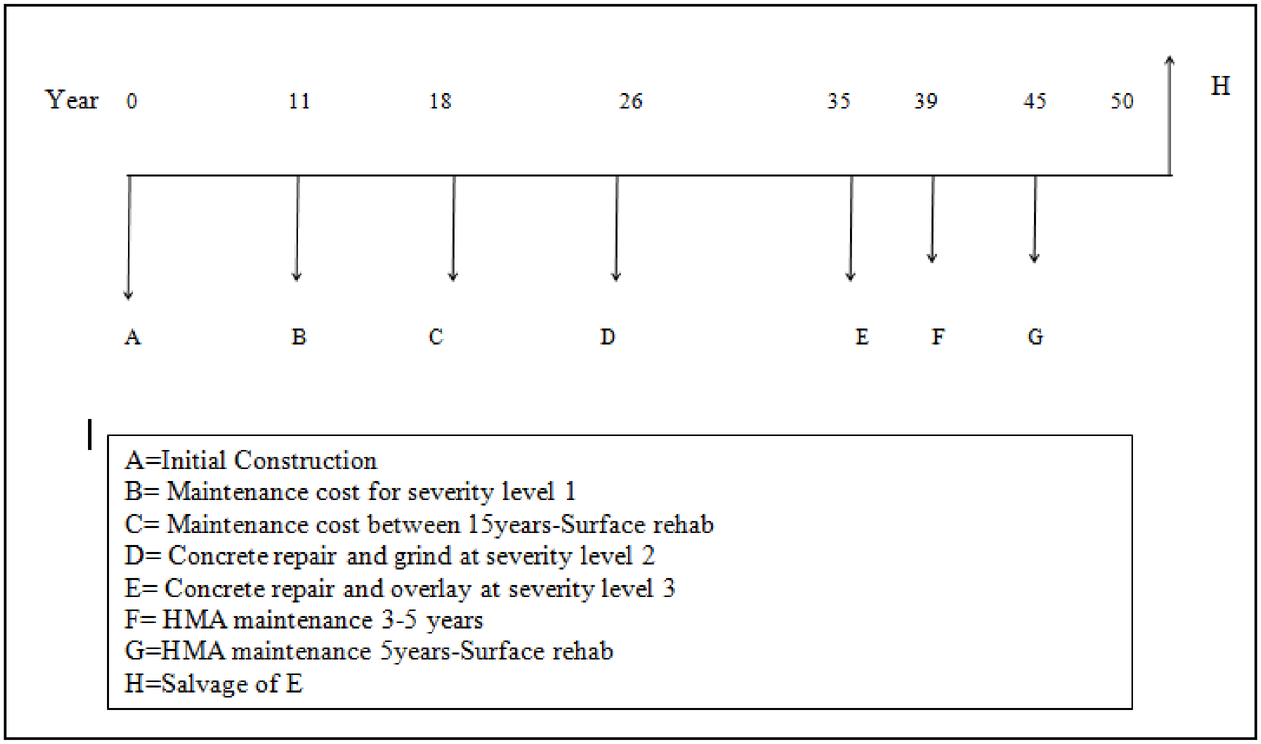


Figure 5.4 Life Cycle Sequence for 12-ft Panel

The 14-ft panel (Figure 5.5) will undergo three major rehabilitation activities during the 50-year analysis period. Two concrete repair and grind cycles will be applied during years 25 and 33, each with an 8-year service life. The last repair and grind activity will be followed by concrete repair and placement of a 2-in overlay in year 41, which has a service life of 15 years. Three maintenance events will occur at years, 15, 21, and 45.

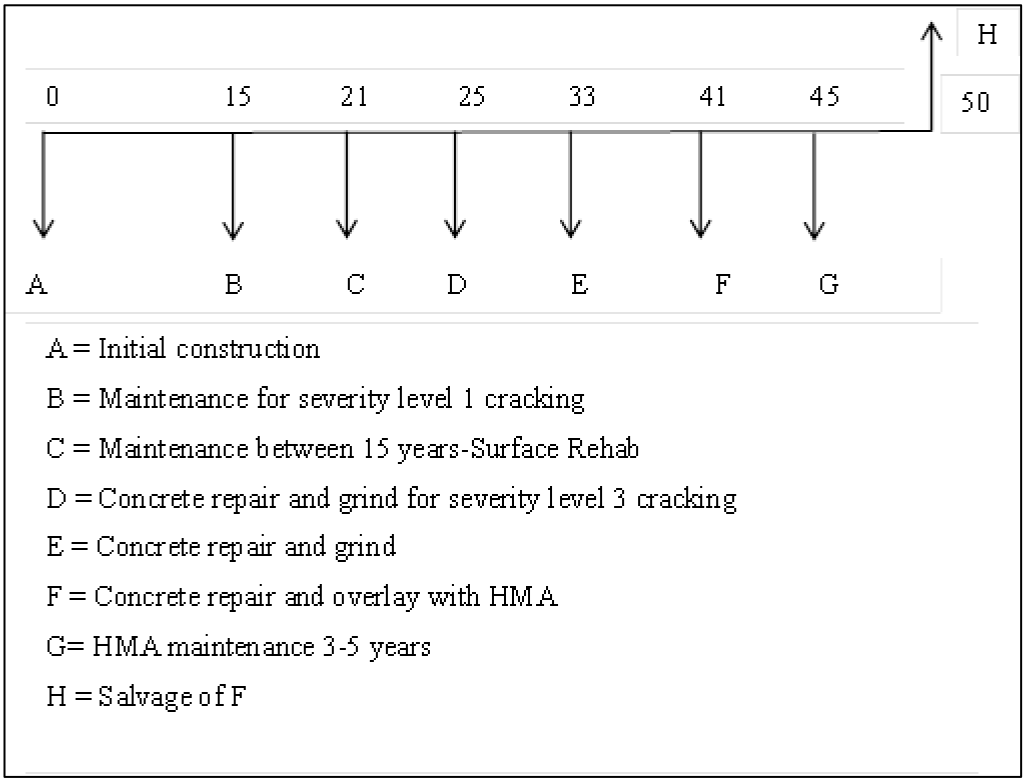


Figure 5.5 Life Cycle Sequence for 14-ft Panel

The 15-ft panel will experience three rehabilitation events involving two repair and grind at years 25 and 33, and repair plus a 2-inch overlay in year 41. Three maintenance events will occur in years 12, and 18 with the last occurring at year 44 to address maintenance at crack severity level 2.

