Federal Highway Administration Pavement Friction Management (PFM) Support Program

PFM Program Utilizing Continuous Friction Measurement Equipment and State-of-the-Practice Safety Analysis Demonstration Project Final Report

U.S. Department of Transportation
Federal Highway Administration

September 2019

FOREWORD

This report details the results of using a continuous friction measurement equipment (CFME) system, the Sideway-force Coefficient Routine Investigation Machine (SCRIM), to perform network-level friction measurements and compare it to a traditional locked-wheel skid tester (LWST). The report summarizes the results of (a) performing SCRIM and LWST friction testing in four States; (b) collecting comprehensive historical friction, crash, and other data from the four States; (c) analyzing the data to identify appropriate investigatory friction and investigatory macrotexture levels; and (d) providing guidance on how to compile and analyze friction and crash data to further the development of a pavement friction management plan (PFMP) and implement it into practice. The research team also prepared a separate document with recommended revisions to the 2008 AASHTO Guide for Pavement Friction to provide additional insight and guidance on the development of pavement friction management (PFM) programs using CFME. The recommended revisions to the AASHTO Guide, together with this report, will provide a much greater level of detail regarding the steps an agency should take in developing a PFM program. It will also address development and implementation barriers, and how they can be overcome by agencies attempting to develop a PFMP using CFME.

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15. Supplementary Notes
Andrew Mergenmeier, FHWA COR

16. Abstract
This report documents a Pavement Friction Management demonstration project conducted in collaboration with four State agencies that collected and analyzed pavement friction, crash, traffic, and other geometric data in each of the States. The research team collected, processed, and analyzed approximately 4,000 miles of data, and recommended a methodology to identify sections of roadway with high friction-related crash risk, suggesting corrective friction treatments in a cost-effective manner, to reduce friction-related crashes.

The study used a Sideway-Force Coefficient Routine Investigation Machine (SCRIM) with macrotexture and road geometry sensors to perform the testing. The study demonstrated methods for establishing investigatory levels of friction for different friction demand categories and developed pilot pavement friction management plans (PFMPs) for the four States using proven safety analysis methods (Safety Performance Functions and empirical Bayes method) that considered friction, macrotexture, geometric data, traffic, and crash counts. The results of the study confirmed a strong association between crashes and continuously measured frictional pavement properties (friction and macrotexture) and that the adoption of continuous friction measurement equipment (CFME) data within a PFMP instead of the traditional sampling approach using locked-wheel skid testers (LWSTs) can have a significant positive impact on crash reductions. The analysis of the networks tested suggests that a PFMP implemented with CFME data can result in high potential crash reductions, yielding significant potential economic savings with favorable benefit/cost ratio.

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Friction, Microtexture, Macrotexture, Continuous Friction Measurement Equipment (CFME), Sideway-Force Coefficient Routine Investigation Machine (SCRIM), Locked-wheel skid tester (LWST), Safety Performance Functions (SPF), Empirical Bayes (EB)	**No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov**

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SI* (MODERN METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		Length		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		Area		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	Acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		Volume (volumes greater than 1,000L shall be shown in m^3)		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		Mass		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		Temperature (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
		Illumination		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		Force and Pressure or Stress		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

Approximate Conversions from SI Units				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		Length		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		Area		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
Ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		Volume		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		Mass		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		Temperature (exact degrees)		
°C	Celsius	1.8c+32	Fahrenheit	°F
		Illumination		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		Force and Pressure or Stress		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003, Section 508-accessible version September 2009.)

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EXECUTIVE SUMMARY

The Federal Highway Administration (FHWA) initiated a study to develop and promote Pavement Friction Management Programs (PFMPs) and investigate the potential benefits of using continuous friction measurement equipment (CFME) as compared to conventional locked-wheel skid trailer (LWST) testing. The overall goal of the study is to reduce highway crashes and related fatalities through the development and demonstration of proactive PFMPs. Such programs, when properly devised and effectively implemented, have the potential to significantly reduce the number and severity of crashes related to pavement friction and texture.

Phase I of the study included a theoretical analysis of vehicle, tire, and pavement interactions as they relate to skidding and resultant crashes, and a detailed evaluation of the pavement friction and macrotexture measurement equipment used in managing pavement friction. The equipment evaluation recommended the use of a Sideway-Force Coefficient Routine Investigation Machine (SCRIM) with macrotexture and road geometry sensors for testing in phase II of the study.

Phase II of the study had the following objectives: (a) assisting four States in developing PFMPs by considering pavement friction, macrotexture, and crash counts; (b) developing and demonstrating methods for establishing investigatory levels (ILs) of friction and macrotexture for different friction demand categories; and (c) demonstrating proven continuous friction and macrotexture measurement equipment for network-level data collection. The States of Florida, Indiana, Washington, and Texas were selected as participants in the study.

This document reports on the results of the following efforts:

- Network-level Data Collection – Collect comprehensive historical friction, crash, and other data and perform SCRIM and LWST friction testing in all the States;
- Network-level Data Analysis – Analyze the data to identify appropriate investigatory friction and investigatory macrotexture levels (using both the American Association of State Highway and Transportation Officials [AASHTO] *Guide for Pavement Friction* [GPF] methodologies and the proposed methodology using CFME data);
- Crash Analysis – Calculate crash risk using safety performance functions (SPFs) and the empirical Bayes (EB) method; and
- Selection of Restoration Treatments – Provide guidance on how to compile and analyze friction and crash data to further the development of a PFMP and implement it into practice, using benefit/cost (B/C) analysis to select treatments.

The study confirmed a strong association between crashes and continuously measured frictional and geometric pavement properties (friction, macrotexture, curvature, etc.), from which a proactive PFMP can be implemented after evaluating different friction-enhancement treatments that will reduce the risk of crashes and associated fatalities. In New Zealand, the B/C ratio of the skid resistance policy has been greater than 20 (Owen, 2014). In the United Kingdom, the B/C ratio of the skid resistance policy has been reported as 5.5 according to one source, and as high as 18.1 by another (Rogers and Gargett, 1991; Stevenson et al., 2011).

Modern PFMPs require that adequate levels of friction be maintained on all roadway sections based on the friction demand needed for different types of roadway segments. If this approach is used, different friction threshold values—*ILs*—can be set based on *friction demand categories*. When friction thresholds are not met, a detailed project-level evaluation needs to be done to verify if an increase in the friction is warranted to reduce the crash risk (e.g., of roadway departure fatalities and serious injuries). Critical aspects of a PFMP include the equipment used to collect friction data, the processes needed to analyze and interpret friction data, the crash data and the geometric parameters that might influence vehicle response in each section, and the comparison of the cost-effectiveness of possible treatments. Furthermore, the PFMP should be an integral part of a network-level systemic approach that involves widely implemented improvements based on high-risk roadway features.

Data Collection

The project team worked with the States' highway staff to select relevant samples of the different State networks to develop pilot PFMPs aligned with the agency's pavement and safety management practices. The team compiled available pavement, inventory, and crash data for the selected networks, which included interstate and primary roads with both Portland cement concrete and asphalt pavements (e.g., dense graded, porous friction course or open graded friction course, chip seals, etc.) and different traffic levels. Additional data were collected using the SCRIM and LWST on highways that covered approximately 4,000 miles in all the States. The SCRIM friction, macrotexture, and surface geometry data were processed using a 0.1-mile analysis segment and friction was standardized to a speed of 30 mph (50 km/h [SR30]). A representative friction value was established for each 0.1-mile (160-m) segment by using a 3-point moving-average filter (20 m ≈ 60 ft) and selecting the minimum value in the 0.1-mile segment. An average mean profile depth (MPD) was assigned to each 0.1-mi segment.

Crash counts were computed to convey the risk for different crash severities (i.e., fatality, serious injury, and total) occurring along each 0.1-mi segment, and the information was paired with friction data collected using GPS coordinates. For the network tested, the distribution of fatal and severe injury crashes follows a similar trend to the total crashes. Thus, the study focused on total crashes to have a larger sample and assumed that a reduction in the total number of crashes will likely result in a reduction in fatalities and serious injury crashes.

Data Analysis

The 0.1-mile segment data were divided into friction demand categories based on the factors perceived as having the most influence on the friction-crash relationship. These include interstate routes, divided primary routes, and non-divided primary routes, with and without events when present. Events were defined as horizontal curves, intersections, sections with significant grade (>5 percent), etc. Finer levels of aggregation considering other factors, such as traffic, pavement type, and aggregate type, were investigated, but the sample sizes were too small for meaningful analysis.

The relationship between crashes and both SCRIM friction and macrotexture were investigated for segments with different types of pavement surfaces, on various roadway categories, and with and without events. The team attempted to separate different friction demand categories in all the States, but sometimes it was not possible due to the lack of information in the State's pavement management system (PMS). Illustrative friction investigatory threshold levels for the various friction-demand categories available were determined. Due to the limited data set, the investigatory threshold levels determined do not provide adequate confidence to be considered a recommendation for all the pavement types analyzed, but rather presented for illustration purposes. The trends to establish the macrotexture thresholds were not as clear as the friction thresholds due to the convoluted relationship between friction and macrotexture.

As a complement to the threshold analysis, the study also tested an alternative approach for the identification of high crash-risk areas using SPFs and EB rate estimation from observed crashes. SPFs incorporating friction and other relevant parameters were developed using the negative binomial model to predict the number of crashes in the 3-year period for each 0.1-mi road segment. The EB method was then used to produce an estimate of the number of crashes in each segment and the possible crash reduction as a result of a treatment selected to restore and/or improve the friction (dense graded asphalt concrete [DGAC] and porous friction course [PFC] overlays for each asphalt pavement, conventional diamond grinding for Portland cement concrete pavement [PCCP], and high-friction surface treatments [HFS] on critical locations for all pavement types).

The overall potential savings of various treatments were assessed using potential crash reductions estimated with the modified SPF and the EB methods and average treatment costs. Due to data limitations, the potential crash reduction analysis was limited to the DGAC and PCCP networks investigated in this study. The relationship between crashes and friction was not so obvious for the PFC and chip seal sections, and not so easy to pinpoint because of its confounding relationship with macrotexture. It is expected that larger data sets will provide the necessary detail to solve this problem. The results showed potential crash reductions of 4 percent to 23 percent in the networks investigated because of friction-improving treatments on the highest crash rate sections where the treated sections were approximately 3 percent of the networks investigated, providing a high return on investment.

