Quantifying the Impact of Crack Sealant on Pavement Surface Friction

Cassie Castorena, PhD

Andrew Fried, MS

Haritha Malladi, PhD

Department of Civil, Construction, and Environmental Engineering

North Carolina State University

NCDOT Project 2017-04

FHWA/NC/2017-04

June 2019

Quantifying the Impact of Crack Sealant on Pavement Surface Friction

FINAL REPORT

Submitted to the North Carolina Department of Transportation
(Research Project No. FHWA/NCDOT 2017-04)

Submitted by

Cassie Castorena, PhD
Associate Professor
Campus Box 7908
Department of Civil, Construction, & Environmental Engineering
North Carolina State University
Raleigh, NC 27695-7908
E-mail: cahintz@ncsu.edu

Department of Civil, Construction, & Environmental Engineering
North Carolina State University
Raleigh, NC

JUNE 2019

Technical Report Documentation Page

1. Report No. FHWA/NC/2017-04	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Quantifying the Impact of Crack Sealant on Pavement Surface Friction		5. Report Date 8/28/2018
		6. Performing Organization Code
7. Author(s) Cassie Castorena, PhD Andrew Fried, MS Haritha Malladi, PhD		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil, Construction, and Environmental Engineering North Carolina State University 2501 Stinson Dr., CB #7908 Raleigh, NC 27695-7908		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address North Carolina Department of Transportation Research and Development Unit 104 Fayetteville Street Raleigh, North Carolina 27601		13. Type of Report and Period Covered Final Report 08/01/2016-12/31/2018
		14. Sponsoring Agency Code 2017-04
Supplementary Notes:		

16. Abstract

Crack sealing is often a cost-effective preventive maintenance strategy for prolonging pavement service life when applied to pavements in relatively good condition. However, crack sealing is often applied to pavements with extensive cracking. The application of crack sealing to pavements with extensive cracking can pose a skid resistance hazard. This study investigates the relationship between the amount and distribution of crack sealant application and pavement skid resistance. Locked-Wheel Skid Tester (LWST) testing was conducted on six pavement projects in North Carolina with varying amounts and patterns of crack sealant. Images of the locations of LWST testing were obtained and processed to determine the percentage of the pavement lane and wheel path area covered by crack sealant. A relationship between the percentage of the wheel path covered by crack sealant and LWST results was established that demonstrates the application of high amounts of crack sealant to the wheel path can pose safety hazards. The effect of crack sealant on pavement skid resistance is a function of the existing pavement's frictional characteristics. The extent of crack sealant application to the wheel path is related to the extent and severity of alligator cracking prior to crack sealing. The results of this study highlight the need for the development of guidelines to prohibit crack sealant applications to roadways where it could pose a skid resistance hazard. Based on the results of this study, it is proposed that these guidelines prohibit crack sealing of pavements with marginal existing skid resistance (i.e., Skid Number (SN) values less than or equal to 37). Furthermore, it is recommended that pavements with good existing skid resistance (i.e., SN values greater than or equal to 43) should not be sealed if the alligator cracking index falls below 75 for low-volume roads and 92 for high volume roads to ensure safety.

17. Key Words Crack sealant, skid number, friction, alligator cracking	18. Distribution Statement		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 30	22. Price

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

DISCLAIMER

The contents of this report reflect the views of the author(s) and not necessarily the views of the University. The author(s) are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the North Carolina Department of Transportation or the Federal Highway Administration at the time of publication. This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support from the North Carolina Department of Transportation under project NCDOT HWY-2017-04. The authors would like to sincerely thank Matthew Hilderbran for coordinating the field experiments and Anthony Prelozny for conducting the Locked-Wheel Skid Tests. The authors also thank Elizabeth Braswell for her assistance in acquiring pavement images.

EXECUTIVE SUMMARY

Crack sealing is often a cost-effective preventive maintenance strategy for prolonging pavement service life when applied to pavements in relatively good condition. However, crack sealing is often applied to pavements with extensive cracking. The application of crack sealing to pavements with extensive cracking can pose a skid resistance hazard. The objectives of this research are to: quantify the effect of crack sealant application on pavement skid resistance, and identify pavement conditions where it is unsafe to apply crack sealant.

To quantify the impact of crack sealant on pavement skid resistance, this study investigates the relationship between the amount and distribution of crack sealant application and pavement skid resistance. Locked-Wheel Skid Tester (LWST) testing was conducted on six pavement projects in North Carolina with varying amounts and patterns of crack sealant. Images of the locations of LWST testing were obtained and processed to determine the percentage of the pavement lane and wheel path area covered by crack sealant. A relationship between the percentage of the wheel path covered by crack sealant and LWST results was established that demonstrates the application of high amounts of crack sealant to the wheel path can pose safety hazards. The results of this study highlight the need for the development of guidelines to prohibit crack sealant applications to roadways where it could pose a skid resistance hazard.

The extent of crack sealant application to the wheel path is related to the extent and severity of alligator cracking prior to crack sealing. Furthermore, the results of this study demonstrate that the impact of crack sealant on pavement skid resistance depends on the existing pavement's skid resistance. Compared with roadways with poor baseline skid resistance, the results suggest that roadways with relatively high amounts of cracking and good baseline skid resistance may be crack sealed without risking a skid resistance safety hazard. Therefore, the maximum percentages of wheel path that can be covered by crack sealant without posing safety hazards were defined by clustering the results into two categories of existing pavement condition: good (i.e., SN values of 43 and higher) and poor (i.e., SN value of 37 and lower). The established limits for the percentage of the wheel path that can be covered by crack sealant without causing unsafe frictional characteristics were related to the pavement distress survey alligator cracking index results to define pavement conditions where sealing should be avoided.

Based on the results of this study, it is proposed crack sealing of pavements with marginal existing skid resistance (i.e., Skid Number (SN) values less than or equal to 37) be prohibited. Furthermore, it is recommended that pavements with good existing skid resistance (i.e., SN values greater than or equal to 43) should not be sealed if the alligator cracking index falls below 75 for low-volume roads and 92 for high volume roads to ensure safety.

It should be noted that all of the pavements evaluated in this project included the overband crack sealant configuration. The effects of other types of crack sealant configurations on pavement skid resistance merits consideration in future work. The use of the flush fill configuration may allow for reducing skid resistance hazards associated with crack sealant application. It should also be noted that the pavements evaluated in this study had either skid numbers greater than or equal to 43 or 37. Additional sections with baseline skid numbers in the range of 37 to 43 should be investigated in future work to better elucidate the safety of crack sealant application on pavements with marginal skid resistance.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Crack sealing is a cost-effective method of preventative maintenance to extend pavement service life. Crack sealing is applied within surface cracks. The sealant is intended to form a water-tight bond and withstand thermal expansion and contraction of the surrounding pavement, thereby preventing weakening of underlying layers and reducing the rate of pavement deterioration. Crack sealant application is generally considered most effective when conducted early in a pavement's life, typically within the first three to five years (Decker 2014). Crack sealing is generally recommended for pavements with minor to moderate cracking and good rideability because crack sealing does not improve the structural integrity of a pavement (Decker 2014).

While crack sealing is effective when applied to pavements in relatively good condition, crack sealing is often applied to pavements with extensive cracking. An example is shown in Figure 1.1 (a). Pavements with extensive cracking are generally structurally compromised, making sealing less effective than when applied to pavements that are structurally sound. Furthermore, if the crack sealant covers too much of the pavement surface area, it can potentially degrade skid resistance. Skid resistance is critical to avoid accidents, particularly in wet weather conditions. Crack sealant may cover too much of a pavement's surface area if either excessive crack sealant is applied (e.g., overband is too wide) or the extent of cracks sealed on the pavement surface is too high. Furthermore, many agencies pay contractors for projects based on the quantity of sealant applied (e.g., NCDOT 2012, Caltrans 2003, MNDOT 2006); therefore, contractors may be indirectly incentivized to over-apply crack sealant even in locations where cracks are absent. Evidence of the application of crack sealant to a pavement area without cracks present is shown in Figure 1.1 (b).

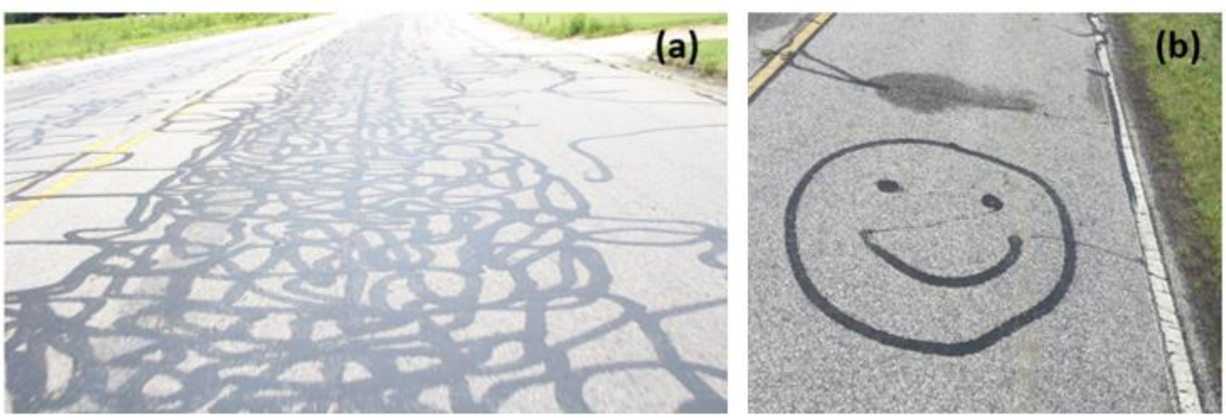

Figure 1.1. *Examples of excessive crack sealant application in North Carolina.*

The objectives of this research are to:

(1) Quantify the effect of crack sealant application on pavement skid resistance.
(2) Identify pavement conditions where it is unsafe to apply crack sealant.