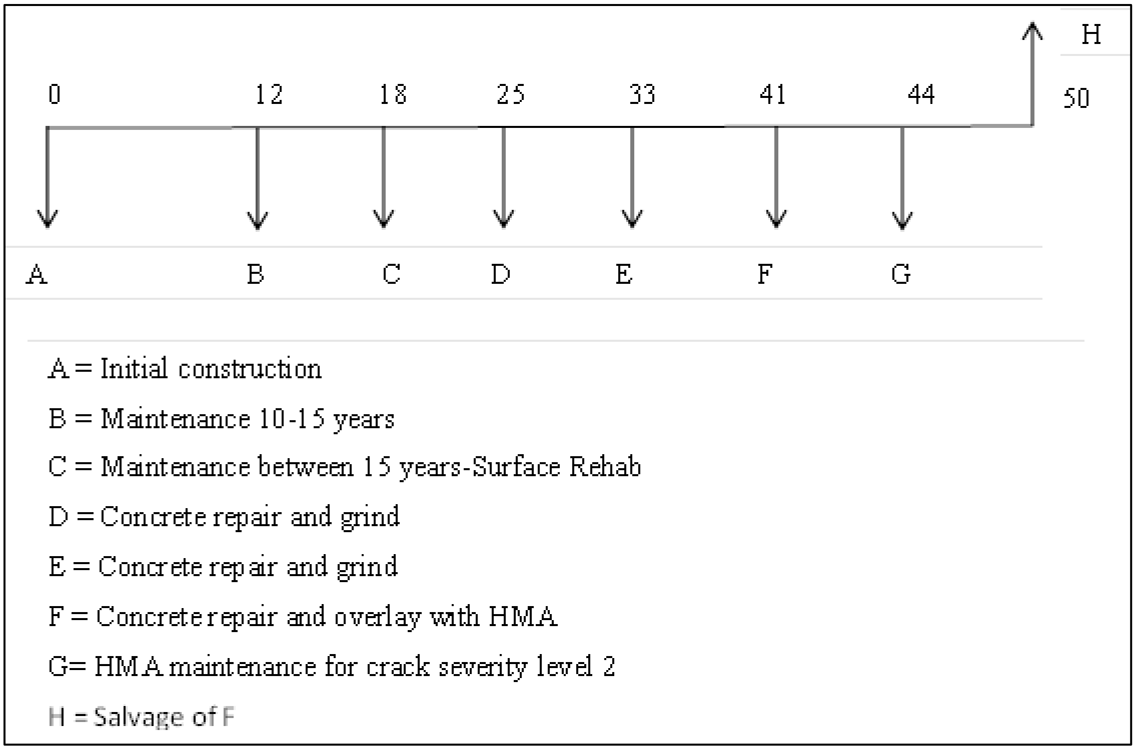


Figure 5.6 Life Cycle Sequence for 15-ft Panel

5.7.3 Cost Data

A life cycle cost analysis (LCCA) is only as valid as the data used; therefore, it is crucial that data used for the completion of LCCA are accurate and current. Designers generally use tools such as "Estimator" and/or "Bid Express" to gather bid prices for similar project types in a similar geographic region. The bid prices include direct construction costs from the material, labor, and equipment, plus indirect costs from job overhead (temporary facilities, supervision, etc.), general and administrative expenses of the company (main office expenses, legal, etc.), bonds, and profit. The use of statewide average bid prices for LCCA such as WisDOT's average unit prices published at the end of each fiscal year is however, discouraged because the results of the LCCA can be misleading when these average prices are used. Allard and McMullen (2013) argue that the statewide averages do not consider relevant factors such as project size and location, complexity of project, and month of project letting. The authors agree with this assessment. For example, a large 10-in PCC project in an urban area, within existing right of way, adjacent to a concrete plant early in the year could very well cost less than a small 9-in PCC project in a rural community where material prices are higher, hauling is more lengthy, and the project is bid late in the year. Hence, a weighted average price approach that recognizes bid price components and project size may be more appropriate.

To achieve the objectives of the LCCA, the costs of all major pay items associated with PCC pavements over a life-cycle had to be collected. The original cost data were obtained from the Bid Express system through the Wisconsin Concrete Pavement Association. The prices originated from the bid tabs for the projects let from January 2010 to May 2013 from several locations around the state. The data included bid prices and project size for 9-in and 11-in concrete pavements, base aggregate, continuous diamond grinding, concrete pavement repair, removing asphalt surface milling, tack coat, HMA pavement types E-3 and E-10. The 9-in concrete pavement was the most commonly bid pavement thickness; hence it was used as the basis for all concrete pavement pricing. Prices for thicker pavements were adjusted based upon the material cost difference only; installation was excluded since this base cost would be expected to be similar for different thicknesses. Thus, all other costs relating to equipment, labor, overhead, profit, etc. were considered constant in the analysis to better compare the material costs associated with the different pavement thicknesses. The price range for the 9-in concrete was \$18/SY for a job size of 238,780 SY to \$90/SY for a job size of 10 SY. The average price per SY without regard to project size was \$34.10, while the weighted average price was \$25.21. Using the \$25.21 as the base price for the 9-in concrete pavement, adjusted costs for thicker pavements were established using a concrete material cost of \$90/CY which translates to \$2.50/SY-in. Table 5.14 provides the relevant prices used for the LCCA.