The final analysis consisted of a quantitative and qualitative assessment of the advantages of using CFME measurements versus the traditional LWST sampling approach. The quantitative analysis included using LWST data and the recommended GPF methodologies. The quantitative analysis was not successful in establishing investigatory friction threshold levels. The qualitative analysis included the recognition that CFMEs provide a much higher spatial coverage, thus reducing the chances of missing localized areas with friction deficiencies. The normal LWST testing frequency of one or two tests per mile results in measuring only 1 percent to 2 percent of the pavement surface, respectively. The CFME measures the pavement continuously and provides a measurement test result at a minimum frequency of every 0.10 m, although it is expected to be more practical to average the data over a greater length, such as every 10 m for network-level analysis of the pavement surface. This is the approach needed for a proactive network-level PFMP, especially when using safety analyses methods such as those found in the AASHTO Safety Analyst SPF-EB methods (AASHTO, 2010). The importance of having higher resolution friction data is illustrated with examples that show how critical locations can be missed by using the current LWST testing and sampling approach, especially in high friction-demand locations, such as curves, intersections, and other sections where there is not only a high demand for friction but also more polishing of the pavement (i.e., lower available friction) because of braking and turning maneuvers.

Conclusions

The main results of the *Pavement Friction Management* demonstration project, conducted in collaboration with four State agencies, can be summarized as follows:

- The study confirmed a strong association between crashes and continuously measured frictional pavement properties (friction and macrotexture).
    - Therefore, a proactive PFMP can help reduce the number of crashes and associated fatalities.
    - The data obtained in this project show that both wet and dry crashes increase when pavement friction decreases.
- It was possible to identify illustrative ILs for frictional properties using the CFME (friction and MPD) measurements for some roadway categories (tangents and curves) with different pavement types.
    - The analysis based on the CFME results allowed the determination of illustrative ILs for four friction demand categories and was able to associate them with a level of crash "risk."
    - Some of the samples of data were not as robust as needed to establish statistically sound ILs for all the friction demand categories considered.
- The collection of continuous friction and macrotexture data through the adoption of CFME instead of the traditional sampling approach using an LWST can have a significant impact on crash reductions and supports a proactive PFMP.
    - Measuring friction continuously, especially when complemented by macrotexture and road geometry data, provides a more effective method for identifying the most critical sections and allows safety improvement efforts to focus on the higher-risk locations, such as controlled intersections, ramps, and curves where friction demand is the highest.
    - Providing an appropriate level of macrotexture is also critical for high-speed roadway segments.
- An analysis to determine the probability of identifying friction thresholds as described in the three GPF methods using LWST data was not successful in establishing investigatory friction threshold levels. The primary reason suspected is that the LWST's discrete measurements are not representative of the friction of interest for crash analysis in a 0.1-mi section of road because of the variability in friction throughout the 0.1-mi section.
- The application of the SPF-EB analysis and B/C method, in conjunction with continuous measurement of the pavement friction, macrotexture, and road geometry, allows the identification of sites with the highest potential payoff for pavement friction improvements.
    - The analysis of approximately 4,000 mi of tested pavement suggests that if PFMPs can be implemented with CFME data to determine recommended treatments, potential reduction of crashes is possible. This, in turn, would result in a reduction of fatalities and serious injuries, with total investment yielding significant potential economic savings with a very favorable B/C ratio.

CHAPTER 1. INTRODUCTION

The United States has experienced gradual improvements in highway safety since the enactment of the Highway Safety Act of 1966. The fatality rate on U.S. highways has decreased steadily from about 5.5 fatalities per 100 million vehicle miles traveled (MVMT) in 1966 to about 1.16 fatalities per 100 MVMT in 2017 (National Center for Statistics and Analysis, 2018). In addition, the total number of highway fatalities during the same time has decreased 27 percent from 50,894 to 37,133. However, over the last decade, the decline in fatalities stopped and was followed by an increase, indicating that there is still much work to be done to improve highway safety.

These recent improvements are at least partly the result of proactive safety policies and programs, such as the Federal Highway Administration (FHWA) Highway Safety Improvement Program (HSIP) instituted in 2005, as well as improved guidance on highway safety, including the 2010 American Association of State Highway and Transportation Officials (AASHTO) *Highway Safety Manual*. Various safety goals have been established to further the progress, the latest being the National Strategy on Highway Safety Toward Zero Deaths (TZD) effort to reduce pavement-related crashes and the number of highway fatalities and serious injuries.

Even with the significant progress that has been made to date, more proactive safety treatments are needed to engineer roads to make them safer and to eventually achieve the long-term goal of zero fatalities. For pavement surfaces, this means ensuring adequate friction and texture through:

- the proper design and construction of pavement surface mixes,
- sufficient routine testing and monitoring of the friction and texture of in-service pavements,
- application of corrective treatments in a cost-effective manner based on carefully established criteria linking friction and texture to crash potential.

An effective pavement friction management program (PFMP) is a critical component in the effort to reduce pavement-related crashes and to lessen the consequences of crashes.

1.1 OVERVIEW OF THE FHWA PAVEMENT FRICTION MANAGEMENT SUPPORT PROGRAM

The FHWA initiated a study to develop and promote PFMPs and investigate the benefits of using continuous friction measurement equipment (CFME) compared to a conventional locked-wheel skid tester (LWST). The overall goal of the study is to reduce highway crashes and related fatalities through the development and demonstration of PFMPs. Such programs, when properly devised and effectively implemented, have the potential to significantly reduce the number and severity of crashes by decreasing crashes related to pavement friction and texture.

Phase I of the study consisted of a theoretical analysis of vehicle, tire, and pavement interactions as they relate to skidding and resultant crashes, and a detailed evaluation of the pavement friction and texture measurement equipment used in managing pavement friction.

The phase I study examined a variety of approaches used in the past to establish links between friction/texture and crashes. It also explored current practices involving the setting of investigatory and intervention thresholds for managing friction and texture at the network level.

Another task in phase I was to recommend a friction measurement system for use in phase II. The study rated the friction measurement systems that are currently available on a variety of factors and recommended the Sideway-Force Coefficient Routine Investigation Machine (SCRIM) for use in phase II of the study.

Phase II of the study, titled "Acceptance Testing and Demonstration of the Continuous Friction Measurement Equipment (CFME)," has the following objectives:

- Assist four States in developing a PFMP by considering pavement friction, texture, and crashes.
- Develop and demonstrate methods for establishing investigatory levels (ILs) for friction and macrotexture for different friction demand categories in the four States, including:
  - Subdividing the highway networks into groups according to friction needs (friction demand categories).
  - Collecting the necessary friction, texture, crash, traffic, and other data.
  - Analyzing the data to set investigatory threshold levels for pavement friction and texture.
- Demonstrate proven continuous friction and macrotexture measurement equipment for network-level data collection.

Phase II began with the purchase, training on, and acceptance of a new SCRIM CFME. Next, several candidate State departments of transportation (DOTs) were evaluated for participation in the study on a range of factors (e.g., friction/texture testing practices, safety and crash/fatality reporting practices, geographic diversity, availability and quality of historical friction and crash data). Based on the results of that evaluation, Florida, Indiana, Texas, and Washington were selected as the participants in the study.

In each of the four States, the research team met with DOT staff to identify a circuit of roads several hundred miles long for the joint SCRIM and State DOT LWST friction testing. The friction and texture data from the testing, together with historical friction, crash, and other data provided by the DOT, made up the data matrix for the analysis of the roads composing the circuit. The complete set of data analyzed using different methodologies established investigatory friction thresholds that identified road sections that should be reviewed for possible friction and/or texture enhancement after having been evaluated for cost-effectiveness.

1.2 OBJECTIVES OF THE REPORT (GUIDE FOR PFMP IMPLEMENTATION)

The purpose of this document is twofold:

1. It provides step-by-step guidance for State DOT staff on how to compile and analyze friction, texture, geometric, and crash data to further the development of a PFMP and implement it into practice.
2. It describes and reports on the results of the efforts to (a) perform SCRIM and LWST friction testing in four States; (b) collect comprehensive friction, crash, and other data from those States' DOTs; (c) summarizes the analyses done to the data to identify appropriate investigatory friction (and macrotexture) thresholds; and (d) recommend modifications to the AASHTO *Guide for Pavement Friction* (GPF).

This document is complemented with an additional document developed under this project, *The Locked-wheel and Sideway-force Continuous Friction Measurement (CFME) Comparison and Evaluation Report*, FHWA-RC-19-001, which should be consulted when a more in-depth analysis is desired for LWST and SCRIM CFME comparisons. This document focuses on (a) network-level friction measurement comparisons obtained with the SCRIM and the LWST; (b) the harmonization experiments done at the two national LWST skid testing calibration facilities and the comparison with the network-level results; and (c) recommended equations for converting the SCRIM friction measurements (SR30) at 30 mph to the traditional friction measurements used by most of the States, SN40R and SN40S, at 40 mph, considering the use of macrotexture in the conversion.

Furthermore, the project made suggested modifications to the AASHTO GPF to provide additional insight and practices on the development of PFMPs in a much greater level of detail regarding the steps an agency should consider in developing a PFMP. Most of these suggested modifications are used in the following chapters of this document.

1.3 BACKGROUND

Pavement characteristics can contribute significantly to highway safety. As a result, they have become a recent area of focus. For example, guidance in designing and managing key pavement surface characteristics, such as surface friction and texture, has been provided in several national publications, such as the 2005 FHWA Technical Advisory T 5040.36 (Surface Texture for Asphalt and Concrete Pavements).

FHWA Technical Advisory T 5040.38—Pavement Friction Management (FHWA, 2010) provides technical information and guidelines for implementing a PFMP. The information provided can assist agencies in refining their friction testing practices with a greater emphasis on the relationship between crashes and pavement friction to minimize friction-related vehicle crashes. This advisory is a reflection of a new emphasis on achieving a more substantive safety analysis using a systemic approach rather than concentrating on hot spots as was the case before.

A study made in 2010 by the National Highway Traffic Safety Administration (NHTSA) found that about 6 million crashes represent a cost of more than $747 billion (Blincoe et al., 2015). Between 1996 and 2016, the average number of highway crashes was about 6.1 million, resulting in averages of 2.7 million injuries and 38,900 fatalities. However, as can be seen in Figure 1 and Figure 2, there has been a sustained increase in both total fatalities and injuries and crashes since 2008.