This study investigates the relationship between the amount and distribution of crack sealant application and pavement skid resistance in North Carolina. Relationships between the crack sealant coverage of the pavement surface and Locked-Wheel Skid Test (LWST) results are used to identify pavement conditions where crack sealant application should be precluded to avoid unsafe conditions.

2. RESULTS OF THE LITERATURE REVIEW

The primary factors that affect the extent of crack sealant coverage of a pavement's surface are: (1) the extent of existing pavement cracking, (2) crack sealant configuration, and (3) crack sealant quality control. Therefore, the literature review focused on these three topics. The NCDOT's current specifications for crack sealing were also reviewed. A brief summary of the results of the literature review is presented in the following sections.

2.1. Current Pavement Selection Criteria for Crack Sealing

Decker (2014) and Truschke et al. (2014) conducted national surveys identify the criteria that are used by agencies to determine if a pavement is a good candidate for crack sealing. The results of Truchke et al.'s (2014) survey are shown in Figure 2.1. The results of Decker's (2014) are similar to those of Truscke's (2014) survey, demonstrating that eighty percent of agencies use three criteria to select pavements for crack sealing: (1) type of crack, (2) percentage of cracked area on pavement (crack density), and (3) crack width.

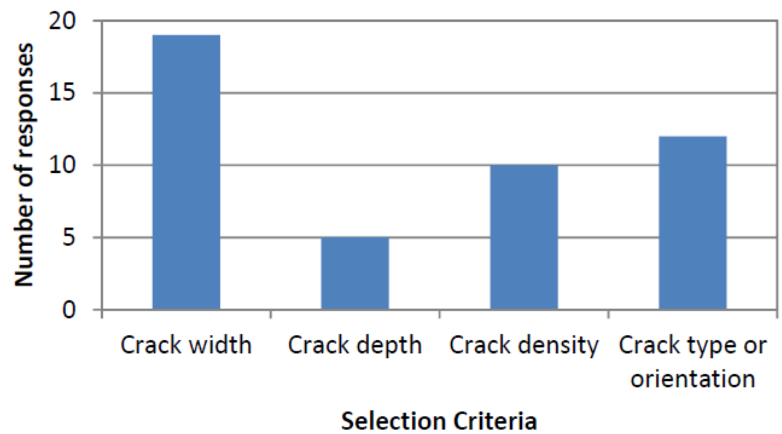

Figure 2.1. *Pavement selection criteria for crack sealing based on survey results of Truschke et al. (2014).*

The national surveys indicate that pavements with transverse, longitudinal, and block cracks are generally good candidates for crack sealing but that pavements with alligator cracking should not be sealed (Truschke et al. 2014, Decker 2014). The literature indicates cracks with widths between ¼ in and ¾ in are ideal for crack sealing (Smith and Romine 1999, Truschke et al. 2014). Wider cracks can be sealed but ride quality is often diminished and specialized crack sealant material is required (Truschke et al. 2014). National best practice guidelines indicate that crack sealing should be limited to pavements with low to moderate crack density as defined by

Table 2.1 (Decker 2014). In addition, crack edge deterioration should be minimal, (i.e., less than 25 percent of crack length) (Smith and Ronnie 1999).

Table 2.1. *Crack Density Classifications (Decker 2014)*

Linear Crack Length per 100 m (328 ft) pavement section	Density Definition
Less than 10 m (33 ft)	Low
10 m (33 ft) to 135 m (443 ft)	Moderate
Greater than 135 m (443 ft)	High

The national surveys did not identify any agencies with crack sealant project selection criteria to prohibit skid loss. To develop such specifications, research is first needed to quantify the effect of crack sealant application on the frictional properties of pavements.

2.2. Crack Sealant Configurations

Several crack sealant configurations are used, which include recessed fill, flush fill, and overband (Decker 2014). The choice of crack sealant configuration will impact the width of sealant application and hence, may influence skid resistance. The overband is the most common configuration because it is relatively easy and efficient to apply compared to the other configurations (Chehovits and Manning 1984). The sealant is simply applied and squeegeed in overband applications whereas greater care must be taken to achieve the flush fill and recessed fill configurations. However, overband configuration will lead to a wider band of crack sealant compared to the other configurations, increasing exposure of the sealant to environment and traffic (Chehovits and Manning 1984). The flushed fill configuration is often recommended in high traffic roadways to avoid the wide band of coverage and to minimize sealant wear (Caltrans 2003). The recessed fill configuration is used primarily in areas where snow plows may damage crack sealants (Chong 1990) and thus, not currently employed in North Carolina.

2.3. Quality Control of Crack Sealant Application

Excessive crack sealant application can result from the following: the use of incorrect finishing tools and techniques, application of cold sealant, excessive sealant application, degradation of the sealant due to overheating, and application of sealant in hot weather conditions (Caltrans 2003). These issues can be minimized by proper quality control. Quality control measures for crack sealant treatments include (1) inspection of the operation, (2) sealant sampling and testing, (3) calibration of the equipment, and (4) inspection of the equipment (Decker 2014). Temperature calibration of the application equipment is critical to ensure that the sealant is heated to the correct temperature (Masson et al. 2003). Equipment inspection consists of visual inspection and routine maintenance per the manufacturer's recommendation (Decker 2014). Sealant material should be periodically sampled and tested to ensure the requisite properties (e.g., viscosity) are met (Decker 2014). Inspection of the operation is perhaps the most critical quality control measure to verify that the sealant is applied properly (Decker 2014).

2.3. NCDOT Specifications for Crack Sealing

NCDOT directs contractors to seal existing longitudinal and transverse cracks as directed by the Engineer and does not require sealing of edge cracks. Cracks must be cleaned using hot compressed air and the adjacent pavement is to be dried and warmed using a hot air lance immediately before sealing. The sealant material must meet the requirements of ASTM D6690 and the National Transportation Product Evaluation Program (NTPEP). A portable melting kettle should be used to indirectly and uniformly heat the sealant to manufacturer-recommended temperature. The cracks should sealed to a minimum depth of ⅛ in with a 2 in overband. The sealant should be immediately squeegeed in order to minimize the sealant height and impact on rideability. Excessive overbanding or wasting of sealant materials is not allowed. However, it is unclear what is considered excessive and how this is monitored. Traffic is not allowed on the roadway until the sealant application is approved by the engineer.

3. METHODOLOGY AND EXPERIMENTAL PLAN

3.1. Test Sections

Six pavement sections in North Carolina were analyzed in this study. Each section exhibited significant variability in the crack sealant application sealant along its length; this allowed for evaluating the relationship between the percentage of the pavement surface covered by crack sealant and pavement skid resistance over sections with relatively consistent existing pavement skid resistance. The crack sealant configuration used in all locations was the overband, which is prevalent in North Carolina.

A summary of the six test sections is given in

Table 3.1. Pavement condition ratings (PCRs), alligator index values, transverse cracking index values, and oxidation rating values were obtained by the NCDDOT using windshield surveys of the existing pavement prior to the application of crack sealant (NCDOT 2016). Location C includes two subsections, C1 and C2 because the route included two segments for which pavement distress condition survey data was obtained and recorded prior to sealing. For the other locations, a single record of pavement distress condition survey data was available for the entire route length. Many of the test sections exhibited evidence of extensive cracking. All sections with the exception of Location F had a transverse cracking index of 80. However, the extent of alligator cracking varied among the test sections. An analysis of the NCDOT distress survey data indicates that values are calculated using Equation 3.1.

$$AC_{Index} = 100 - \left(0.5 \cdot \%LOW + \%MED + 4 \cdot \%HI\right) \qquad (3.1)$$

where %LOW refers to the percentage of the total area of the lane that is low severity. %MED is the percent of the total area that is medium severity. %HI is the percent of the total area that is high severity. %NONE refers to the percentage of the total area that exhibits no alligator cracking. It should also be noted that both longitudinal and alligator cracks are grouped together under alligator cracking NCDOT distress surveys (NCDOT 2016). The test locations did not exhibit visual evidence of oxidation with the exception of Location C; an oxidation rating of zero indicates that oxidation was not observed and a rating of 100 indicates severe oxidation.

Table 3.1. *Summary of Test Sections*

Location	A	B	C1	C2	D	E	F
Length mi [km]	2.0 [3.2]	1.1 [1.8]	2.2 [3.5]	1.9 [3.0]	1.4 [2.2]	1.0 [1.6]	1.5 [2.4]
Number of Test Sites*	16 (20)	11 (11)	10 (11)	10 (14)	7 (14)	4 (8)	8 (15)
Test Interval mi [m]	0.1 [161]	0.1 [161]	0.2 [322]	0.2 [322]	0.1 [161]	0.1 [161]	0.1 [161]
PCR	80.10	76.80	71.19	76.44	63.60	69.30	65.60
Alligator Index	86.67	82.22	73.40	77.50	64.44	72.63	76.56
Oxidation Rating	0	0	100	100	0	0	0
Transverse Cracking Index	80	80	80	80	80	80	100

*First number corresponds to the number of test site results deemed acceptable, number in parentheses corresponds to the total number of test sites.