Table 5.14 Input Cost Values for Life-Cycle Cost Analysis

Description	Unit	Price
CONCRETE PAVEMENT 9-INCH	SY	\$ 25.21
CONCRETE PAVEMENT 10-INCH	SY	\$ 27.71
CONCRETE PAVEMENT 11-INCH	SY	\$ 30.21
CONCRETE PAVEMENT 12-INCH	SY	\$ 32.71
CONC PVMT CONTINUOUS DIAMOND GRINDING	SY	\$ 3.21
CONCRETE PAVEMENT REPAIR	SY	\$ 69.41
REMOVING ASPHALTIC SURFACE MILLING	SY	\$ 1.30
TACK COAT	GAL	\$ 3.00
HMA PAVEMENT TYPE E-3	TON	\$ 46.89
HMA PAVEMENT TYPE E-10	TON	\$ 53.96
BASE AGGREGATE DENSE 3/4-INCH	TON	\$ 12.64

Tables 5.15 through 5.17 provide respective cost estimates for the three panel alternatives for prescribed pavement thicknesses. Detailed estimates are provided so all costs are traceable.

Table 5.16 Cost Estimate for 12-ft Panel Configuration

Cost Index	Description	$/1.14mile Average Study Segment
A	• 10-inch PCC,$27.71/SY*1SY/9SF*12ft*5280ft/mi*1.14mi • Base aggregate mainline,$12.64/ton*1ton/2000lb*115-lb/SY/in*6in*1SY/9SF*12ft*5280ft/mi*1.14mi • 3.5-inch E-3 AC shoulder,$46.89/ton*1ton/2000lb*110-lb/SY/in*3.5in*1SY/9SF*10ft*5280ft/mi*1.14mi • Tack coatshoulder,$3.00/gal*0.025gal/SY*1SY/9SF*10ft*5280ft/mi*1.14mi*2 layers • Base aggregate under shoulder,$12.64/ton*1ton/2000lb*115-lb/SY/in*12.5 in*1SY/9SF*10ft*5280ft/mi*1.14mi • 9-inch PCC,$25.21/SY*1SY/9SF*12ft*5280ft/mi*1.14mi • Base aggregate mainline,$12.64/ton*1ton/2000lb*115-lb/SY/in*6in*1SY/9SF*12ft*5280ft/mi*1.14mi • 3.5-inch E-3 AC shoulder,$46.89/ton*1ton/2000lb*110-lb/SY/in*3.5in*1SY/9SF*10ft*5280ft/mi*1.14mi • Tack coat shoulder,$3.00/gal*0.025gal/SY*1SY/9SF*10ft*5280ft/mi*1.14mi*2 layers • Base aggregate under shoulder,$12.64/ton*1ton/2000lb*115-lb/SY/in*11.5 in*1SY/9SF*10ft*5280ft/mi*1.14mi	222,389 34,998 60,368 1,003 60,760 **∑=379,518** 202,325 34,998 60,368 1,003 55,900 **∑=354,594**
B	Maintenance at $2000/lane mile*1.14mile	2,280
C	Maintenance at $4000/lane mile*1.14mile	4,560
D	• Concrete repair,$69.41/SY*1SY/9SF*12ft*5280ft/mi*1.14mi • Concrete continuous diamond grinding, $3.21/SY*1SY/9SF*12ft*5280ft/mi*1.14mi	557,057 25,762 **∑=582,819**
E	• Concrete repair,$69.41/SY*1SY/9SF*12ft*5280ft/mi*1.14mi • 2.0-inch HMA PAVEMENT TYPE E-10 overlay, $53.96/ton*1ton/2000lb*110-lb/SY/in*2.0in*1SY/9SF*12ft*5280ft/mi*1.14mi • Tack coat for overlay mainline, $3.00/gal*0.025gal/SY*1SY/9SF*12ft*5280ft/mi*1.14mi*2 layers • 2.0-inch E-3 AC shoulder,$46.89/ton*1ton/2000lb*110-lb/SY/in*2.0in*1SY/9SF*10ft*5280ft/mi*1.14mi • Tack coat shoulder,$3.00/gal*0.025gal/SY*1SY/9SF*10ft*5280ft/mi*1.14mi*2 layers	557,057 47,637 1,204 34,496 1003 **∑=641,397**
F	HMA overlay maintenance, $1000/lane-mile*1.14mi	1,140
G	HMA overlay maintenance,$1250/lane-mile*1.14mi	1,425
H	Salvage of E	0