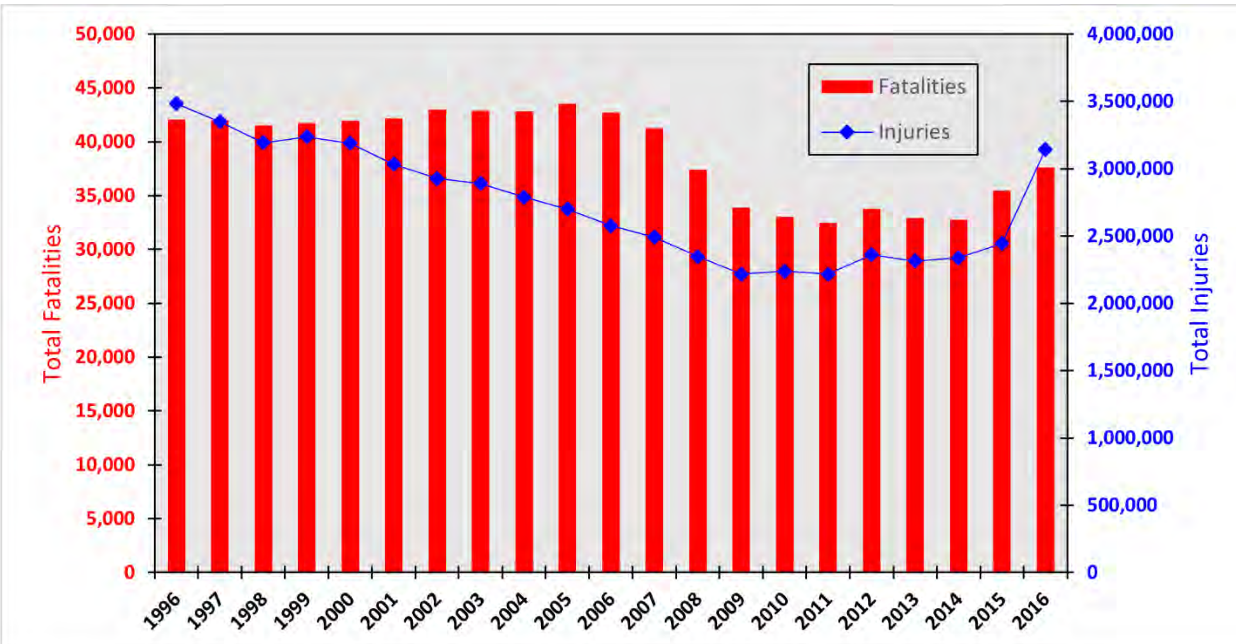


Figure 1. Chart. Number of fatalities and injuries in the United States, 1996–2016 (NHTSA, 2019).

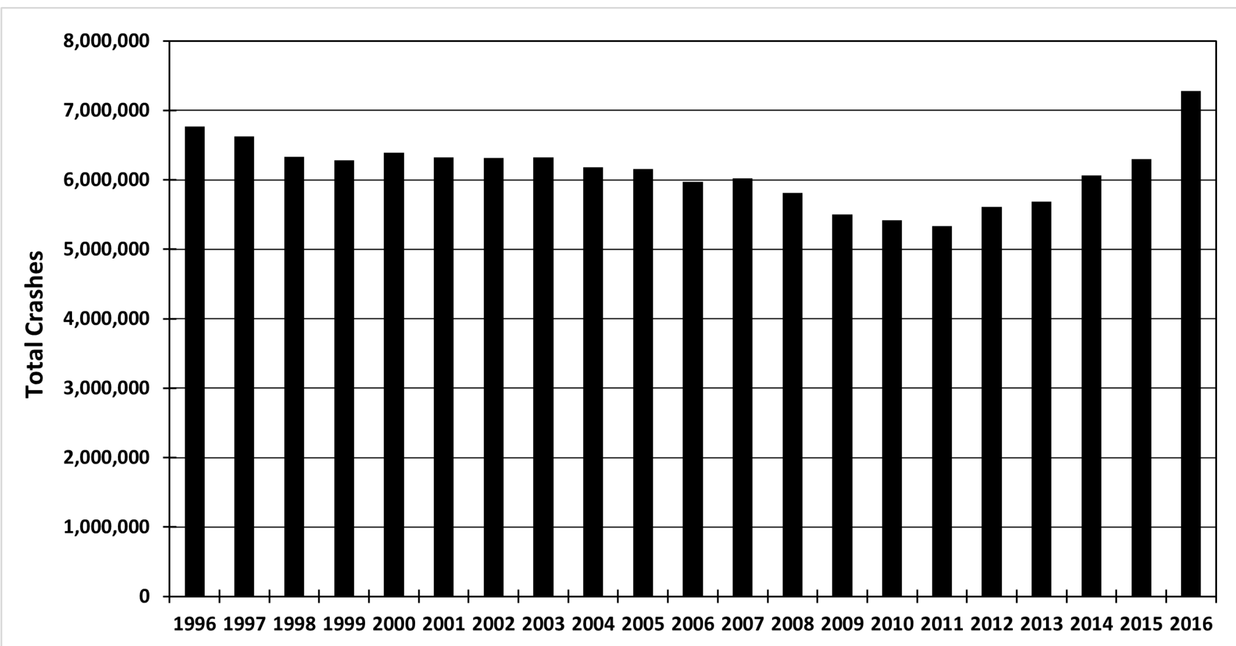


Figure 2. Chart. Number of crashes in the United States, 1996–2016 (NHTSA, 2019).

One or more factors contribute to highway crashes. These factors fall under three main categories: driver-related, vehicle-related, and highway condition-related (Treat et al., 1979). Of these three categories, only highway conditions can be controlled by highway agencies through design, construction, maintenance, and management practices and policies. Although many highway-related conditions influence safety (e.g., geometric design, intersection and roadside design, pavement surface conditions [friction, texture, distress, and smoothness]), this updated report focuses on the provision and maintenance of adequate levels of friction and texture.

A typical network approach to solve friction problems in a State highway agency has been to designate a group from their pavement field-testing unit to test the friction of specific roadway locations identified as having “high crash counts”— commonly referred to as “hot spots”—by the Traffic Engineering or Safety Engineering Division. The values selected to define “high crash counts” have been chosen by various methods and vary from State to State. Subsequently, the agency uses a singular friction threshold value to decide if a section should be investigated for a friction-improving treatment. For the majority of agencies, the threshold usually does not discriminate by the type of road or road section (e.g., whether it is located on a tangent, curve, vertical curve, etc.), so there is no application of the friction demand concept.

Modern PFMPs should define adequate levels of friction to be maintained on all roadway sections based on the friction demand needed for the different types of roadway segments. If this approach is used, different friction threshold values can be set based on road types (interstate, primaries, etc.), geometry of the roadway section (curve, grade, etc.), controlled intersections, ramps, etc. When friction thresholds are not met, pavement evaluations can verify if an increase in the friction level is warranted to reduce the crash risk (e.g., of roadway departure fatalities and serious injuries). Critical aspects of a PFMP include (1) the equipment used to collect friction data, (2) the processes needed to analyze and interpret friction data along with the crash data and the geometric parameters that might influence the vehicle response in each section, and (3) the cost-effectiveness comparison of different possible treatments on those sections that warrant it.

Furthermore, the PFMP should be an integral part of a network-level systemic approach that involves widely implemented improvements based on high crash-risk roadway features correlated with specific severe crash types. This approach provides a more comprehensive method for safety planning and implementation to supplement and complement the traditional hot-spot site analysis. It helps agencies broaden their traffic safety efforts and consider risk as well as crash history when identifying where to make safety improvements.

This was the methodology that was introduced to the four States participating in this study, where reductions in fatalities and serious injuries drive Strategic Highway Safety Plan priorities. Although crash statistics show that driver-related factors, such as impairment, speeding, and lack of restraint, are major causes of injuries and fatalities, the results of the analysis in this study show that implementing friction-enhancement treatments, such as the ones recommended by a PFMP, have the potential to reduce fatal and serious injuries as a consequence of reducing all crashes. The results varied depending on the pavements surveyed and the friction conditions of the pavements found in each State examined, but potential reductions from 4 percent to 25 percent in the number of fatalities and serious injuries were found, representing significant economic savings. At this moment, it is challenging to make more accurate estimations for the following reasons:

- This is the first time that this type of effort has been evaluated in the United States with a comprehensive PFMP approach using continuous friction data.
- The sample sections in the networks evaluated were composed of many different classifications of roadways, and many times the samples were not as robust as needed.
- The relationship of crash risk to friction is highly dependent on many factors that cannot be predicted with small samples of data.

Finally, the analysis of the friction data collected as part of the study showed that the collection of continuous friction and macrotexture data through the adoption of CFME instead of an LWST can have a significant impact on crash reduction efforts by providing a key piece of missing data in safety treatment decision-making. The results show that the typical frequency of network friction testing of one or two tests per mile is not sufficient to identify the most critical sections with friction deficiencies. Continuous friction, macrotexture, and geometrical data measurements allow safety improvement efforts to focus on higher-risk locations, such as those found at curves and intersections in different State highways.

CHAPTER 2. PAVEMENT FRICTION MANAGEMENT PROGRAMS

Published in 2008, the AASHTO GPF contains guidelines and recommendations for managing and designing for friction on highway pavements. In addition to emphasizing the importance of providing adequate levels of friction for the safety of highway users, the GPF:

- Discusses the factors that influence friction and the concepts of how friction is determined.
- Presents methods for monitoring the friction of in-service pavements, identifying where friction deficiencies exist, and determining appropriate actions for addressing friction deficiencies (friction management).
- Presents aggregate tests and criteria for ensuring adequate microtexture and discusses how paving mixtures and surface texturing techniques can be selected to impart sufficient macrotexture to achieve the design friction level (friction design). The GPF is still the reference for this type of information and thus will not be duplicated in this document.

To develop a comprehensive PFMP, the GPF recommends that agencies identify an overall approach, which includes the following five key components (AASHTO, 2008):

- Network definition
- Network-level data collection
- Network-level data analysis
- Detailed site investigation
- Selection and prioritization of short- and long-term restoration treatments

The GPF was intended for use by a variety of highway practitioners, most notably materials, design, construction, pavement management, and safety engineers. However, in practice, it is common that safety engineers are not fully aware of the principles that govern the friction-texture relationships that affect skid resistance, and therefore, are not always using these concepts in crash analyses. It is also important to note that the GPF published in 2008 used terms such as “crash rate” to convey the risk for a crash occurring along a segment of roadway. Safety engineers now consider that using a term like crash rate is misleading because crash frequency and measures of exposure are usually nonlinear (Herbel et al., 2010).

A PFMP is a systematic approach to measuring and monitoring the friction qualities and all (wet and dry) crash risks of roadways, identifying those pavement surfaces and roadway situations that are or will soon be in need of remedial treatment, and planning and budgeting for treatments and remedial work that will ensure appropriate friction characteristics. The development of pavement friction management (PFM) policies within a highway agency is facilitated with a good understanding of the agency’s current practices and resources. Figure 3 presents the new flowchart proposed by this research that can be used by an agency to develop a comprehensive PFMP.

Highway agencies interested in establishing a PFMP should hold kickoff meetings with their staff to discuss the PFM study and the Department’s role in the project, learn about their pavement and safety management practices, and develop a preliminary plan for conducting the data collection measurement testing on a portion of their roadway networks. The size of the network in the study should be adequately large enough to construct safety performance function models that take into consideration the different types of friction demand categories, which should consider the different types of facilities (e.g., interstate, primary, etc.), pavement surfaces, speed limits, geometric alignment, etc. In this study, the data sets used covered an average of 750 miles of roadways, which limited the reliability of some models for some of the friction demand categories; for example, horizontal curves with tight radius in Florida.

Table 1. Proposed pavement friction management program (PFMP).