3.2. Locked-Wheel Skid Testing

The LWST was used to measure the skid resistance of pavements with varying amounts of crack in the wheel path in accordance with ASTM E274. The LWST consists of a trailer with a test wheel, water supply and dispensing system, and instrumentation system to measure frictional force. The trailer is towed by a vehicle traveling at 40 mph (64 km/h). Once up to speed the LWST sprays water 12 in to 18 in in front of the test tire as well as 1 in to the left and right of the tire to ensure a wetted surface for the tire. The trailer's test wheel is positioned in the left wheel path and is locked and dragged over wetted sections of pavement in order to measure the steady-state friction. The LWST used in this study is a smooth, single tire and is shown in Figure 3.1.

Figure 3.1. *Locked-Wheel Skid Tester.*

The LWST was used to determine the skid number (SN) at each site of testing. The SN number is recorded as the average value for the duration of each skid test and is calculated by using Equation 3.2.

$$SN = (F/W)*100 \qquad (3.2)$$

Where *SN* = skid number, *F* = tractive force (horizontal force applied to test tire at the tire-pavement contact patch), (lbf or N), *W* = dynamic vertical load on test wheel (lbf or N).

LWST tests were conducted at constant intervals with different intervals depending on the overall length of the section. Longer sections included measurements every 0.2 miles (322 m) while shorter sections took measurements around 550 feet (168 m). A handheld GPS was used to record the location of each LWST test. SN values were removed from the data set if the speed was not 40 mph (64 km/h) or if the photo showed significant amount of wandering from the wheel path.

Based on a nationwide survey of LWST use, Jayawickrama et al. (1996) proposed minimum SN thresholds to ensure safety in low and high volume roads of 30 and 35, respectively. They further suggested that pavements with SN between 31 and 34 should be monitored closely to ensure that safe conditions are maintained (Jayawickrama et al. 1996). The thresholds proposed by Jayawickrama et al. (1996) have been adopted by many state agencies and were used herein to develop guidelines to preclude safety hazards associated with the application of crack sealant.

3.3. Image Acquisition and Processing

A vehicle with a camera mounted to its hood closely followed the LWST to obtain images of the pavement sections over which SN values were measured to allow for the comparison of skid resistance with crack sealant coverage. The camera mounted to the vehicle is shown in Figure 3.2. The location of each LWST test was easily identified by the watermark left on the pavement. Two photographs were taken for each skid mark. The camera contained a Global Positioning System (GPS) unit, which allowed for reconciling the images with the corresponding LWST result. A handheld GPS unit was also used to record the location of each photograph in case of failure of the camera’s GPS unit.

Figure 3.2. *Camera with GPS unit attached mounted to hood of car.*

The LWST test results and the corresponding unprocessed images were first used to create a database. The images were then reviewed and filtered. If an image was blurry or contained significant shadows that significantly reduced contrast between crack sealant and the surrounding pavement, the image and corresponding SN value were removed from the database. The number of test sites removed due to blurry images and/or improper LWST speed is shown in

Table 3.1.

An algorithm was developed to calculate the percentage of the lane and wheel path within each section of LWST testing covered by crack sealant using both Adobe Photoshop® and MATLAB®. The image processing algorithm first conducts a perspective warp to convert the image to a top-down view using Photoshop®. Then, the image is cropped to include only the lane of interest over the length where LWST testing was conducted. Auto-contrast, brightening tools, and a color balancing tool in Photoshop® are applied to improve the contrast between the crack sealant and the surrounding pavement. For isolated analysis of the wheel path location where the LWST test was conducted, the image is further cropped to a fixed width of 140 pixels centered around the water mark, which corresponded to approximately three wheel widths, capturing the expected range of traffic wander within the wheel path (Luo et al. 2012).

Each cropped lane width and wheel path image is then imported into MATLAB®. In MATLAB®, each image is converted from color to greyscale and subsequently converted to a binary image (i.e., black and white) using adaptive thresholding. This is a built-in function in MATLAB® that sorts through an image and converts a color image to a binary one. The way that this process works in MATLAB® is by examining a smaller selection of the image and determining what is the foreground and background via differences in overall contrast (Puneet 2013). For the purposes of this research the background (roadway) was determined to be lighter than the crack sealant and as a result the adaptive thresholding results in an image that highlights the crack sealant in black.

An example of (a) an original photograph, (b) perspective-corrected, and (c) wheel path only and (d) final binary wheel path image is shown in Figure 3.3. The algorithm was verified using a subset of images by overlaying final binary images with the initial perspective-corrected color image to ensure that the crack sealant was properly identified and delineated from the surrounding pavement.

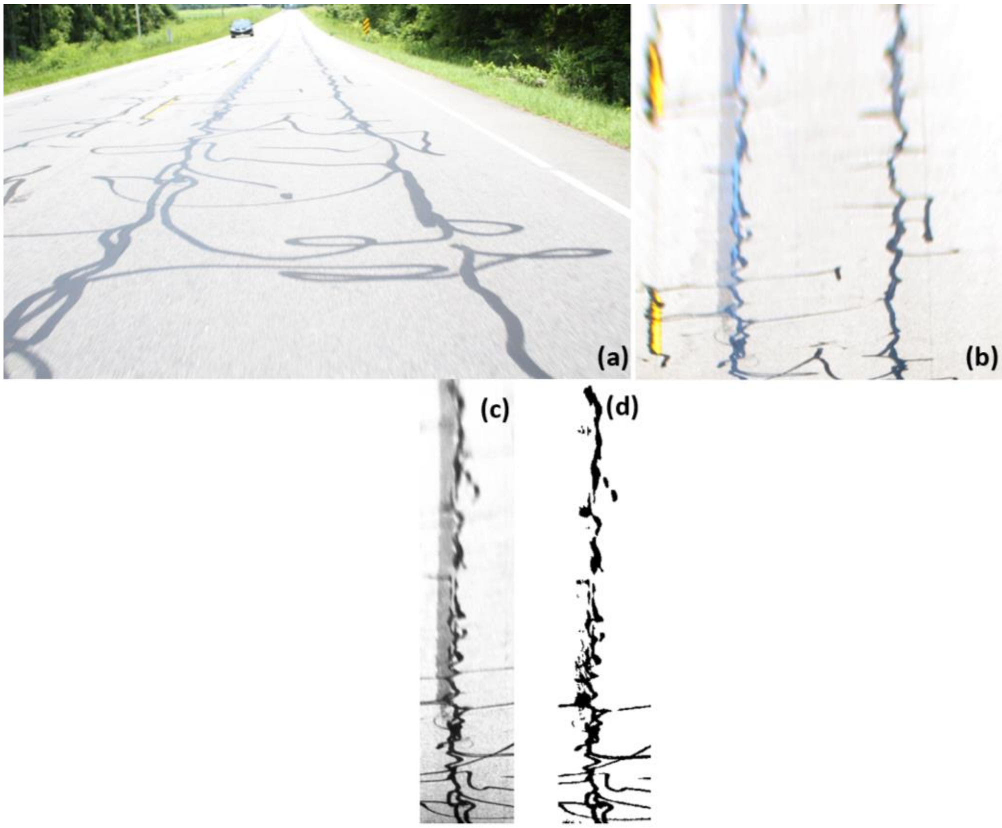

Figure 3.3. *Image analysis process (a) initial image, (b) perspective corrected, (c) contrast increased wheel path focused, and (d) binary image.*

4. RESULTS

4.1. Baseline Skid Numbers

For each testing location, a baseline SN value was established based on the LWST results on a portion of the roadway without crack sealant. In cases where there was only a single LWST site with no sealant, only a single value could be used to establish a baseline. In other cases the average of all SN values corresponding to sections without crack sealant is reported. Note that the baseline pavement frictional characteristics were not found to vary appreciably along the length of a given route.

The baseline SN results are shown in Table 4.1.The baseline SN values for Locations A, B, D, E and F were similar and indicate that the existing pavements had good skid resistance prior to the application of crack sealing. Locations C1 and C2 has a significantly lower baseline SN value, approaching unsafe conditions. Baseline SN values could not be directly related to the existing pavement condition results given in

Table 3.1.