Table 5.16 Cost Estimate for 14-ft Panel Configuration

Cost Index	Description	$/1.14mile average study segment
A	• 10-inch PCC,$27.71/SY*1SY/9SF*14ft*5280ft/mi*1.14mi • Base aggregate mainline,$12.64/ton*1ton/2000lb*115-lb/SY/in*6in*1SY/9SF*14ft*5280ft/mi*1.14mi • 3.5-inch E-3 AC shoulder,$46.89/ton*1ton/2000lb*110-lb/SY/in*3.5in*1SY/9SF*8ft*5280ft/mi*1.14mi • Tack coat shoulder,$3.00/gal*0.025gal/SY*1SY/9SF*8ft*5280ft/mi*1.14mi*2 layers • Base aggregate under shoulder,$12.64/ton*1ton/2000lb*115-lb/SY/in*12.5 in*1SY/9SF*8ft*5280ft/mi*1.14mi	259,454 40,831 48,294 803 48,608 **∑=397,990**
	• 11-inch PCC,$30.21/SY*1SY/9SF*14ft*5280ft/mi*1.14mi • Base aggregate mainline,$12.64/ton*1ton/2000lb*115-lb/SY/in*6in*1SY/9SF*14ft*5280ft/mi*1.14mi • 3.5-inch E-3 AC shoulder,$46.89/ton*1ton/2000lb*110-lb/SY/in*3.5in*1SY/9SF*8ft*5280ft/mi*1.14mi • Tack coat shoulder,$3.00/gal*0.025gal/SY*1SY/9SF*8ft*5280ft/mi*1.14mi*2 layers • Base aggregate under shoulder,$12.64/ton*1ton/2000lb*115-lb/SY/in*13.5 in*1SY/9SF*8ft*5280ft/mi*1.14mi	282,862 40,831 48,294 803 52,497 **∑=425,287**
	• 12-inch PCC,$32.71/SY*1SY/9SF*14ft*5280ft/mi*1.14mi • Base aggregate mainline,$12.64/ton*1ton/2000lb*115-lb/SY/in*6in*1SY/9SF*14ft*5280ft/mi*1.14mi • 3.5-inch E-3 AC shoulder,$46.89/ton*1ton/2000lb*110-lb/SY/in*3.5in*1SY/9SF*8ft*5280ft/mi*1.14mi • Tack coat shoulder,$3.00/gal*0.025gal/SY*1SY/9SF*8ft*5280ft/mi*1.14mi*2 layers • Base aggregate under shoulder,$12.64/ton*1ton/2000lb*115-lb/SY/in*14.5 in*1SY/9SF*8ft*5280ft/mi*1.14mi	306,270 40,831 48,294 803 56,386 **∑=452584**
	• 9-inch PCC,$25.21/SY*1SY/9SF*14ft*5280ft/mi*1.14mi • Base aggregate mainline,$12.64/ton*1ton/2000lb*115-lb/SY/in*6in*1SY/9SF*14ft*5280ft/mi*1.14mi • 3.5-inch E-3 AC shoulder,$46.89/ton*1ton/2000lb*110-lb/SY/in*3.5in*1SY/9SF*8ft*5280ft/mi*1.14mi • Tack coat shoulder,$3.00/gal*0.025gal/SY*1SY/9SF*8ft*5280ft/mi*1.14mi*2 layers • Base aggregate under shoulder,$12.64/ton*1ton/2000lb*115-lb/SY/in*11.5 in*1SY/9SF*8ft*5280ft/mi*1.14mi	236,046 40,831 48,294 803 44,720 **∑=370,694**

Table 5.16 (cont.) Cost Estimate for 14-ft Panel Configuration

Cost Index	Description	$/1.14mile average study segment
B	Maintenance at $2000/lane mile*1.14mile	2,280
C	Maintenance at $4000/lane mile*1.14mile	4,560
D	• Concrete repair,$69.41/SY*1SY/9SF*14ft*5280ft/mi*1.14mi • Concrete continuous diamond grinding, $3.21/SY*1SY/9SF*14ft*5280ft/mi*1.14mi	649,900 30,056 **∑=679,956**
E	• Concrete repair,$69.41/SY*1SY/9SF*14ft*5280ft/mi*1.14mi • Concrete continuous diamond grinding, $3.21/SY*1SY/9SF*14ft*5280ft/mi*1.14mi	649,900 30,056 **∑=679,956**
F	• Concrete repair,$69.41/SY*1SY/9SF*14ft*5280ft/mi*1.14mi • 2.0-inch HMA PAVEMENT TYPE E-10 overlay, $53.96/ton*1ton/2000lb*110-lb/SY/in*2.0in*1SY/9SF*14ft*5280ft/mi*1.14mi • Tack coat for overlay mainline, $3.00/gal*0.025gal/SY*1SY/9SF*14ft*5280ft/mi*1.14mi*2 layers • 2.0-inch E-3 AC shoulder,$46.89/ton*1ton/2000lb*110-lb/SY/in*2.0in*1SY/9SF*8ft*5280ft/mi*1.14mi • Tack coat shoulder,$3.00/gal*0.025gal/SY*1SY/9SF*8ft*5280ft/mi*1.14mi*2 layers	649,900 55,576 1,404 27,597 803 **∑=735,280**
G	HMA overlay maintenance, $1000/lane-mile*1.14mi	1,140
H	Salvage of F= 6/15*(735,280)	294,112