Number	Task
1	Pavement Network Definition
2	Data Collection and Processing a. Collect Network-Level Data i. Friction, Texture, Geometrics, etc. ii. Complementary Data • Crashes • Traffic • PMS Data b. Collate all the data into 0.1-mi sections
3	Threshold Analysis a. Define Friction Demand Categories b. Determine Friction ILs
4	Safety Analysis: Perform Network-Level Safety Analysis using Crash Data a. Safety Performance Functions (SPFs) b. Empirical Bayes (EB) Estimates
5	Network Screening a. Identify candidate sections for friction treatments. b. Measured friction ≤ ILs
6	Benefit-Cost Analysis: evaluate and select friction treatments a. Predict potential crash reduction with SPF-EB approach. b. Estimate treatment costs and crash reduction savings. c. Compute total savings and benefit-cost ratio (B/C). d. Choose treatments that are only with B/C > 1. e. Sites with total savings > local agency minimum savings criteria
7	Return to Task 2 the following year and repeat the process.

2.1 NETWORK DEFINITION

Defining a section for a PFM network involves identifying a basic set of pavement characteristics to help make informed management decisions. The main characteristic of interest is friction demand, which is defined here as the level of friction (micro- and macrotexture) needed to safely perform braking, steering, and acceleration maneuvers.

According to the GPF, for network-level evaluation it is desirable to test all pavement sections annually because of the year-to-year variation in pavement friction. However, the length of network to be tested and available resources determines the testing frequency for each agency. Agencies may want to adjust their testing frequency for specific pavement sections based upon experience with those surfaces with a propensity for faster changes in friction parameters. All of the States tested usually did their interstate network every year, and all other pavements in 2- and 3-year cycles. In New Zealand and the United Kingdom, network friction testing is performed annually using CFME and adjusted for seasonal variation to account for different weather conditions through the year (Highways England, 2020; NZTA, 2013).

The goal of this study was to demonstrate the use of CFME and obtain enough data to gain insight into whether CFME has a strong potential of being of value to safety analyses. For this study, the friction testing circuits were not developed to assess all the items an agency may choose to consider if they were to evaluate changing their standard practice to a PFMP that utilizes CFME data.

PFM section length is generally driven by the shortest practical length where the confidence in the quality of the data is high and the length is practical from an analysis perspective. In this study, the experience with the four DOTs resulted in sections that were 0.1-mi in length. Crash and pavement surface data need to be over a 3-year period. The surface characteristics data should be verified from the State pavement management system (PMS).

However, it is very important to note that a statistical sampling friction-collection effort should not include interpolation between 0.1-mi sections. LWST measurements represent only 59-ft of pavement for each test performed at 40 mph. This is approximately 1 percent of the pavement surface if one test is conducted per mile. Even if the tests were made 10 times a mile, it would still represent less than 10 percent of the pavement length and would not likely include curves and intersections, where friction tends to be lowest.

2.2 NETWORK-LEVEL DATA COLLECTION

Prior to starting the measurements in the network selected with the CFME, the research team collected the following information from State databases:

- Pavement surface data (construction year, last rehabilitation year, surface types and mixes, and aggregate types and surface texturing used)
- Historical friction data, if available
- Highway location referencing information (mile markers [MMs] and GPS coordinates)
- Functional class and setting
- Roadway type (divided, undivided, one-way)
- Traffic data (annual average daily traffic [AADT], percent trucks, posted speed limit)
- Geometric data (horizontal and vertical curve properties) and intersection location data
- Crash data, including crash location and conditions (wet/dry, night/day, lighted/dark) and crash severity (fatal, serious, evident, and property damage only)

Sometimes, the intersection, ramp, and geometric data are not always available in all States. In their absence, the horizontal and vertical curve, ramp, and intersection data will have to be extracted from other sources, such as the data collected by the CFME. These data are critical as they are used in developing friction demand categories and are key to a robust analysis.

Table 2 presents a summary of all the information that was gathered in each State in the study.

Table 2. Information from the States in the study.

Study Data	Florida (FL)	Indiana (IN)	Texas (TX)	Washington (WA)
Total Network (lane-mi)	269,708	202,501	674,296	173,554
Network Owned (lane-mi)	43,665	28,868	195,964	18,699
Network Tested per Year (lane-mi)	8,200	6,000	30,000	9,350
SCRIM Tested (lane-mi)	875	875	900	570
LWST Units Owned	4	2	7	1
LWST Crew Size	2	2	2	1
LWST Tire	Ribbed	Smooth	Smooth	Ribbed
LWST Test Frequency (mi)	0.3	1.0	0.5	1.0
LWST Test Speed (mph)	40-50	30-50	30-50	40
LWST Report Speed (mph)	40	40	30-50	40
LWST Testing Season	All Year	April-November	April-August	July-September
LWST Calibration (units/year)	2	2	1	1
LWST Verification	Bimonthly	Weekly	Weekly	Bimonthly
Average Total Crashes per Year	370,000	220,000	540,000	120,000
Crash Study Period	2012-2014	2013-2015	2013-2015	2012-2014
Fatalities	7,328	2,350	10,914	1,336
Serious Injuries	52,204	10,489	51,846	6,043
Total Fatalities and Serious Injuries	59,532	12,839	62,760	7,379
SCRIM Network Study Period	2012-2014	2013-2015	2014-2016	2012-2014
SCRIM Network Fatalities	160	46	223	75
SCRIM Network Serious Injuries	1,227	945	958	311
SCRIM Network – Total Fatalities and Serious Injuries	1,387	991	1,181	386

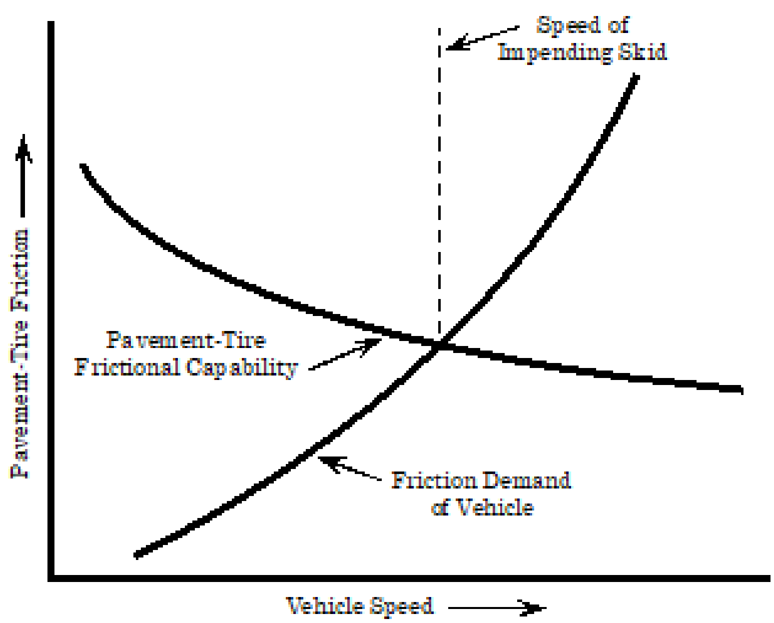
2.2.1 Friction and Texture Data Collection

Factors that affect friction demand can be grouped into four basic categories: highway alignment, highway features/environment, highway traffic characteristics, and driver/vehicle characteristics. Other factors, including driver skills and age, vehicle tire characteristics, and vehicle steering capabilities, are not discussed herein. The specific factors involved in the first three categories are discussed below.

- Highway Alignment – Friction demand is significantly influenced by both the horizontal and vertical alignment of a highway. Considerations should be made for these two.
- Highway Features/Environment – For example, entrance/exit ramps, access driveways, intersections, special lanes, the presence and type of median barriers, and setting (urban versus rural). Understanding the various features of this characteristic provides the basis for determining how a friction threshold might provide useful information regarding safety at one of these particular locations.
- Highway Traffic Characteristics – Traffic characteristics that influence friction demand include traffic volume, composition, and speed. Key aspects of these factors are as follows:

- Traffic Volume – As traffic volume increases, the number of driving maneuvers taking place along any given segment increases. The risk associated with these increased maneuvers is elevated, especially in high-speed areas.
- Traffic Composition – For the same traffic volume, the composition of traffic vehicles (i.e., the percentage of trucks in the traffic stream) can significantly affect highway safety and thus friction demand.
- Traffic Speed – Vehicle speed is one important factor influencing friction demand. Figure 3 shows the conceptual relationship between friction demand and friction availability. This figure indicates that an increase in speed results in an increase in friction demand and a decrease in available surface friction (Glennon, 1996).

The risk of a crash has also been linked to other roadway characteristics. Friction measurements should be complemented by additional data, such as macrotexture, road surface geometry, traffic, crashes, etc. In addition to measuring friction, modern survey CFME technologies allow for testing macrotexture and road surface geometry. Measurements of pavement friction should consider (1) testing protocol and equipment, (2) testing frequency, (3) testing conditions, and (4) equipment calibration and maintenance.



Source: Hall et al. (2009)

Figure 3. Graph. Conceptual relationship between friction demand, speed, and friction availability.

2.2.2 Friction and Texture Data Collection Equipment

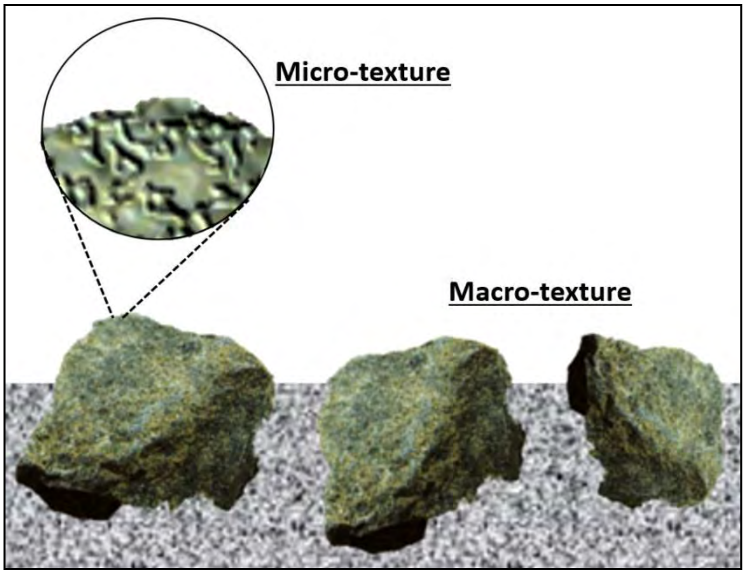
High-speed equipment offers the more practical alternative for network-level testing. There are two categories of high-speed test methods, continuous (CFME) and not continuous. Locked-wheel (AASHTO T 242/ASTM E 274) is a friction measurement test that is not continuous. There are three general types of CFME: fixed-slip (ASTM E 2340), sideway-force coefficient, and variable-slip (ASTM E 1859) (Henry, 2000). These high-speed methods generally operate between 30 and 50 mph, while they simultaneously wet the surface with a user-defined, uniform water film thickness on the pavement surface in front of the test wheel(s), usually 0.0197 inches (0.5 mm).