Table 4.1. *Baseline Skid Numbers*

Location	Measured Baseline SN Values
A	49.0
B	48.6
C1	37.1
C2	37.6
D	44.9
E	43.0
F	47.1

4.2. Relationship between SN Values and the Percentage of the Pavement Surface Area Covered by Crack Sealant

Once the crack sealant images had been processed and filtered, the relationship between the SN value and percentage of the pavement surface area covered by crack sealant was investigated. Figure 4.1 shows the relationship between SN values and the percentage of the total lane covered by crack sealant for each location of testing. While Location B exhibits a linear relationship between the percentage of the lane covered by crack sealant and SN, the other sections do not exhibit a clear trend. There is a significant amount of spread in the measured SN values for each testing location, with many of the reported SN values falling below generally accepted threshold values of 30 for low volume roads and 35 for high volume roads (Jayawickrama et al. 1996). Similarly, there is a wide range in the percentage of the lane covered by crack sealant along the length of each testing location; the percentages of the pavement lane covered by crack sealant exceed 40 percent in some test sites, indicating highly excessive crack sealant application. Interestingly, Location C exhibits the highest percentage of the pavement covered by crack sealant but did not have the worst alligator index or PCR (see

Table 3.1), which can be explained by visual observations within Location C that the applied crack sealant had a wide overband and was additionally applied to regions where cracks were not present. The results indicate that the amount of crack sealant covering the lane width and SN are not correlated; this is not surprising because the LWST measures skid resistance in the left wheel path only. Therefore, the relationship between SN values and the percentage of the left wheel path area covered by crack sealant was investigated. It should be noted that skid resistance in the wheel path is most critical because it is where the majority of the traveling public's wheels will pass.

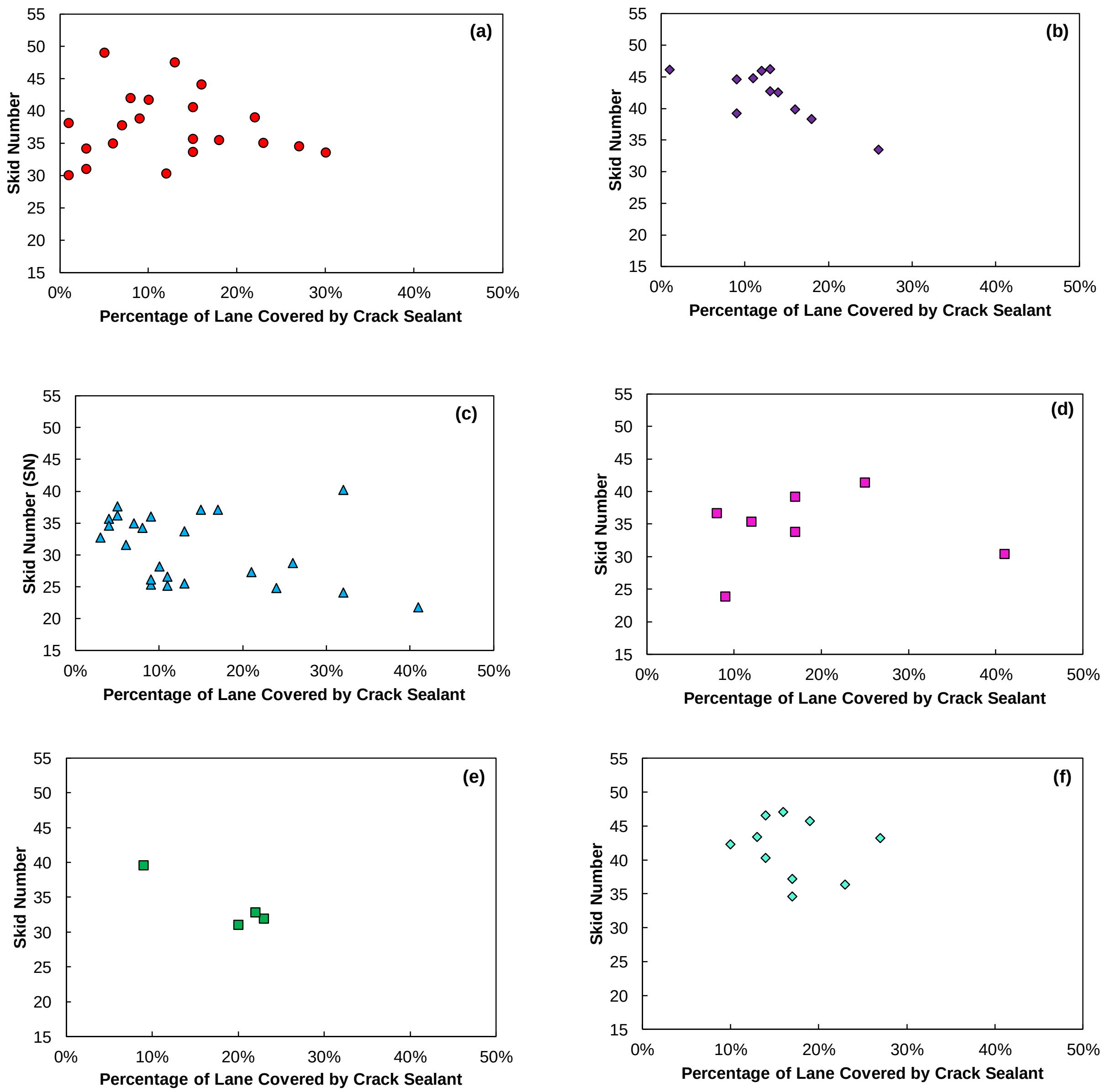

Figure 4.1. *Relationship between LWST skid numbers and the percentage of the pavement lane covered by crack sealant for test sections in (a) Location A, (b) Location B, and (c) Location C (d) Location D, (e) Location E.*

4.3. Relationship between SN Values and the Percentage of the Wheel Path Covered by Crack Sealant

Figure 4.2 shows the relationship between SN values and the percentage of the wheel path area where LWST testing was conducted covered by crack sealant. For each location, a linear regression analysis of the data was conducted and the corresponding coefficients of determination (R^2) and standard error (SE) values for each location are reported in Figure 4.2. The moderately high R^2 values and low SE values indicate that SN values are correlated with the percentage of the wheel path area covered by crack sealant. The trends in Figure 4.2 demonstrate that SN values generally decrease as the percentage of the wheel path covered by crack sealant increases for each location. These results support the hypothesis that the application of excessive crack sealant can pose a safety hazard. The primary distresses that lead to sealing in the wheel path are longitudinal cracking and alligator cracking, suggesting that sealing of cracks with extensive longitudinal and alligator cracking should be avoided. In addition to posing skid loss, pavements with alligator and longitudinal cracking area generally poor candidates for crack sealing because these distresses indicate an underlying structural problem in the pavement that cannot be overcome by crack sealing.

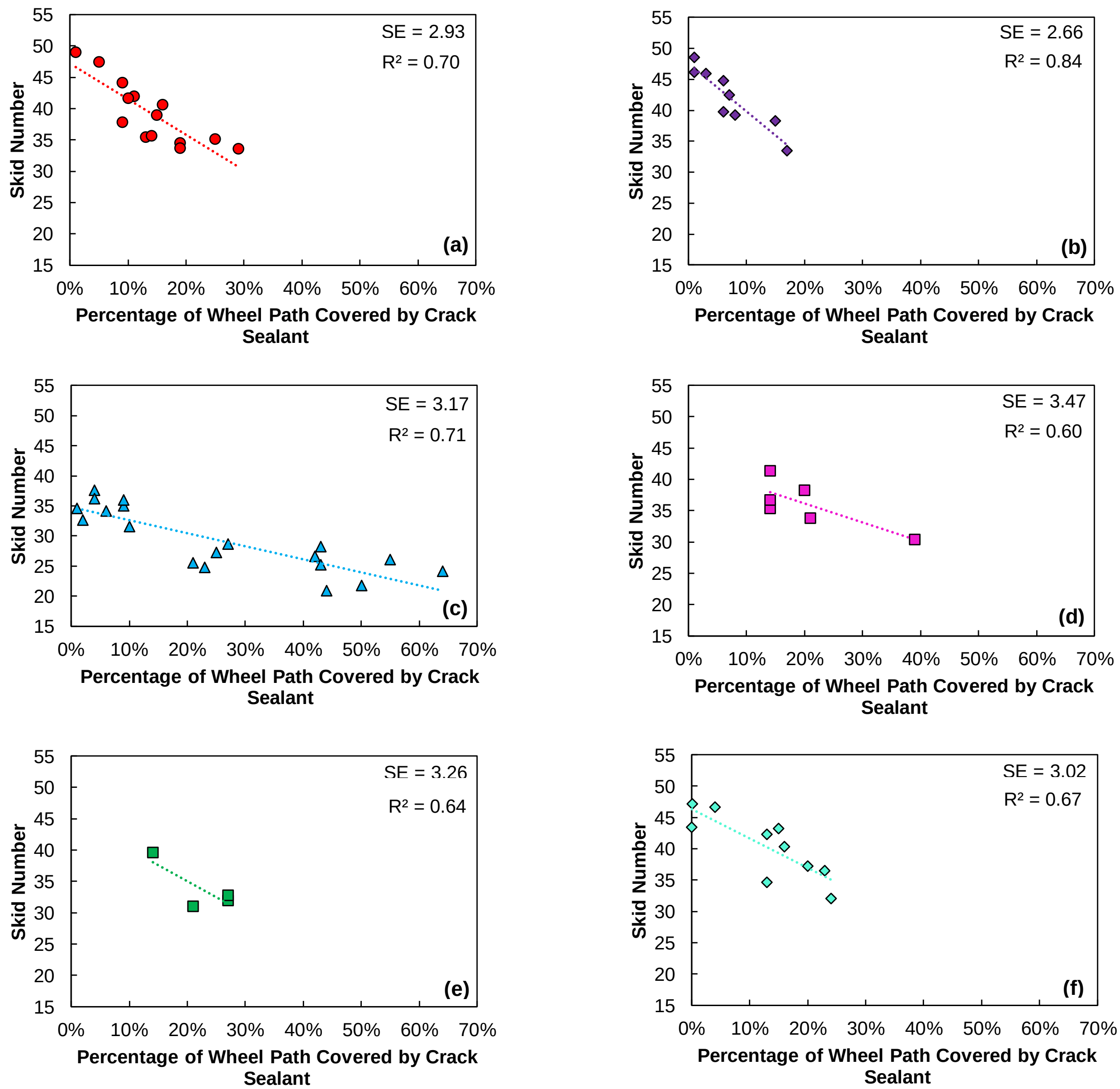

Figure 4.2. *Relationship between LWST skid numbers and the percentage of the wheel path covered by crack sealant for test sections in (a) Location A, (b) Location B, (c) Location C, (d) Location D, (e) Location E and (f) Location F.*