Table 5.17 Cost Estimate for 15-ft Panel Configuration

Cost Index	Description	$/1.14mile average study segment
A	• 10-inch PCC,$27.71/SY*1SY/9SF*15ft*5280ft/mi*1.14mi • Base aggregate mainline,$12.64/ton*1ton/2000lb*115-lb/SY/in*6in*1SY/9SF*15ft*5280ft/mi*1.14mi • 3.5-inch E-3 AC shoulder,$46.89/ton*1ton/2000lb*110-lb/SY/in*3.5in*1SY/9SF*7ft*5280ft/mi*1.14mi • Tack coat shoulder,$3.00/gal*0.025gal/SY*1SY/9SF*7ft*5280ft/mi*1.14mi*2 layers • Base aggregate under shoulder,$12.64/ton*1ton/2000lb*115-lb/SY/in*12.5 in*1SY/9SF*7ft*5280ft/mi*1.14mi • 9-inch PCC,$25.21/SY*1SY/9SF*15ft*5280ft/mi*1.14mi • Base aggregate mainline,$12.64/ton*1ton/2000lb*115-lb/SY/in*6in*1SY/9SF*15ft*5280ft/mi*1.14mi • 3.5-inch E-3 AC shoulder46.89/ton*1ton/2000lb*110-lb/SY/in*3.5in*1SY/9SF*7ft*5280ft/mi*1.14mi • Tack coat shoulder,$3.00/gal*0.025gal/SY*1SY/9SF*7ft*5280ft/mi*1.14mi*2 layers • Base aggregate under shoulder,$12.64/ton*1ton/2000lb*115-lb/SY/in*11.5 in*1SY/9SF*7ft*5280ft/mi*1.14mi	277,987 43,748 42,258 703 42,532 **∑=407,228** 252,907 43,748 42,258 703 39,130 **∑=378,746**
B	Maintenance at $2000/lane mile*1.14mile	2,280
C	Maintenance at $4000/lane mile*1.14mile	4,560
D	• Concrete repair,$69.41/SY*1SY/9SF*15ft*5280ft/mi*1.14mi • Concrete continuous diamond grinding, $3.21/SY*1SY/9SF*15ft*5280ft/mi*1.14mi	696,321 32,203 **∑=728,524**
E	• Concrete repair,$69.41/SY*1SY/9SF*15ft*5280ft/mi*1.14mi • Concrete continuous diamond grinding, $3.21/SY*1SY/9SF*15ft*5280ft/mi*1.14mi	696,321 32,203 **∑=728,524**
F	• Concrete repair,$69.41/SY*1SY/9SF*15ft*5280ft/mi*1.14mi • 2-inch HMA PAVEMENT TYPE E-10 overlay, $53.96/ton*1ton/2000lb*110-lb/SY/in*2.0in*1SY/9SF*15ft*5280ft/mi*1.14mi • Tack coat for overlay mainline, $3.00/gal*0.025gal/SY*1SY/9SF*15ft*5280ft/mi*1.14mi*2 layers • 2.0-inch E-3 AC shoulder,$46.89/ton*1ton/2000lb*110-lb/SY/in*2.0in*1SY/9SF*7ft*5280ft/mi*1.14mi • Tack coat shoulder,$3.00/gal*0.025gal/SY*1SY/9SF*7ft*5280ft/mi*1.14mi*2 layers	696,321 59,546 1,505 24,147 702 **∑=782,221**
G	• Maintenance at $2000/lane-mile*1.14mile	2280
H	• Salvage of F=6/15* 782,221	312,888

Once cost inputs for all three alternatives were determined, engineering economic analysis with the net present worth (NPW) method was applied to estimate the overall costs and benefits throughout the life of each alternative. Thus, all future costs were converted to their equivalent present costs using a discount rate of 5% per WisDOT policy. The NPW was determined using Equation 5.4.

$$\text{NPW}=\sum\left(\frac{F}{(1+i)^{N}}\right) \tag{5.4}$$

Where,

NPW = net present worth
F = cost at Year N
N = Number of years
I = discount rate =5%

Tables 5.18 through 5.20 provide the respective NPW cost per 1.14-mi average study segment for the three panel alternatives of 12, 14, and 15 ft. Table 5.21 provides NPW components (initial construction, rehabilitation, maintenance, and salvage value) and their relationship with pavement thickness as well as width-to-thickness ratio (w/t). Table 5.21 shows that, for a given thickness, w/t increases with increasing panel width and initial construction cost; this would be expected with a $2.50/SY-in additional cost. The 12-ft panel has the lowest overall rehabilitation and NPW costs but the highest maintenance costs among the 9-in and 10-in pavements. Although the maintenance cost is highest for the 12-ft panel, the influence on the overall NPW is minimal. The 15-ft has the largest rehabilitation cost, which is approximately 1.7 times ($466,567 / $280,191) that of the 12-ft panels and 1.1 times ($466,567 / $436,167) that of the 14 ft panels.

Table 5.18 Net Present Worth Cost for 12-ft Panel

Pavement Thickness (w/t ratio)	Cost Index	Year, N	Initial $/1.14mi average segment	$(1+i)^N$	NPW $/1.14mi average segment
9 (1.3)	A	0	354,594	1.0000	354,594
	B	11	2,280	1.7103	1,333
	C	18	4,560	2.4066	1,895
	D	26	582,819	3.5557	163,912
	E	35	641,397	5.5160	116,279
	F	39	1,140	6.7048	170
	G	45	1,425	8.9850	159
	H	50	0	11.4674	0
				Total	**638,342**
10 (1.2)	A	0	379,518	1.0000	379,518
	B	11	2,280	1.7103	1,333
	C	18	4,560	2.4066	1,895
	D	26	582,819	3.5557	163,912
	E	35	641,397	5.5160	116,279
	F	39	1,140	6.7048	170
	G	45	1,425	8.9850	159
	H	50	0	11.4674	0
				Total	**663,266**

Table 5.19 Net Present Worth Cost for 14-ft Panel

Pavement Thickness (w/t ratio)	Cost Index	Year, N	Initial $/1.14mi average segment	$(1+i)^N$	NPW $/1.14mi average segment
9 (1.5)	A	0	370,694	1	370,694
	B	15	2,280	2.078928	1,097
	C	21	4,560	2.785963	1,637
	D	25	679,956	3.386355	200,793
	E	33	679,956	5.003189	135,905
	F	41	735,280	7.391988	99,470
	G	45	1,140	8.985008	127
	H	50	-294,112	11.4674	-25,648
				Total	**784,075**
10 (1.4)	A	0	397,990	1	397,990
	B	15	2,280	2.078928	1,097
	C	21	4,560	2.785963	1,637
	D	25	679,956	3.386355	200,793
	E	33	679,956	5.003189	135,905
	F	41	735,280	7.391988	99,470
	G	45	1,140	8.985008	127
	H	50	-294,112	11.4674	-25,648
				Total	**811,371**
11 (1.3)	A	0	425,287	1	425,287
	B	15	2,280	2.078928	1,097
	C	21	4,560	2.785963	1,637
	D	25	679,956	3.386355	200,793
	E	33	679,956	5.003189	135,905
	F	41	735,280	7.391988	99,470
	G	45	1,140	8.985008	127
	H	50	-294112	11.4674	-25,648
				Total	**838,668**
12 (1.2)	A	0	452,584	1	452,584
	B	15	2,280	2.078928	1,097
	C	21	4,560	2.785963	1,637
	D	25	679,956	3.386355	200,793
	E	33	679,956	5.003189	135,905
	F	41	735,280	7.391988	99,470
	G	45	1,140	8.985008	127
	H	50	-294112	11.4674	-25,648
				Total	**865,965**