In the United States, the locked-wheel technique is the most commonly used method by State highway agencies (Henry, 2000). The locked-wheel equipment consists of a trailer equipped with two wheels with full-size tires (15 by 6 inches), one or both of which are used to test longitudinal friction. A test wheel on a locked-wheel device is fitted with either a standard smooth tire (AASHTO M 286/ASTM E 524) or a standard ribbed tire (AASHTO M 261/ASTM E 501). According to Hall (2009), the smooth tire is "sensitive to macrotexture," while the ribbed tire is more "sensitive to microtexture." A locked-wheel device measures friction by completely locking up the test wheel(s) and recording the average sliding force for a period of 3 s and reporting a 1-s average after reaching the fully locked slip. Thus, with a 40-mph test speed, a 1-s test time is equivalent to testing the pavement surface for approximately 59 ft.

Since locked-wheel equipment rely on a fully locked wheel state to measure friction, the measurements can only be recorded periodically. For example, one test per mile results in approximately 1.1 percent of the pavement surface being tested. Alternatively, the high-speed continuous friction test methods allow for continuous friction measurement—where 100 percent of the pavement surface is tested. In this project, the sideway-force continuous friction measurement method uses a free-rolling test wheel with a fixed 20-degree slip-angle to measure side-force "transverse" friction. The SCRIM records a measure of friction called a SCRIM Reading, or SR. SR can be reported at an interval as short as 4 inches (0.1 m). The SCRIM used for this project includes additional sensors to measure surface macrotexture and roadway surface geometry (curvature, cross-slope and longitudinal grade), and GPS coordinates.

Both microtexture and macrotexture influence friction and skid resistance; however, only macrotexture can be currently measured directly in the field. Similar to friction, for network-level measurements, the more practical alternative for testing macrotexture on in-service roads is to use high-speed equipment. High-speed vehicle-mounted laser devices are used to obtain the profile of the pavement surface. Either the mean profile depth (MPD) and/or the root mean square texture depth (RMSTD) of this profile are the reported macrotexture parameters of the SCRIM system.

MPD-measured macrotexture is the average value of the mean 50-mm subsegment depth of a 100-mm segment. Its wavelength ranges from 0.5 mm to 50 mm. The spacing between the aggregates creates channels for water to flow so that the peak of each aggregate is exposed to interaction with the tire tread (Figure 4). At a wavelength of less than 0.5 mm, microtexture characterizes the surface texture of each aggregate (Hall, 2009). The SCRIM records macrotexture (MPD) measurements with a 64-kHz single-spot laser and records average MPD values every 1, 2.5, 5, 10, or 20-m intervals as selected by the user. Normally, the interval is the same for friction and texture.



Source: CSTI

Figure 4. Illustration. Pavement surface texture characteristics that influence pavement friction.

Smith et al. (2011) also concluded that although similar difficulties were noted in developing good friction-crash relationships using output from different friction-measuring devices, the SCRIM tester has a distinct advantage over the locked-wheel tester in terms of the opportunity of achieving a good relationship. This is in large part due to its capability of measuring friction and texture continuously, which can better characterize and represent the available friction at specific crash locations. Additionally, by measuring near-peak friction its operation resembles how the anti-lock braking system braking mechanism on most of today's vehicles operates. Possible alternatives to shifting from the locked-wheel tester are suggested in the evaluation study, which presents the relationship of the friction data from a CFME device to the friction from locked-wheel testers to maintain the historical friction data at the DOTs (de León Izeppi et al., 2019).

2.2.3 Benefits of using CFME Friction Data Collection Devices Versus the LWST

A significant advantage of CFME over LWST is that the continuous devices provide a much higher spatial testing coverage, thus reducing the chances of missing localized areas with friction deficiencies. As was explained previously, the standard LWST test procedure results in measuring approximately 59 ft of road (at 40 mph). If the standard practice is to conduct one test every mile, the tested sample represents only 1.1 percent of the pavement surface. In contrast, the CFME measures every foot of the road, ideal for a proactive network-level analysis process such as the SPF-EB method. This high resolution is particularly important to identify potential friction problems on road sections with a high friction demand, such as curves and intersections.

Kummer and Meyer (1967) in National Cooperative Highway Research Program (NCHRP) Report 37 established that "because the intensity of the polishing process increases markedly with tread element slip, all other factors being equal, the lowest friction levels are found on high-speed roads, curves, and approaches to intersections; in short, in locations at which high friction values are needed most." Due to the LWST standard practice of testing on a sampling basis and the challenge that LWST has testing on curves and intersections, road sections with lower friction and higher friction demand are often not tested in the United States.

The importance of having a higher testing resolution is illustrated in the following example. Figure 5 compares the LWST and SCRIM measurements on one of the routes surveyed. In this section, LWST measurements were taken at two different testing frequencies. From mile 35 to mile 40, the measurements were taken every 0.1-mi, while for the rest of the route they were done at the usual 1.0-mi interval. Figure 6 zooms in on the results of the measurements from mile 39 to mile 40. For the following figures, the FN40R data points are the test results from an LWST using a ribbed tire. The SR30 data line comes from the SCRIM test results.

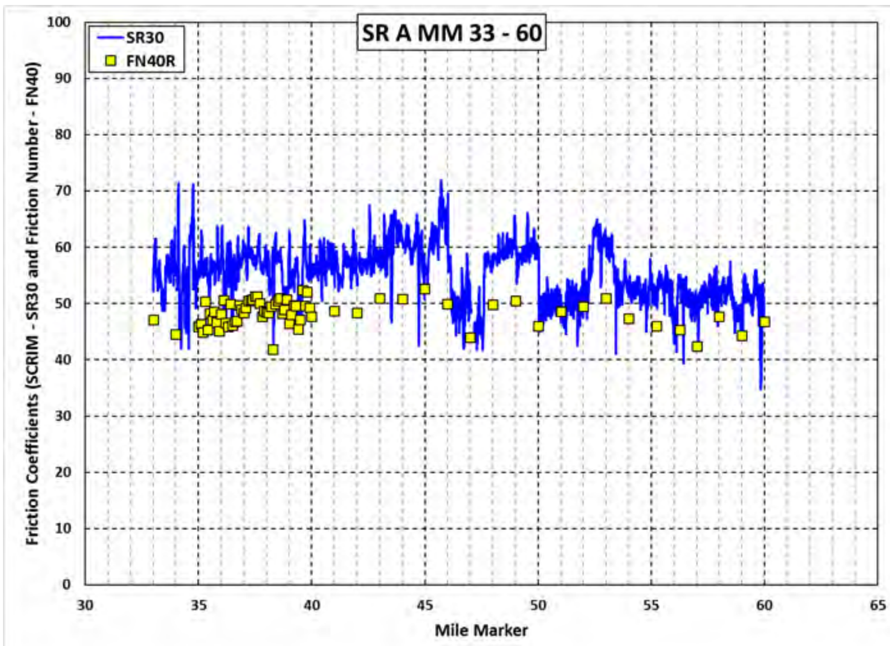


Figure 5. Graph. Example of friction measurements along State Route A (MM 33 to 60).

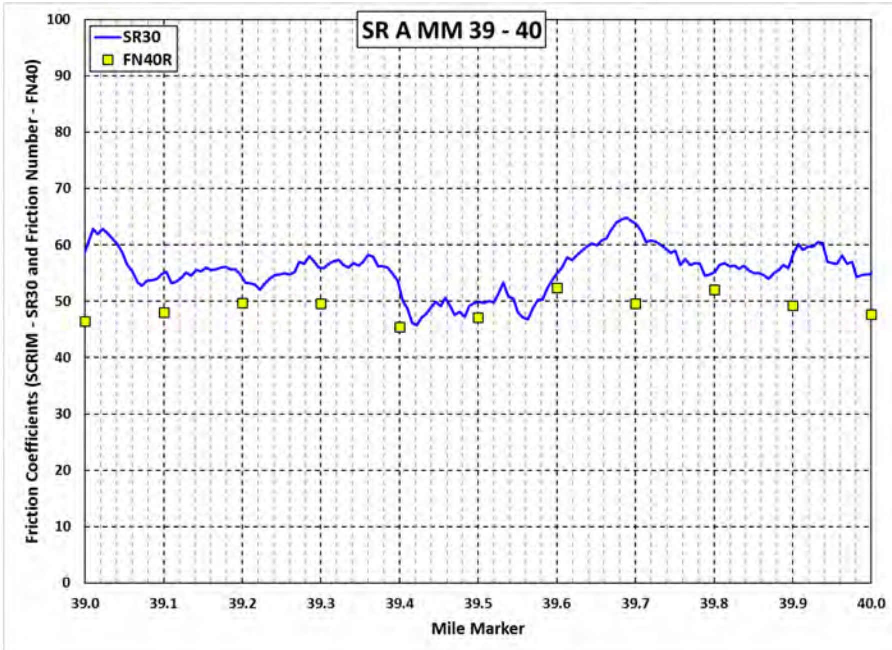


Figure 6. Graph. Detail of measurements on State Route A between MM 39 and 40 (with high LWST spatial frequency).

This figure highlights that the two sets of measurements in general follow the same trend but the SCRIM measurements are more sensitive to fluctuations in spatial friction. For example, both systems identified relatively lower friction values near MM 39.4. However, the figure also shows several examples where the LWST does not fully reflect the sensitivity of the SCRIM friction. The higher granularity of the continuous friction measurements identified relatively higher values at MM 39.0 and MM 39.7.

The discrepancy in resolution provided between the SCRIM and LWST is magnified when the LWST measurements are taken at the conventional frequency of one test every 1 mile. Figure 7 shows the friction measurements from mile 54 to mile 60, where the LWST is only measuring 59 ft every 1.0-mi. In this plot, the data collected with the SCRIM detected a low friction spot in mile 59.8, which the LWST does not identify. Further investigation at this location revealed that the cause of this low friction section is probably exacerbated by the braking and turning of vehicles at this location. This phenomenon is typical of many intersections where vehicles are braking and thus polishing the pavement aggregates at a higher rate than a section of road where the traffic is not stopping due to turning maneuvers, as was recognized by Kummer and Meyer (1967) and discussed previously.