Once it was established that the wheel path coverage by crack sealant affects skid resistance, efforts were made to unify the results of the different testing locations. Figure 4.3 shows the relationship between SN and the percentage of the wheel path covered by crack sealant for all locations. The results demonstrate that the baseline skid resistance of the pavement affects the relationship between SN and the percentage of the wheel path covered by crack sealant. Locations A, B, D, E, and F all have good baseline conditions (see Table 4.1) and the results of both data sets follow a similar trend in Figure 4.3. Both sections C1 and C2 had a significantly lower baseline SN value than the other locations, and it can be seen that the Location C results generally fall below Locations A, B, D, E, and F in Figure 4.3. While the Location C results suggest that the baseline SN value affects the relationship between SN value and skid resistance, there is no discernable trend with baseline skid values for the other sections that all had relatively good baseline skid resistance (i.e., baseline SN values ranging from 43 to 49).

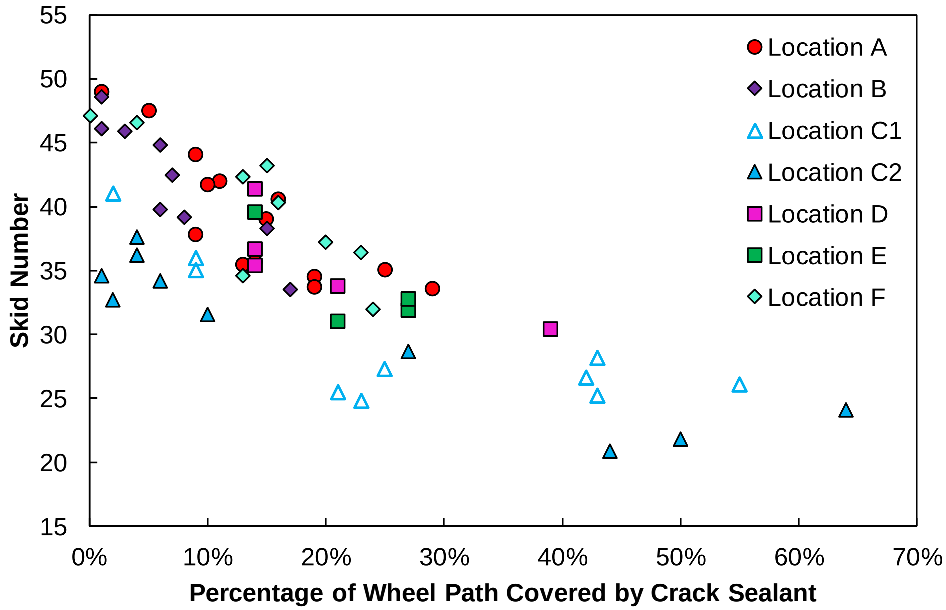

Figure 4.3. *Relationship between LWST skid numbers and the percentage of the wheel path covered by crack sealant for all test sections.*

In a further effort to unify the results of the different locations, the relationship between crack sealant coverage in the wheel path and the difference between the baseline SN and the SN value measured at each test site with crack sealant present, referred to as the 'change in SN' herein, was investigated. Figure 4.4 shows the relationship between the change in SN and the percentage of the wheel path covered by crack sealant for each location. Linear regression analysis of the data was performed and the corresponding R^2 and SE values are shown for each location. While there is significant scatter in the results, all locations exhibit an overall positive trend, indicating that higher amounts of crack sealant application in the wheel path generally correspond to greater loss in skid resistance. The slope of the relationship between the change in SN and the percentage of the wheel path covered by crack sealant is significantly lower for Location C than the other testing locations, indicating the change in SN due to crack sealant application is also affected by the baseline pavement skid resistance. In addition, the slopes of the change in SN versus the percentage of the wheel path covered by crack sealant for Locations A, B, D, E, and F differ somewhat. However, when these results are combined, as shown in Figure 4.5, it can be seen that the results of the different sections are generally in agreement.

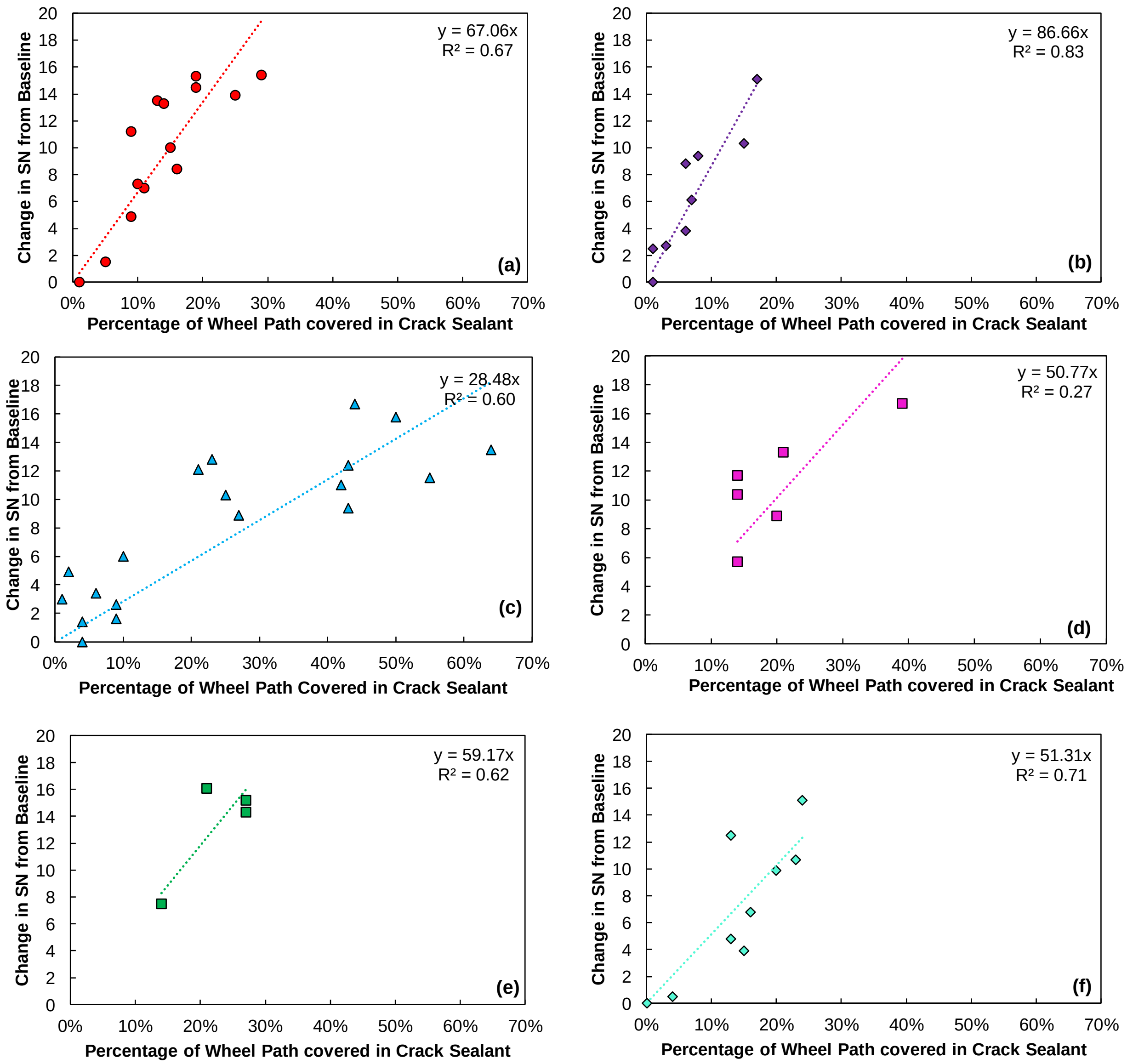

Figure 4.4. *Relationship between the change in skid numbers from the baseline and the percentage of the wheel path covered by crack sealant for test sections in (a) Location A, (b) Location B, and (c) Location C (d) Location D (e) Location E (f) Location F.*