Table 5.20 Net Present Worth Cost for 15-ft Panel

Pavement Thickness (w/t ratio)	Cost Index	Year, N	Initial $/1.14mi average segment	$(1+i)^N$	NPW $/1.14mi average segment
9 (1.7)	A	0	378,746	1.0000	378,746
	B	12	2,280	1.7959	1,270
	C	18	4,560	2.4066	1,895
	D	25	728,524	3.3864	215,135
	E	33	728,524	5.0032	145,612
	F	41	782,221	7.3920	105,820
	G	44	2280	8.5572	266
	H	50	-312,888	11.4674	-27,285
				Total	**821,459**
10 (1.5)	A	0	407,228	1.0000	407,228
	B	12	2,280	1.7959	1,270
	C	18	4,560	2.4066	1,895
	D	25	728,524	3.3864	215,135
	E	33	728,524	5.0032	145,612
	F	41	782,221	7.3920	105,820
	G	44	2280	8.5572	266
	H	50	-312,888	11.4674	-27,285
				Total	**849,941**

Table 5.21 Categorical Cost Comparison of Panel Alternatives

Panel width (ft)	Pavement Thickness (in)	Width-to-thickness ratio	Initial construction	Rehabilita-tion	Maintenance	Salvage	NPW Cost/1.14 mi average segment
12	9	1.3	354,594	280,191	3,557	0	638,342
14		1.6	370,694	436,167	2,861	-25,648	784,075
15		1.7	378,746	466,567	3,431	-27,285	821,459
12	10	1.2	379,518	280,191	3,557	0	663,266
14		1.4	397,990	436,167	2,861	-25,648	811,370
15		1.5	407,228	466,567	3,431	-27,285	849,941
12	11	1.1	--	--	--	--	--
14		1.3	425,287	436,167	2,861	-25,648	838,667
15		1.4	--	--	--	--	--
12	12	1.0	--	--	--	--	--
14		1.2	452,584	436,167	2,861	-25,648	865,964
15		1.3	--	--	--	--	--

For the 9 and 10-in thicknesses, the NPW costs were further evaluated in relation to the mean crack length per the 1.14-mi segment. Table 5.22 shows the relationship between the average crack length and NPW cost for the various panels. For all panel widths, a one-inch increment in thickness from 9 in. to 10 in. results in 70-80 ft reduction in the mean observed crack length per 1.14-mi segment. The incremental cost associated with the crack length reduction varies from approximately $25,000 to $28,500. The 12-ft panel produces the minimum overall incremental cost of $312 per foot reduction of crack length for an inch increase in pavement thickness. The corresponding incremental costs per foot reduction of crack length for the 14-ft and 15-ft panels are respectively about 1.2 and 1.3 times that of the 12-ft panel.

Table 5.22 Average Segment Crack Length and Cost Relationship for Panel Widths

Panel width	Pavement Thickness (in)	NPW/1.14-mi segment ($)	Mean Crack Length/1.14 mi segment (ft)	Incremental Cost (($)	Crack Length Reduction (ft)	Cost/unit Crack Length Reduction ($/lf-in)
12	9	638,342	100			
	10	663.266	20	24,924	80	312
14	9	784,075	238			
	10	811,370	164	27,295	74	369
15	9	821,459	430			
	10	849,941	362	28,482	68	419

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Conclusions

A set of guidelines for consideration in JPCP panel width practice to improve performance was developed in this research study. The guidelines were developed through a series of tasks including: a) review of literature on the causes and treatment practices for longitudinal cracking in JPCP b) online survey of six Midwestern states on panel width practices, and c) data collection and comparative statistical analysis of the in-service performance of wider concrete panels (14 and 15 ft) with standard width panels (12 and 13 ft). On the basis of the study, the following summary and conclusions are provided:

6.1.1 Literature review

1. The literature suggests that cracking on JPCP is the result of several interrelated factors including: temperature variations, moisture gradients between slab top and bottom, jointing practices, and base material type.
2. Cracking of concrete slabs occurs when tensile stresses exceed tensile strength due to initial shrinkage from moisture loss, restraint by base or subbase friction from expansion and contraction caused by temperature changes, and thermal and moisture gradients between the top and bottom of the slabs.
3. The majority of longitudinal cracking tends to be random or uncontrolled in nature and can occur in some new pavements within the first two months of construction, initially appearing at large intervals (30 to 150 ft) and forming at closer intervals over time.
4. Random cracking that first occurs or continues to develop well after paving and sawing is the result of slab restraint or movement that result in high tensile stress development within the slab. The movement may be the result of grade settlement or frost heave whilst the restraint may be from the presence of a stabilized subbase
5. The traditional approach to minimizing the effect of induced stresses in concrete slabs is to apply proper jointing techniques to create transverse and longitudinal saw cut joints.

The joints induce a plane of weakness that can allow the crack to initiate and propagate to the bottom of the slab.