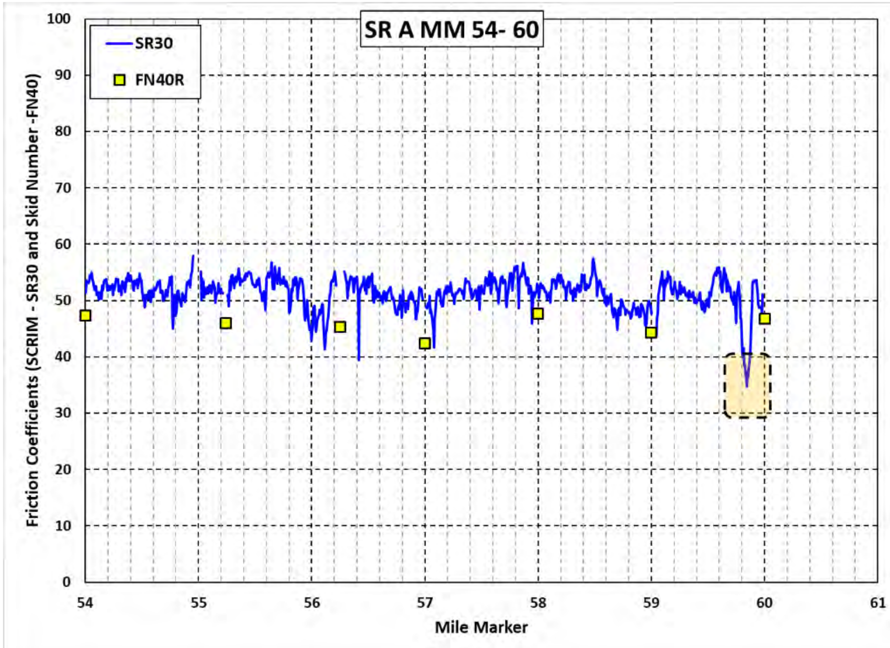


Figure 7. Graph. Detail of measurements for State Route A between MM 54 to 60 (with low LWST spatial frequency).

It is also interesting to note that this is one of the locations with the highest number of crashes on that route. For the whole road segment from miles 33 to 60, the two locations with the highest number of crashes are MM 34.8 with 43 crashes and MM 59.9 with 25 crashes in the 3-year analysis period. Therefore, the section identified using the SCRIM but missed with the LWST conducting one test per mile could be a good candidate for the installation of a friction-enhancement treatment. This information also illustrates the potential benefit of conducting continuous friction measurements before the installation of a friction-enhancement treatment to better identify the beginning and end of the treatment for construction purposes.

2.2.4 Friction and Texture Data Testing Conditions

Because pavement friction is influenced by various factors, such as pavement surface temperature, test speed, and ambient weather conditions, testing should be performed under standardized conditions to control the effect of these factors on test results. Controlling testing conditions will minimize variability in test results and produce repeatable measurements.

Proper calibration and maintenance of the friction testing equipment is essential to the collection of reliable friction data. To this end, agencies should follow the manufacturer-specified regime or guidance for calibration and routine maintenance. Furthermore, it is important to take into account that sometimes the conditions to perform friction testing are not adequate. Table 3 includes guidance on some of the issues. This information is extracted from guidance provided for the United Kingdom strategic road network (Highways Agency, 2005). The standard network friction testing system in the United Kingdom is the SCRIM.

Table 3. Summary of Issues Relating to Standardized Test Conditions.

Factors	Consideration
Season for testing	Friction testing should be limited to the months of the year when temperature is higher and friction is typically lowest. This will help maintain some consistency in year-to-year measurements and reduce variability in measured data. Agencies that cannot perform all testing within this period should develop temperature correction factors to normalize raw friction test data to a common baseline season.
Test speed	The SCRIM is operated according to the standards recommended in HD 28/15 (Highways England, 2020). The recommended speed is 30 mph (50 km/h). In-service testing speed varies with the roadway condition, and measured value of friction (SR) is corrected to 30 mph (50 km/h) using the following equation: SR 30 = SR(S) × (−0.0152 × S2 + 4.77 × S + 799) / 1000 where: SR30 = Adjusted value of friction at 30 mph (50 km/h), and SR(S) = Measured friction value at speed S in km/h. Agencies that begin using the SCRIM in the United States should develop their own correction equation to normalize the raw friction test data to the baseline test speed.
Test lane and line	Friction measurements must be done in the most heavily trafficked lane, as this lane, which usually carries the heaviest traffic, is expected to show the highest rate of friction loss. For two-lane highways with a near 50–50 directional distribution of traffic, testing a single lane will suffice. For multilane highways, the outermost lane in both directions is typically the most heavily trafficked and should be tested. Test measurements must be carried out within the left wheelpath, (the left wheelpath in the United Kingdom is the outer wheelpath in the United States) as this is the location where friction loss is greatest.
Ambient conditions	Ambient conditions can have an effect on pavement friction. The following ambient conditions should be avoided: Heavy rainfall (where there is standing water on the pavement surface) because these conditions can affect the measurements. Air temperatures below 41 °F (5 °C) or as determined in the seasonal factors mentioned before.
Contamination	Contaminants on the pavement surface (mud, oil, grit, or others) must be avoided.

2.2.5 Crash Data Collection

Crash data are generally available from an agency's crash database or from other sources, such as law enforcement agencies and statistical bureaus. Inputs to classify and describe crashes should include (1) the location (route, milepost, direction) of each crash, (2) vehicles involved along with their characteristics, (3) drivers and passengers involved along with their characteristics, (4) ambient weather conditions at the time of the crash, and (5) injury levels and property damage as a result of the crash. In addition to these five inputs, a sixth input is crash severity type. The severity of an injury resulting from an accident is often reported using the KABCO scale shown below (AASHTO, 2010)

- K – Fatal Injury (Killed)
- A – Suspected Serious Injury (Incapacitating Injury)
- B – Suspected Minor Injury (Non-Incapacitating Injury
- C – Possible Injury
- O– No Apparent Injury

Normally, a minimum of the most recent 3 years of crash data are needed. The crash data should only be used when there have been no major changes in pavement characteristics to evaluate all the sections correctly. Use of multiple years of data addresses the statistical phenomenon of regression-to-the-mean (RTM). RTM is the natural variation in crash data (Highway Safety Manual).

2.2.5.1 Database Development

The data files provided have to be reviewed and compiled in spreadsheets, focusing only on the data that are pertinent to the SCRIM/LWST test circuit. Measured data have to be sorted by route and direction, and then assigned to individual 0.1-mi sections. Hence, for example, with 911.7 mi of road included in a test circuit, the database will consist of 9,117 individual 0.1-mi sections. Data elements are usually arranged in columns across the top of the spreadsheet and grouped into six major categories:

- Location
- Project/site and traffic characteristics
- Geometrics
- Pavement event history
- Friction and macrotexture measurements
- Crash statistics

Some details of the steps taken to populate the database are described below.

- Location Data – The route, direction, and from/to limits (both MMs and landmarks) for each highway section are established. District and county information are also included. Each section is then subdivided into 0.1-mi segments, with the beginning and ending MM values assigned, as appropriate.
- Friction Data – Historical LWST friction data, if available, should include the test speed, the type of tire (smooth-S or ribbed-R), if possible, the GPS coordinates of the test, and the pavement surface type. Normalized friction data should be used in the database with the appropriate speed correction factor. Available historical friction data should be assigned to the appropriate 0.1-mi section based on test location. Most States normally have one or two FN values per mile. Friction is not constant and thus friction data should

not be extrapolated over the length of the testing interval (i.e., assigning the same value or some proportion of the difference to each 0.1-mi segment in 1.0-mile).

- The SCRIM friction and macrotexture data will be processed to complement this information at every 0.1-mi section.
- Project/Site and Traffic Data – For each highway section, the divided/undivided highway designation, number of travel lanes, 1-way AADT, and current pavement type are also assigned to each 0.1-mi segment in that section.
- Geometrics Data – Horizontal curve, longitudinal grade, cross-slope and intersection data are also recorded with the data collected from the SCRIM and added to the database. These data include the average (and sometimes absolute) value of the gradient, horizontal curvature, and horizontal curve radius for each 0.1-mi segment.
- Pavement Event History Data – For segments in which one or more construction or rehabilitation activities took place during the study period, the description and year of each activity have to be entered. For segments in which no activities took place over this time period, the most recent activity prior is entered, along with the year of the activity. If no pavement history information is available for a section, those sections should be dropped from the analysis.
- Crash Data – Data for individual crashes that occurred along the test circuits for the study periods are processed and transformed into crash counts for each 0.1-mi segment. Several problems can be encountered in the processing and transformation of the crash data.
    - Sometimes, when a high percentage of the crashes are not referenced to an MM, a synchronization tool is developed to "estimate" the MMs of crashes using the crash GPS coordinates and the MM-GPS linkages established from the SCRIM. Because some crashes also have no GPS coordinates, they cannot be included.
    - One common problem found is that roadway direction is only indicated for a small fraction of the crash events in some of the crash data files. Sometimes, direction information is often not reported because the police officer at a crash scene is the only individual who records direction and the officer is not mandated to record it. Moreover, in cases where direction is reported, it is sometimes given by compass direction rather than the route's officially designated travel direction (e.g., northbound, southbound, eastbound, and westbound). To try and address this issue, the team divided the crashes evenly between travel directions for each 0.1-mi segment. This entailed summing the crashes for each segment, dividing the count by two, and then rounding to the nearest whole number to give the count in one direction.

2.2.5.2 Study Experiences and Lessons Learned

During the course of the study, a number of issues were encountered in developing reliable databases that could support the planned analyses. First, the from/to landmarks and from/to MMs listed for each roadway section did not always match up with the GPS data or geographic information system (GIS) maps. In some cases, an MM was as much as 1 mile off from the associated corresponding landmark. Discrepancies between the MM mile points and their actual distance in the field created problems in assigning historical friction values to the 0.1-mi segments of some sections, as well as aligning crash count and other collected data.

A second issue that occurred was related to the agency's historical LWST friction data. In one of the States in this study, the LWST friction data were not adjusted with a friction-speed normalization formula (see Table 3). The friction-speed normalization formula is needed to provide LWST friction values at a standard speed for the test circuit network. As noted earlier, test speeds range between 30 and 55 mph, with about half of the tests performed around 50 mph. Some agencies in this study have developed and used normalization formulas, but those formulas are not applicable to other State roads due to unique conditions and paving materials. However, for comparison purposes for the project, a 0.6 friction number (FN)/mile speed conversion factor around a normal value at 40 mph was used to standardize the friction.

A third issue in one agency was the location of the crash data. Although crash counts for individual 0.1-mi segments were able to be developed, they may not be very accurate due to the fact that MMs had to be estimated for nearly 70 percent of the crashes. In addition, the counts may have been affected by the approach used to assign directions to crashes (i.e., divide crashes evenly between travel direction). The combination of errors in crash location and direction can greatly confound the identification of trends between friction and crashes.

A fourth issue found involves reviewing the types of pavements reported from the PMS. The pavement types did not always match what was observed in the video recordings, so all sections were reviewed via video to verify the pavement type. In one State, 4 of the 48 highway sections were lacking more than 1 year of time-series LWST friction data. Furthermore, a few other sections had only a portion of the length tested as part of the inventory testing.