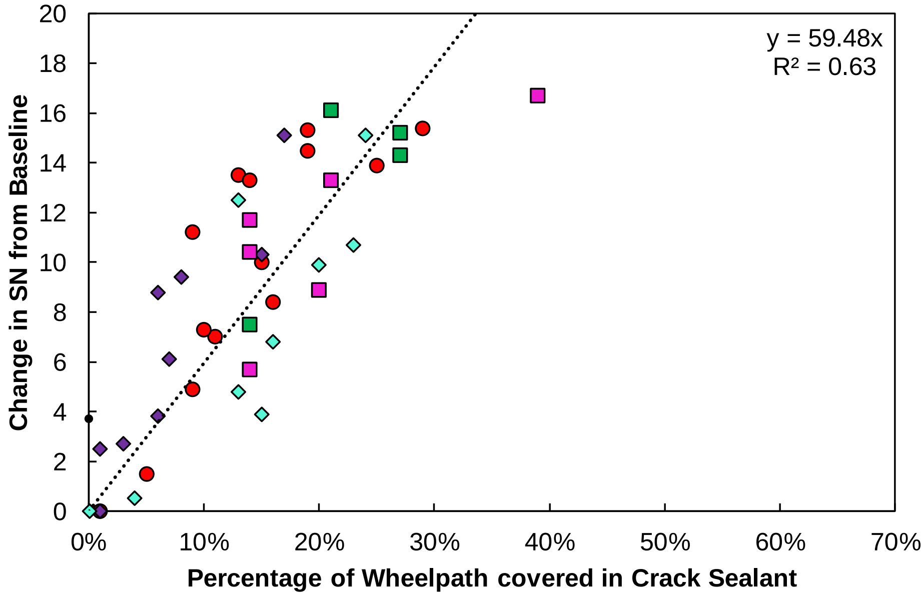

Figure 4.5. *Combined relationship between change in skid numbers from the baseline and the percentage of the wheel path covered by crack sealant for test sections A, B, D, E, and F.*

The change in SN versus the percentage of wheel path covered by crack sealing for all locations is shown in Figure 4.6. The results of Location C fall towards the lower bound of the scatter of the results for the other test sections and deviate from the trends of the other sections at relatively high percentages of crack sealant coverage in the wheel path. Based on these results, it does not appear that the change in SN can be used to unify the results of all test sections. However, the data corresponding to Location C extend to higher crack sealant coverages than the other sections, so definitive trends are difficult to ascertain.

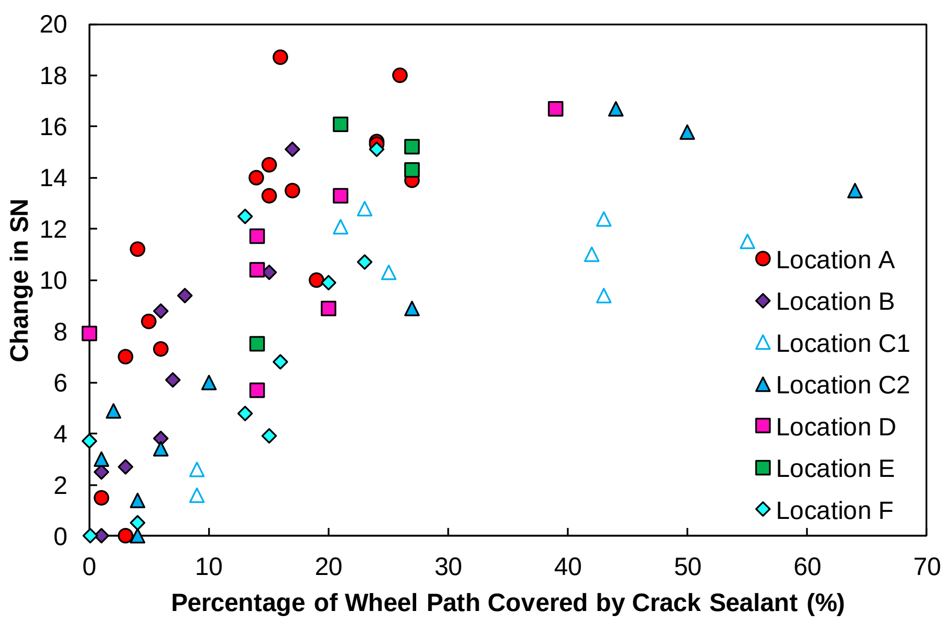

Figure 4.6. *Relationship between the change in skid numbers from the baseline and the percentage of the wheel path covered by crack sealant for all test sections.*

4.4. Establishment of Guidelines to Avoid Safety Hazards Associated with the Application of Crack Sealant

The sensitivity of the relationship between SN and the percentage of the wheel path covered by crack sealant to the existing pavement SN suggests that the pavement conditions for which sealing will pose a safety hazard depend on the existing pavement skid resistance. The results presented suggest that roadways with relatively high amounts of cracking and good baseline skid resistance may be crack sealed without risking a skid resistance safety hazard compared to roadways with poor baseline skid resistance. Therefore, maximum percentages of the wheel path that can be covered by crack sealant without posing safety hazards were defined by clustering the results into two categories of existing pavement condition: good (i.e., SN values of 43 and higher) and poor (i.e., SN value of 37). The good baseline SN value sections include Locations A, B, D, E, and F and the poor baseline SN value section corresponds to Location C. As previously discussed, trends in the results with baseline SN value could not be identified within the good baseline sections and only one of the locations evaluated had a poor baseline SN condition approaching safety thresholds. The established limits for the percentage of the wheel path that can be covered by crack sealant without causing unsafe frictional characteristics were related to the pavement distress survey results to define pavement conditions where sealing should be avoided.

It should be noted that the effect of crack sealant configuration could impact the established limits based on pavement distress survey results; however, the effect of crack sealant configuration on skid resistance could not be evaluated in this study because all test sections evaluated included the overband configuration. The overband configuration leads to greatest surface coverage and thus, the established thresholds can be regarded as conservative for other configuration types.

Allowable Percentage of Crack Sealant in the Wheel Path

Linear regression of the relationship between SN value and the percentage of the wheel path covered by crack sealant was conducted after clustering the results into good and poor baseline SN conditions. Based on the regression results, 90 percent confidence intervals were established with upper and lower bounds defined by Equation 4.1.

$$Bound = \hat{y} \pm SE \cdot t_{crit} \tag{4.1}$$

Where $\hat{y}$ is the SN value predicted by the regression line, *SE* is the standard error of the regression line, and t_{crit} is the critical value on the t distribution for the desired confidence level. To define the two-sided confidence interval bounds, an α value of 0.1 was used, meaning that there is a 5 percent probability of a value falling below the lower bound and 5 percent probability of a value falling 5 percent above the upper bound. Given the sample sizes, the t_{crit} value for the poor baseline SN results is 1.734 and the t_{crit} value for the good baseline SN results is 1.680. The results are shown in Figure 4.7.

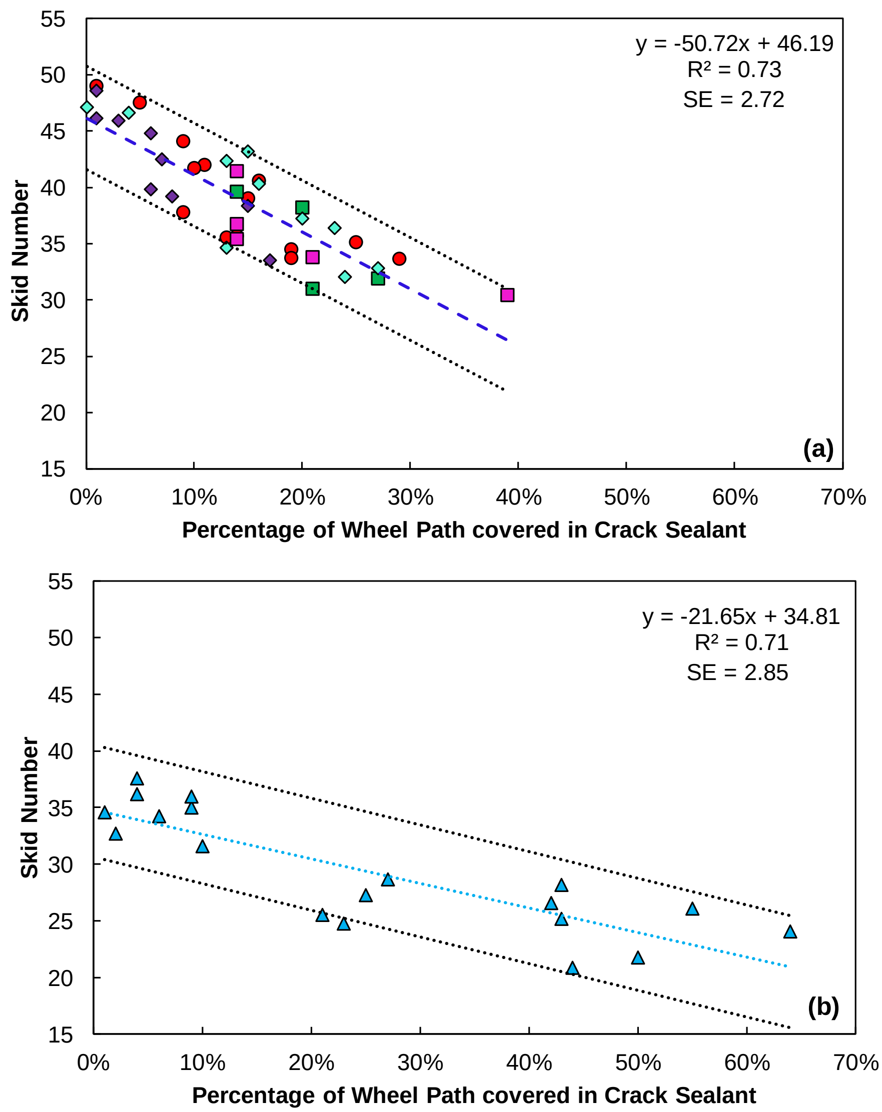

Figure 4.7. *Relationship between LWST skid number and the percentage of the wheel path covered by crack sealant with 90 percent confidence intervals (dotted lines) for (a) Locations A, B, D, E, and F, and (b) Location C.*