6. Early-age sawing with depths of 1/4 × slab thickness provide better crack control than greater saw depths.
7. Fourteen-foot panel widths are less susceptible to longitudinal cracking compared to other panel widths.
8. Common methods for repairing longitudinal cracks include: saw and seal, panel removal and replacement, and cross-stitching.

6.1.2 Survey of Midwest States

Practices on JPCP and how they impact longitudinal cracking development were sought through an online survey from six Midwest states (Iowa, Ohio, Michigan, Wisconsin, Illinois, and Minnesota). The information sought pertained to cross-section practices including criteria for determining panel widths on rural highways, commonly used panel widths, the frequency of longitudinal cracking occurrence, and probable causes of cracking from construction practice and design features such as thickness, tie bar longitudinal cracking treatment practices and typical costs. On the basis of the survey, the following conclusions are reached:

1. Pavement thickness is the dominant factor considered in the selection of JPC panel width on rural highways. Other factors include traffic volume, percent trucks, ease of construction, and construction & maintenance costs.
2. The most commonly used panel width on 2-lane 2-way rural pavements is 12 ft followed by the 15-ft panel. On multi-lane highways, the 12-ft panel is commonly used.
3. The 12-ft and 15-ft wide panels experience higher longitudinal cracking frequencies compared to 13-ft and 14-ft wide panels. The cracking generally occurs more near panel edge and at mid-panel locations compared to the vicinity of sawn longitudinal joints.
4. Premature longitudinal cracking initiation time varies from less than a month to as high 60 months with an average initiation time of 24 months.
5. Thicker pavements (≥11 in) do not tend to exhibit longitudinal cracking compared to more vulnerable thinner pavements.
6. High longitudinal cracking frequencies tend to be associated with inadequate subbase compaction, poor joint saw-cut timing, misaligned dowel bars, and faulty vibrators. In

addition, 12-ft panels are prone to more construction related longitudinal cracking compared to all other panels.

7. The main methods for fixing premature or normal longitudinal cracking include rout and seal, cross-stitching, and partial or full panel replacement.

6.1.3 In-Service Performance Data Analysis

A total of 1,008 concrete segments (Sequence Numbers) within the state, averaging 1.14 miles in length, were analyzed to directly determine which factors cause longitudinal cracking and statistically compare the performance of wider concrete panels (14 and 15 ft) to standard width panels (12 and 13 ft). The overall objective was to determine the maximum allowable pavement width as a function of pavement thickness in order to achieve optimal concrete pavement performance. Performance was defined in terms of the presence or absence of cracking, the length of cracking, and severity of cracking. On the basis of the analysis, the following observations are made:

1. Approximately 60% (599/1,008) of 1.14-mile segments in the state had longitudinal cracking while 40% did not (409/1,008). Approximately 56% (502/891) of 14-ft panels experienced longitudinal cracking compared to 100% (8/8) of 13-ft panels. The respective proportions of cracked pavements were 81 %(58/72) and 84 %(31/37) for the 12-ft and 15-ft panels.
2. The significant factors explaining the presence or absence of longitudinal cracking included width-to-thickness ratio, joint spacing, longitudinal jointing method, tining orientation, dowel bar installation, traffic level, age, and region
3. The significant factors explaining the length and/or severity of longitudinal cracking included offset of crack, pavement thickness, width-to-thickness ratio, joint spacing, transverse joint orientation (skewed or normal), rumble strips, base gradation (dense or open), dowel bar installation, AADTT, age, and region.
4. A majority of longitudinal cracking across all panel widths is between wheel paths or in the right wheel path compared to pavement edges.
5. For 14 ft panels, a 1 in thickness increase from 9 in (i.e. width-to-thickness ratio, w/t=1.6) to 10 in (w/t=1.4) reduced the number of cracks by 25%. Conversely, if the w/t ratio is raised from 1.4 to 1.6, the average cracking length within a pavement segment increases

by 45% for the 14-ft panels. If the w/t ratio is raised from 1.5 to 1.7 in 15-ft panels, the average cracking length within a pavement segment increases by 18%.

6. The largest w/t ratios for all panel widths had 100% segment cracking. The 12 ft panel had 100% cracking in 8 in (w/t = 1.5) and 12 in (w/t = 1.0) thick panels; 14 ft panel had 100% cracking in 7 in (w/t = 2.0) and 12 in (w/t = 1.2) thick panels; 15 ft panel had 100% cracking in 8 in (w/t = 1.9) and 9.5 in (w/t = 1.6) thick panels.

6.1.4 Life Cycle Cost

A life cycle cost analysis (LCCA) was performed to quantify the costs and benefits associated with each panel width over its life cycle. The results of the life cycle cost analysis indicate the following:

1. For a given thickness, width-to-thickness ratio increases with increasing panel width and initial construction cost.
2. The 12-ft panel has the lowest overall rehabilitation and NPW costs but the highest maintenance costs among the 9-in and 10-in pavements.
3. The largest rehabilitation cost is associated with the 15-ft panel and is approximately 1.7 times ($466,567 / $280,191) that of the 12-ft panels and 1.1 times ($466,567 / $436,167) that of the 14 ft panels.
4. For all panel widths, a one-inch increment in thickness from 9 in. to 10 in. results in 70-80 ft reduction in the mean observed crack length per 1.14-mi segment. The incremental cost associated with the crack length reduction varies from approximately $25,000 to $28,500.
5. The 12-ft panel produces the minimum overall incremental cost of $312 per foot reduction of crack length for an inch increase in pavement thickness. The corresponding incremental costs per foot reduction of crack length for the 14-ft and 15-ft panels are respectively about 1.2 and 1.3 times that of the 12-ft panel.