For this study, the crash data covered a 3-year period, as explained above, to provide sufficient information and to avoid possible RTM situations. Data collected from the State DOT database included:

- Crash counts
- AADT
- Divided roadway
- Pavement type
- Location and dates of pavement changes

Data collected with the SCRIM included:

- Macrotexture (MPD in mm)
- SCRIM Reading (SR)
- Horizontal curvature (1/m)
- Cross-slope (%)
- Gradient (%)
- GPS coordinates of measurements

2.2.5.3 Study Data Synchronization

The following process was followed to pair the data collected with the SCRIM with the data provided by each State:

1. The GPS coordinates of the 10-m measurements from the SCRIM were paired with the GPS coordinates of the DOT mileposts.

2. Both the SCRIM/DOT mileposts and the remaining unpaired DOT data were summarized into 0.1-mi roadway segments as described in Table 4.
3. All of the summarized data (i.e., SCRIM/DOT mileposts and the unpaired DOT data) were paired using milepost data.

Table 4. Steps for summarizing data into 0.1-mi roadway segments.

Data	Steps for Processing
Crash Counts	1. Sum each crash severity by surface condition by year. 2. Compute the sum for the 3-year period, while keeping the separation by severity and pavement surface condition.
AADT	1. Compute the average. 2. Take the natural log.
Divided Roadway	0 – No; 1 – Yes
Pavement Type	Dense graded asphalt concrete (DGAC), Portland concrete cement pavement (PCCP), Chip seal, Porous friction course (PFC) (*reference group = Chip Seal*)
Route Type	0 – primary; 1 – interstate
Macrotexture (MPD in mm)	Compute the average.
County Region	0 – County A; 1 – County B
SR	1. Run a 3-point (20-m) moving average filter. 2. Take the minimum value.
Horizontal Curvature (1/m)	1. Convert to feet. 2. Compute the absolute value. 3. Compute the average absolute value.
Gradient & Cross-slope	1. Compute the absolute value. 2. Compute the average absolute value.

2.2.6 Study Database Development

After pairing all of the data into 0.1-mi segments, data from any roadway segment that received a pavement surface change after the start of the study period were removed. After data pairing and removal, the remaining lane-miles were used in the analysis.

One additional categorical variable and three interaction terms were created using the data items listed in Table 4.

The first categorical variable, Route ID, identifies to which route a road segment belongs. Route ID establishes the unique impact of the data from Table 4 on each specific route. To this purpose, a Route ID variable was created for each route, except for the road to be treated as the baseline, for which all the Route ID variables were set as zero. The three interaction terms are SR × Divided Roadway, SR × Pavement Surface Type, and SR × Route Type. These were created to determine the combined impact of SR and three other variables on crash risk.

A minimum horizontal radius of curvature of 2,000 ft was selected for the total tested network as a threshold for highlighting severe curvature. This value is based on the value recommended by the AASHTO *A Policy on Geometric Design of Highways and Streets* (AASHTO, 2011) for a design speed of 70 mph and maximum super elevation of 6 percent. Under these conditions, AASHTO recommends a minimum radius of 2,040 ft.

2.2.7 Network-Level Data Analysis

Since the 1930s, highway safety has served as an integral part of highway design and management. Pavement friction evaluation has been a component of the safety strategy for several decades. For many years, locations with elevated wet crashes were identified as being the only ones that could benefit from treatments that increased friction because it was generally believed that friction was more of a factor in wet weather crashes than dry crashes. However, about eight years ago, high friction surface treatments (HFSTs) started being applied in many locations in the United States. In a study done in Kentucky, the data demonstrated that at all the locations treated (ramps and curves) there were significant reductions in both wet and dry crashes (von Quintus and Mergenmeier, 2015).

Giving consideration to all crashes on a roadway is also consistent with the new shift to making substantive safety analysis focused on systemic improvements to reduce fatal and serious injuries, rather than the previous standards-based (nominal) safety analysis, which focused on identifying hot spot locations based on wet-weather crashes (which account for approximately 15 percent of all crashes).

Phase I of the study conducted a comprehensive review of the literature that identified attempts over the past half century to find relationships between pavement friction and highway skid crashes, with varied levels of success largely determined by the unique set of roadway circumstances and unique data collection and analysis practices of individual highway agencies. Several studies have shown that in general crash risk is higher for sections with lower friction (Bray, 2003; Kuttesch, 2004; Viner et al., 2005; Reddy et al., 2008; Larson et al., 2008). In the United States, because the devices used to measure friction do not have the ability to measure friction continuously, the ability to develop an accurate relationship that can reliably detect the need for friction restoration has been somewhat limited (Smith et al., 2011). However, the international evidence supports the premise that a PFMP using CFME has the potential to reduce a percentage of the overall crashes. It can have a greater impact on reducing the crashes where DOTs can have significant influence (road environment factors) (Viner et al., 2005).

2.2.8 Subdivide the Highway Network into Pavement Friction Demand Categories

Friction demand is the level of friction needed to safely perform acceleration, braking, and steering maneuvers. The goal is for pavement surface friction supply to meet or exceed friction demand at all times. Friction demand categories are established logically and systematically based on highway alignment, highway features/environment, and highway traffic characteristics. Ideally, friction demand categories should be established for individual highway classes, facility types, or access types. Also, the number of friction demand categories should be kept reasonably small so that a sufficient number of PFM sections are available for each category from which to define investigatory friction levels.

PFMs are already in place, and friction demand categories have been established in many countries around the world. An example of friction demand categories currently in practice is shown below in Table 5. The standards shown are from the United Kingdom (with text edits to adapt them to U.S. customary). Since friction demand categories are a reflection of the risks associated with each PFM network, the categories and the friction demand levels may not be the same for all local and State jurisdictions. (A non-event is a tangent section of roadway with a gradient less than 5 percent, and with no intersection, ramp, or crossings. Events include curves, intersections, ramps, and crossings, and sections with gradient greater than 5 percent).

Table 5. Recommended friction demand categories in the United Kingdom (adapted from Highways England 2020).

Friction Demand Category	Definition	SR30 IL 0.30	SR30 IL 0.35	SR30 IL 0.40	SR30 IL 0.45	SR30 IL 0.50	SR30 IL 0.55
A	Interstate highways	LR	ST				
B	Divided highways – no event	LR	ST	ST			
C	Two lane road – no event		LR	ST	ST		
Q	Approaches to intersections (& roundabouts)			ST	ST	ST	
K	Pedestrian crossings and other high risk areas				ST	ST	
R	Roundabout			ST	ST		
G1	Slope 5-10%, longer than 160 feet			ST	ST		
G2	Slope >10%, longer than 160 feet			LR	ST	ST	
S1	Curve radius < 1600 feet – divided roads			ST	ST		
S2	Curve radius < 1600 feet – two lane roads				LR	ST	ST

Note: Sections with the same demand category can have different levels of risk. ST = sections with significant traffic and LR = sections with lower risk, such as lower traffic levels.

2.2.9 Study Preliminary Data Analysis – Crash Data

In this section, the preliminary results obtained in one of the study States will be used as an example of what can be found with the methods described earlier. Table 6 and Table 7 show the average traffic and the total number of lane-miles by pavement type on the interstate and primary highways surveyed. Notice that, on average, on the interstate the AADT of the DGAC is higher than that of the PCCP pavements, which as will be seen later, also results in higher crashes.

Table 6. Average AADT type by pavement type.

Road Type	DGAC	PCCP	Chip Seal	PFC	Average
Interstate	94,739	87,829	N/A	61,755	86,363
Primary	13,955	27,421	5,524	17,798	14,630

Table 7. Lane-miles by pavement type.

Road Type	DGAC	PCCP	Chip Seal	PFC	Total
Interstate	52.3	691.8	0.0	49.8	793.9
Primary	762.7	520.6	599.2	178.2	2,060.7
Total	815.0	1,212.4	599.2	228.0	2,854.6

Table 8 and Table 9 show the number of crashes and the average crashes per lane-mile by type of pavement for the interstate and primary road networks surveyed. Note that the average number of crashes per lane-mile on DGAC pavements on the interstate is higher than that for the PCCP pavements, which is explained by the strong relationship between AADT and crashes. This fact will be emphasized later in the section discussing the PFMP result recommending improvements on high traffic sections with low friction rather than on sections with only low friction.

Table 8. Total crashes by pavement type.

Type of Road	DGAC	PCCP	Chip Seal	PFC	All Types
Interstate	2,661	27,639	0	1,304	31,604
Primary	6,440	7,751	823	1,214	16,228
Total	9,101	35,390	823	2,518	47,832

Table 9. Average crash count per lane-mile by pavement type.

Type of Road	DGAC	PCCP	Chip Seal	PFC	All Types
Interstate	50.9	40.0	0.0	26.2	39.8
Primary	8.4	14.9	1.4	6.8	7.9

Figure 8–Figure 11 illustrate the relationships between traffic volumes, the number of lane-miles, and the percentages of crashes and crashes per lane-mile by type of pavements for the highways surveyed. In general, the higher the traffic, the higher that average crashes per lane-mile will be for any type of road.

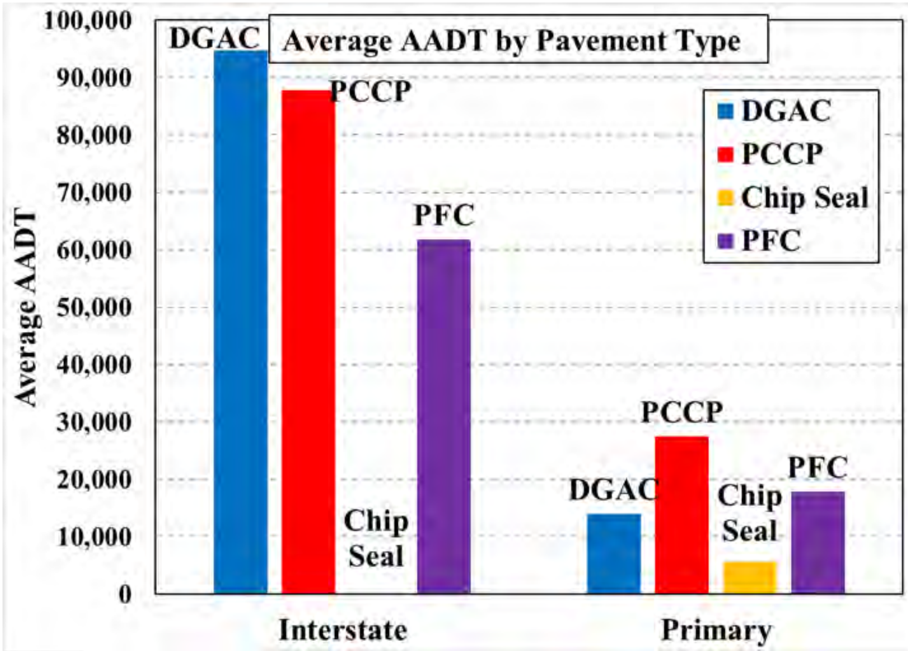


Figure 8. Chart. AADT by pavement type.