The linear regression models and confidence intervals were used to establish limits for the percentage of the wheel path that can be covered by crack sealant in pavements with good and poor baseline skid resistance without dropping below critical the SN thresholds for low and high volume roads of 30 and 35, respectively (Jayawickrama et al. 1996). When establishing these limits, two reliabilities were considered: 50 percent and 95 percent. The reliability concept employed herein is analogous to the reliability concept implemented in Pavement ME (ARA Inc. 2003). The 50 percent reliability thresholds corresponds to the Figure 4.7 regression model predictions of the percentage of the wheel path covered by crack sealant that correspond to SN values of 30 and 35. The 95 percent reliability threshold corresponds to the lower confidence interval bound predictions of crack sealant covered in the wheel path for SN values of 30 and 35 in Figure 4.7; that is, there is 95 percent confidence that the established limit for crack sealant coverage will not lead to an SN value lower than the critical safety threshold.

Table 4.2 shows the established limits for acceptable crack sealant application in the wheel path. It can be seen that the allowable amount of crack sealant in the wheel path is significantly higher for the good baseline condition (minimum SN value of 43) than the poor baseline condition (SN value of 37). These results indicate that the existing condition of the roadway plays a significant role in establishing whether crack sealant can be applied without reaching an unsafe condition. The relatively high limits for allowable amounts of crack sealant in the wheel path for pavements with good baseline skid resistance indicate that many pavements are good candidates for crack sealing without posing a safety hazard. Figure 4.8 provides examples of pavement sections exhibiting 17 percent and 27 percent crack sealant coverage in the wheel path to provide some context to these thresholds given in

Table 4.2.

The thresholds for pavements with poor baseline skid resistance imply that crack sealing may be an inappropriate preventive maintenance strategy for pavements with SN approaching safety limits (i.e., 37) because even small amounts of crack sealant in the wheel path can lead to a drop in skid resistance that could pose a safety hazard to traffic. For high volume roadways where the SN value should not drop below 35, sealing should be avoided. For low volume roadways, crack sealing may be possible without leading to conditions dropping below the commonly accepted SN threshold of 30 if relatively minor wheel path cracking exists such as that shown in Figure 4.8 (a). However, it is generally recommended that crack sealing be avoided in conditions where the existing pavement has marginal skid resistance and that an alternative preventive maintenance strategy be sought that would increase frictional characteristics (e.g., chip seal, microsurfacing).

Table 4.2. *Thresholds for Allowable Percentages of Crack Sealant in the Wheel Path to Maintain Safe Conditions*

Existing Skid Resistance	**SN Threshold**	**Threshold for Percentage of Wheel Path Covered by Crack Sealant (%)**	
		50% Reliability	**95% Reliability**
Good Condition (≥43)	35	22	17
	30	32	27
Deteriorated Condition (37)	35	3	0
	30	24	19

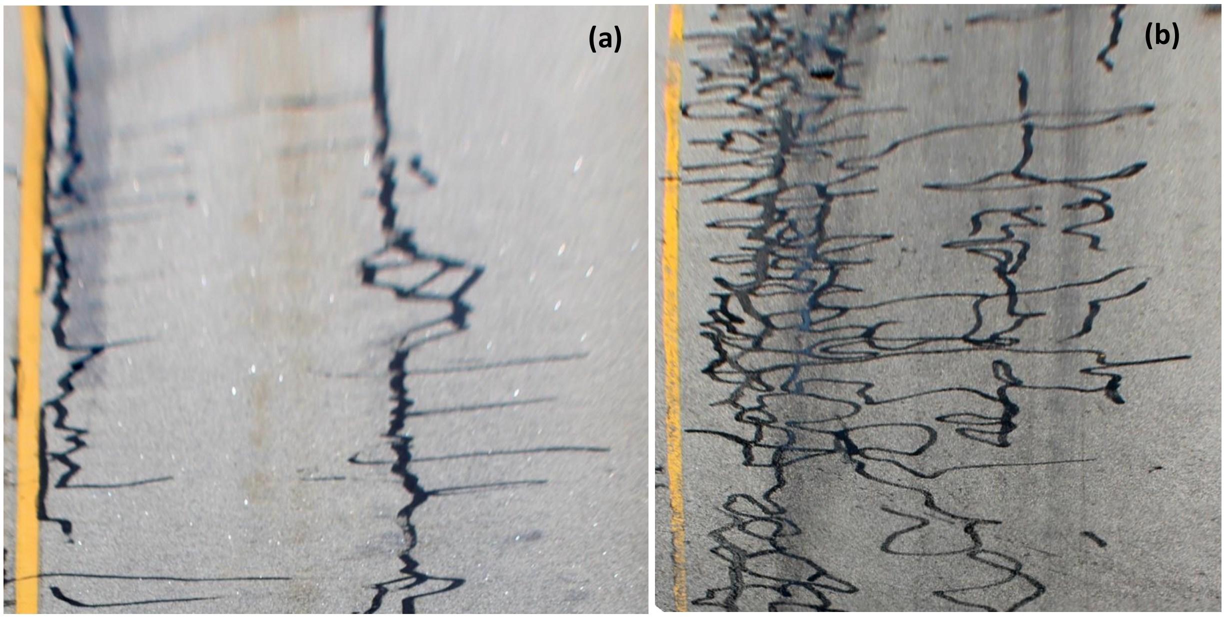

Figure 4.8. *Visual representation of (a) 17 percent crack sealant within the wheel path and (b) 27 percent crack sealant coverage within the left wheel path.*

Allowable Pavement Distress Conditions

The effects of the existing pavement condition on the crack sealant coverage in the wheel path and corresponding skid resistance were investigated. The compiled, pertinent information is presented in Table 4.3. The maximum and average values reported in Table 4.3 correspond to the maximum and average values for a given location, respectively. The results presented demonstrate that the crack sealant coverage varies considerably along the different locations of testing; therefore, it is speculated that the pre-existing pavement condition also varied within each location of testing. However, pavement distress survey results of the pre-existing pavement are reported as a single value for each segment indicated in Table 4.3. Therefore, the worst conditions for a given location, in terms of skid number and crack sealant coverage in the wheel path, were compared to the pavement distress survey data to establish pavement conditions where crack sealant application should be avoided.

Table 4.3. *Summary of Crack Sealant Coverage, SN Values, and Pre-existing Condition of Locations Evaluated*

Location	A	B	C1	C2	D	E	F
Maximum Percentage of Wheel Path Covered by Crack Sealant	29%	17%	55%	64%	39%	27%	27%
Average Percentage of Wheel Path Covered by Crack Sealant	14%	11%	27%	21%	20%	22%	16%
Minimum SN	30.10	33.50	24.80	20.9	30.40	31.00	32.80
Average SN	37.49	42.68	29.57	30.24	36.15	33.83	44.16
Alligator Cracking Index	86.80	76.80	71.19	76.44	64.44	72.63	76.40
Oxidation Rating	0	0	100	100	0	0	0
Transverse Cracking Index	80	80	80	80	80	80	100

Table 4.3 demonstrates that the sections evaluated are relatively similar in terms of transverse cracking. Also, because transverse cracks are perpendicular to the flow of traffic, sealant application is expected to have a minimal impact on overall skid resistance. In contrast, the sealing of alligator cracks leads to a high concentration of crack sealant in the wheel path. Location C is the only roadway that did not exhibit evidence of severe oxidation; it is interestingly also the pavement with the worst baseline SN value and highest amount of crack sealant coverage in the wheel path. Furthermore, the results of Location F compared to the other locations indicate transverse cracking did not lead to excessive crack sealant application; while Location F shows the greatest transverse cracking, it does not show nearly the highest crack sealant coverage in the wheel path. Therefore, pavement conditions where crack sealing should be avoided due to the risk of posing a safety hazard were developed based on relationship between alligator cracking index, which includes the combined effects of low, moderate, and high severity alligator cracking, and maximum crack sealant coverage in the wheel path. It should be noted that the literature suggests that crack sealing of pavements with alligator cracking is not recommended because the pavement is likely structurally compromised (Decker 2014). Thus, establishing thresholds to preclude crack sealant application to pavements with significant alligator cracking may also mitigate crack sealant application to pavements where the treatment will be relatively ineffective for extending pavement service life.

The relationship between maximum crack sealant coverage in the wheel path and minimum skid numbers of the different locations is shown in Figure 4.9; the results indicate the two values are highly correlated and thus, demonstrate the validity in using the maximum crack sealant coverage in the wheel path in the analysis to establish safety thresholds in terms of existing pavement condition. Interestingly, Locations C1 and C2 follow the same trends as the other locations despite their lower baseline SN values.