6.2 Recommendations

A systematic process was employed to develop guidelines for panel width practices to achieve optimal concrete pavement performance. Based on the process, the following recommendations are made:

1. Specify a standard panel width of 14-ft to limit cracking severity and extent. Field performance analysis coupled with the literature indicates that it exhibits the lowest cracking frequency compared to all other panels.
2. For the specified 14-ft panel, a width-to thickness-ratio of 1.2 (12 in thickness) to 1.5 (9.5 in thickness) must accompany it to minimize cracking severity and extent. It is highly recognized that several interrelated factors influence cracking severity and extent for specific panels and that panel width selection cannot be treated in isolation. For the recommended 14-ft panel width, better performance is expected when used in conjunction with a normal joint, untreated aggregate base, transverse joint spacing of 15 ft, dowel basket installation, and longitudinal tining.
3. Cracking can occur at various locations across the pavement including wheel paths, edges, and between wheel paths. For 14-ft panels cracking extent at all locations, with the exception of the left edge (LE), can be reduced through the use of 15-ft joint spacing in conjunction with normal joint application, PCC rumble strip installation, and open graded base course. However, for mid-panel cracking, the width-to-thickness ratio is another factor to consider. Normal joint application will minimize severity at both wheel paths and mid panel locations for 14-ft panels.

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Appendix A Online Survey Questionnaire

Jointed Plain Concrete Pavement Longitudinal Cracking Survey

Jointed Plain Concrete Pavement Longitudinal Cracking Survey

Question 1

What criteria does your agency use in selecting panel widths for mainline Jointed Plain Concrete Pavements on RURAL HIGHWAYS? Mark all that apply.

- ☐ Traffic volume
- ☐ Percent truck traffic
- ☐ Ease of construction
- ☐ Highway Functional Class
- ☐ Pavement Thickness
- ☐ Contruction & Maintenance Cost
- ☐ Other, please specify

Question 2

What are the standard Jointed Plain Concrete Pavement panel widths used by your agency on RURAL 2-LANE highways? Mark all that apply.

- ☐ 12 feet
- ☐ 13 feet
- ☐ 14 feet
- ☐ 15 feet
- ☐ Other, please specify

Question 3

What are the standard Jointed Plain Concrete Pavement panel widths used by your agency on RURAL MULTI-LANE highways? Mark all that apply.

- ☐ 12 feet
- ☐ 13 feet
- ☐ 14 feet
- ☐ 15 feet
- ☐ Other, please specify

Question 4

Which panel width(s) exhibit greater frequency of longitudinal cracking in Jointed Plain Concrete Pavements? Mark all that apply

- ❑ 12 feet
- ❑ 13 feet
- ❑ 14 feet
- ❑ 15 feet
- ❑ Other, please specify

Question 5

Which slab thickness(es) exhibit greater frequency of longitudinal cracking in Jointed Plain Concrete Pavement? Mark all that apply

- ❑ 7-inch
- ❑ 8-inch
- ❑ 9-inch
- ❑ 10-inch
- ❑ 11-inch
- ❑ 12-inch
- ❑ Other, please specify

Question 6

Which transverse joint spacing(s) exhibit greater frequency of longitudinal cracking in Jointed Plain Concrete Pavement? Mark all that apply.

- ❑ 12 feet
- ❑ 15 feet
- ❑ 18 feet
- ❑ Other, please specify

Question 7 - Yes or No

Do tie bars appear to have an effect on longitudinal cracking in Jointed Plain Concrete Pavements?

- ❍ Yes
- ❍ No
- ❍ Additional Comment

Question 8 - Yes or No

Have longitudinal parting strips been used by your agency on RURAL highways?

- ❍ Yes
- ❍ No
- ❍ Additional Comment

Question 9

Has there been an increased frequency of longitudinal cracking in Jointed Plain Concrete Pavements with parting strips?

- ❍ Yes
- ❍ No
- ❍ Do not use parting strips

Question 10

What possible construction related practices might have contributed to premature longitudinal cracking of Jointed Plain Concrete Pavement under your jurisdiction? Mark all that apply

- ❑ Misaligned dowel bars
- ❑ Improper timing of saw-cut at longitudinal joints at shoulder and centerline
- ❑ Saw-cut depth at shoulder and centerline joints
- ❑ Inadequate subbase compaction
- ❑ vibrator trails from faulty vibrators on paver
- ❑ Other, please specify

....

Question 11

What are the common locations for longitudinal cracking that tend to appear in Jointed Plain Concrete Pavements under your jurisdiction? Mark all that apply.

- ❑ Center of panel
- ❑ Near panel edge
- ❑ Near sawed longitudinal joint
- ❑ Other, please specify

....

Question 12

Which locations along Jointed Plain Concrete highways under your jurisdiction experience frequent longitudinal cracking? Mark all that apply

- ❑ Vicinity of bridges
- ❑ Vicinity of culverts
- ❑ Vicinity of pavement structures (manholes and stormwater inlets)
- ❑ Cut sections
- ❑ Fill sections
- ❑ Areas with differential heaving of subgrade
- ❑ Other, please specify

....

Question 13

What methods does your agency use for correcting longitudinal cracking that appear prematurely in Jointed Plain Concrete Pavements under your jurisdiction? Include any internet sites that will provide a link to policies or guidelines pertaining to the methods or email any related material to: owusu@uwplatt.edu

Question 14

For Jointed Plain Concrete Pavements that experienced premature longitudinal cracking,how many months or years elapsed before the first appearance of the cracks?

Question 15

What methods does your agency use for correcting longitudinal cracking that do not occur prematurely (i.e. expected normal cracking)?

Question 16

What is the approximate average cost per linear foot for the treatment of longitudinal cracking that appear prematurely in Jointed Plain Concrete Pavements under your jurisdiction?

Question 17

Please enter your contact information.

- Survey completed by
- Title
- Name of organization
- Phone Number
- Email

Thank you very much for taking the survey!

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