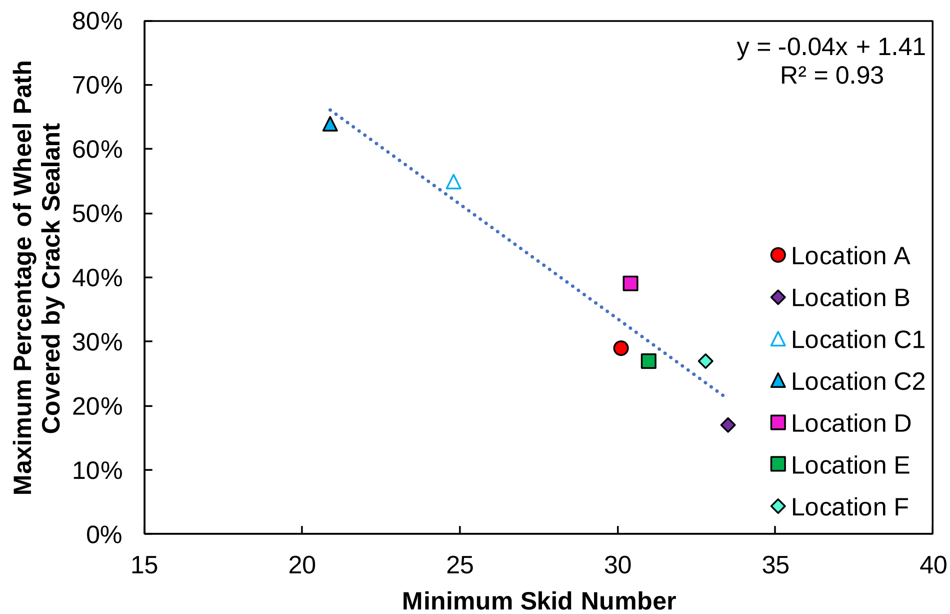

Figure 4.9. *Relationship between location minimum skid number and max crack sealant coverage in the wheel path.*

The relationship between the alligator cracking index and maximum crack sealant coverage in the wheel path is shown in Figure 4.10. It can be seen that a relationship exists between maximum crack sealant coverage and alligator cracking index, with the exception of Location C which shows outlier behavior. Location C was omitted from the analysis to establish thresholds for acceptable alligator cracking indices for sealing because the low baseline SN value prohibits safe application of sealant, as previously discussed. The scatter in the relationship between maximum crack sealant coverage in the wheel path and alligator cracking index is somewhat expected because each section exhibited a wide range of values in the percentage of the wheel path covered by crack sealant but only a single alligator index is given for the entire section. Thus, the exact location of alligator index measurement may not align with that of the maximum sealant coverage. A regression analysis was performed to obtain a functional relationship between alligator cracking index and maximum sealant coverage in the wheel path for all other locations. This relationship was used to establish alligator cracking index thresholds to maintain SN values of 35 and 30 using the 95 percent reliability thresholds for crack sealant coverage in the wheel path given in

Table 4.2. The corresponding alligator index thresholds are shown in Table 4.4. Note that the established thresholds pertain to pavements with good baseline skid resistance (i.e., SN of 43 or higher). It is recommended that the established threshold be strengthened in the future by incorporating a larger database of locations.

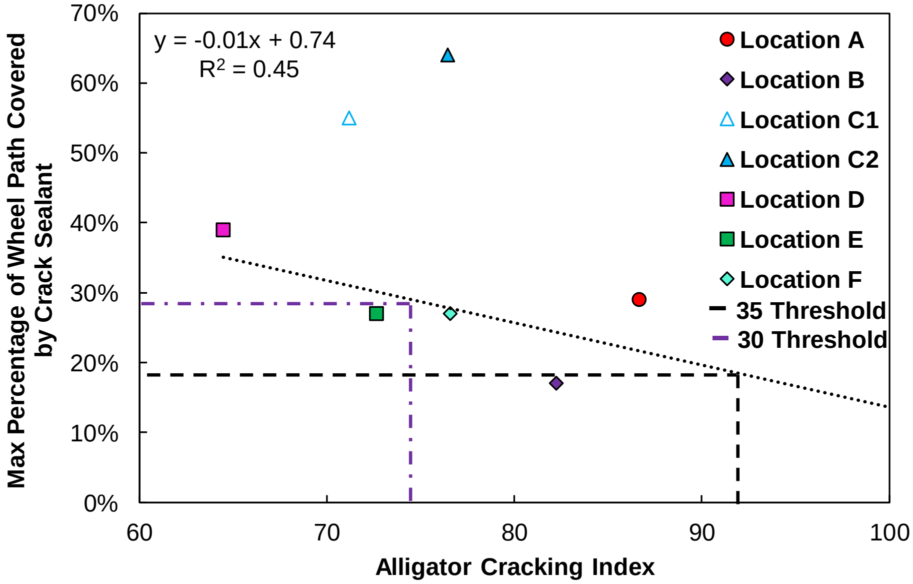

Figure 4.10. *Relationship between alligator cracking index and maximum percentage of wheel path covered by crack sealant.*

Table 4.4. *Alligator Cracking Index Thresholds for Pavements with Good Baseline Skid*

Resistance (SN ≥ 43)

SN Threshold	Alligator Cracking Index Threshold
35	92
30	75

5. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are drawn from the results of this study:

1. An increase in the percentage of the wheel path covered by the crack sealant generally leads to a decrease in pavement skid resistance.
2. The effect of crack sealant in the wheel path on skid resistance is a function of the existing pavement's frictional characteristics. Pavements with deteriorated frictional characteristics (i.e., SN values of 37 or lower) are poor candidates for crack sealing due to safety concerns. Pavements with good skid resistance which are good candidates for preventive maintenance treatment (i.e., low to moderate cracking) can generally be safely be sealed.
3. The concentration of crack sealant in the wheel path is influenced by the extent and severity of alligator cracking. Therefore, future crack sealant specifications should include alligator cracking condition thresholds for crack sealant project selection to avoid safety hazards.
4. All of the sections evaluated in this project included the overband crack sealant configuration. The effects of other types of crack sealant configurations on pavement skid resistance merits consideration in future work. The use of the flush fill configuration may allow for reducing skid resistance hazards associated with crack sealant application.
5. The pavements evaluated in this study had either skid numbers greater than or equal to 43 or 37. Additional sections with baseline skid numbers in the range of 37 to 43 should be investigated in future work to better elucidate the safety of crack sealant application on pavements with marginal skid resistance.

6. CITED REFERENCES

1. ARA Inc. *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, Appendix BB: Design Reliability*, National Cooperative Highway Research Program, National Research Council, Washington, D.C., 2003.
2. American Society for Testing and Materials. *Standard Specification for Joint and Crack Sealants, Hot Applied, for Concrete and Asphalt Pavements,* ASTM D6690, West Conshocken, PA, 2015.
3. American Society for Testing and Materials. *Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire,* ASTM E274, West Conshocken, PA, 2011
4. California Department of Transportation. *Chapter 3 Crack Sealing and Filling*. Caltrans Flexible Pavement Materials Program, California, 2003.
5. Chehovits, J., M. Manning. Materials and Methods for Sealing Cracks in Asphalt Concrete Pavements. *Transportation Research Record*, No. 990, 1984, pp. 21-30.
6. Chong, G. J., Rout and Seal Cracks in Flexible Pavement: A Cost- Effective Preventative Maintenance Procedure. *Transportation Research Record*, No. 1268, 1990, pp. 8-16.
7. Decker, D. S. *Best Practices for Crack Treatments for Asphalt Pavements*, NCHRP Report 784, National Research Council, Washington, D.C., 2014.
8. Jayawickrama, P. W., R. Prasanna, S.P. Senadheera. Survey of State Practicies to Control Skid Resistance on Hot-Mix Asphalt Concrete Pavements. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1536, 1996, pp. 52-58.
9. Masson, J. F., P. Collins, and M. Lowery. Temperature control of hot-poured sealants during the sealing of pavement cracks. *Construction and Building Materials*, Vol. 19, No. 6, 2005, pp. 423-429.
10. Luo, W., K. Wang, and L. Li. Wheel Path Definition based on A Multi-Factor Traffic Wander Model. *Proceedings of the Transportation Research Board 91st Annual Meeting, Washington, D.C.*, 2012.
11. Minnesota Department of Transportation. *Special Provisions 2005.* MNDOT Special Provisions SP2005BOOK, 2006.
12. North Carolina Department of Transportation. *Section 657 Seal Existing Pavement Cracks and Joints*. NCDOT Specifications, North Carolina, 2012.
13. North Carolina Department of Transportation. *Pavement Condition Survey Manual*. NCDOT, North Carolina, 2016.
14. Puneet, G. B., N. K. Garg. Binarization Techniques used for Grey Scale Images. *International Journal of Computer Applications*. Vol. 7, 2013
15. Smith, K. L., and A. R. Ronnie. *Materials and Procedures for Sealing and Filling Cracks in Asphalt-Surfaced Pavements: Manual of Practice*, FHWA Report No. FHWA-RD-99-147, National Research Council, Washington, D.C., 1999.
16. Truschke, C., D. Peshkin, K. Smith, and K. Smith. *Colorado Department of Transportation hot mix asphalt crack sealing and filling best practices guidelines*. Colorado Department of Transportation Report CDOT-2014-13, 2014.