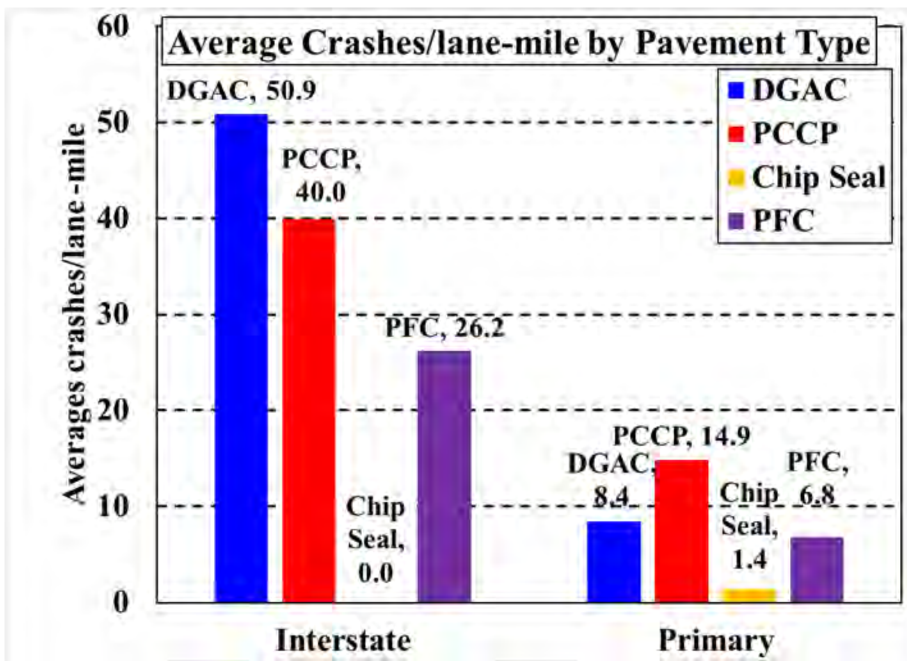


Figure 9. Chart. Average crashes per lane-mile by pavement type.

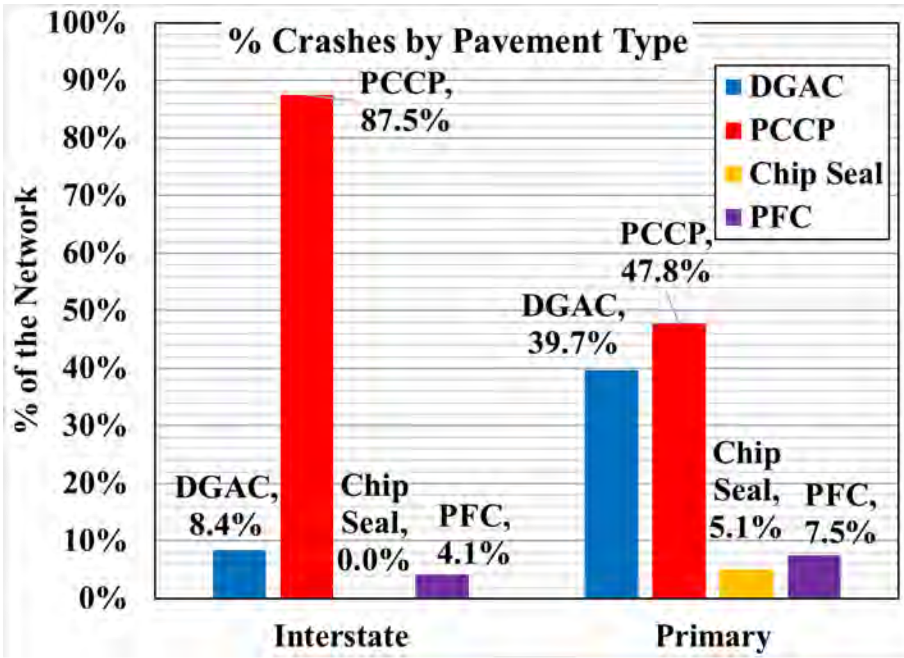


Figure 10. Chart. Percentage of crashes pavement type.

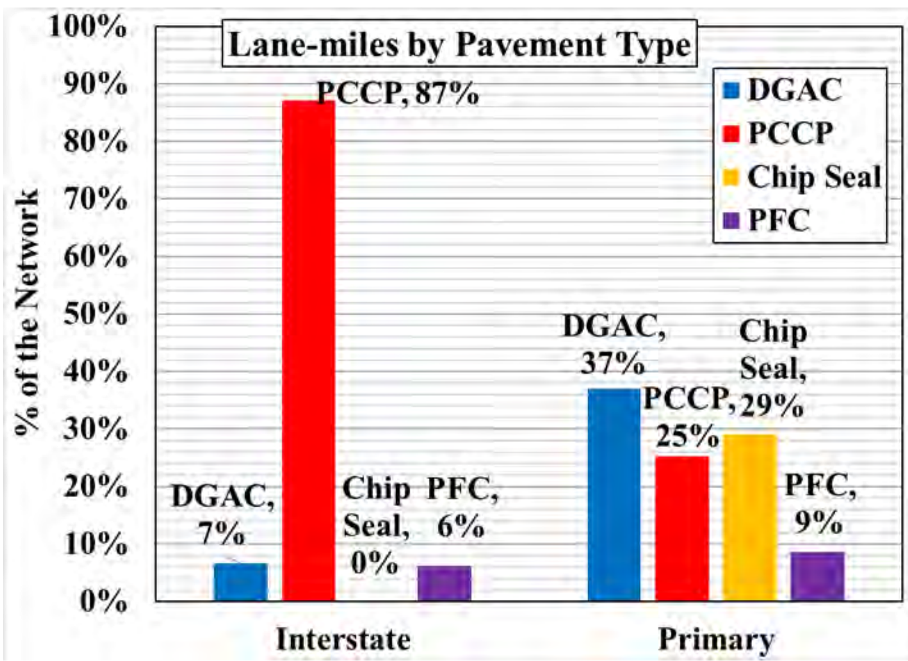


Figure 11. Chart. Percentage of network by pavement type.

The figure is a good example of why traffic volume is often a key factor in crashes; the risk of a crash usually increases with higher AADT (Srinivasan & Bauer, 2013). However, the data also show an exception in the PFC pavement type on the interstate network because there seems to be a relatively lower number of average crashes per lane-mile than those observed for the DGAC, PCCP, and chip seal pavements. The higher macrotexture values of these pavements could be a probable cause for this.

However, it is important to point out that the effect of pavement type cannot be inferred with this information. RTM could be a factor related in the crash analysis, which requires further investigation of independent sections for both interstate and the primary roads, and all types of pavements. Table 10, Table 11, and Table 12 show an example of the number of crashes per lane-mile for each friction demand category as analyzed in this study. This information shows that the sections with the higher traffic volumes have a higher average number of crashes per lane-mile for all friction demand categories.

Table 10. Total crashes by pavement type for friction demand categories.

Friction Demand Category	DGAC	PCCP	Chip Seal	PFC	All Types
Curves	341	466	61	84	952
Interstate Non-event	2,661	27,329	0	1,304	31,294
Primary Divided Non-event	2,649	6,164	160	534	9,507
Primary Undivided Non-event	3,450	1,431	602	596	6,079
Total	9,101	35,390	823	2,518	47,832

Table 11. Lane-miles by pavement type for friction demand category.

Friction Demand Category	DGAC	PCCP	Chip Seal	PFC	All Types
Curves	32.0	17.5	38.2	12.7	100.4
Interstate Non-event	52.3	681.5	0.0	49.8	783.6
Primary Divided Non-event	76.9	301.9	18.0	43.7	440.5
Primary Undivided Non-event	653.8	211.5	543.0	121.8	1,530.1
Total	815.0	1,212.4	599.2	228.0	2,854.6

Table 12. Crashes per lane-mile by pavement type for friction demand categories.

Friction Demand Category	DGAC	PCCP	Chip Seal	PFC	All Types
Curves	10.7	26.6	1.6	6.6	9.5
Interstate Non-event	50.9	40.1	0.0	26.2	39.9
Primary Divided Non-event	34.4	20.4	8.9	12.2	21.6
Primary Undivided Non-event	5.3	6.8	1.1	4.9	4.0

Finally, Figure 12 shows the percentages of each network with and without crashes. Based on this figure, approximately 61 percent of the total sections experienced a crash while the other 39 percent did not experience a crash within the 3-year analysis period. The sections that did experience crashes by pavement type included 56 percent of the DGAC, 86 percent of the PCCP, 29 percent of the chip seal, and 65 percent of the PFC sections.

Figure 13 shows the cumulative distribution of AADT. This plot shows that approximately 50, 5, 84, and 32 percent of the DGAC, PCCP, chip seal, and PFC sections, respectively, have an AADT of less than 10,000.

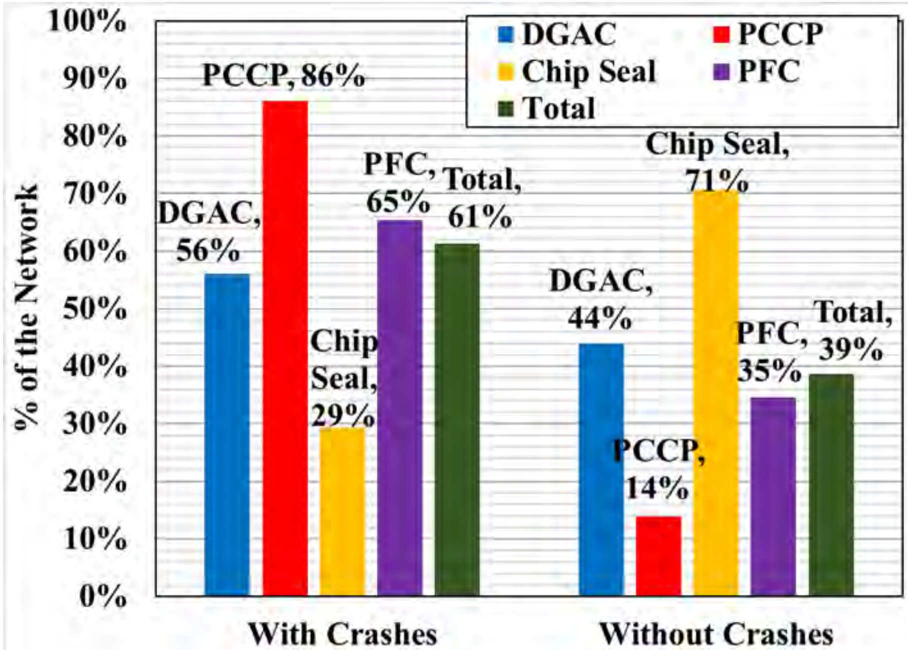


Figure 12. Chart. Distribution of crash count by pavement type.

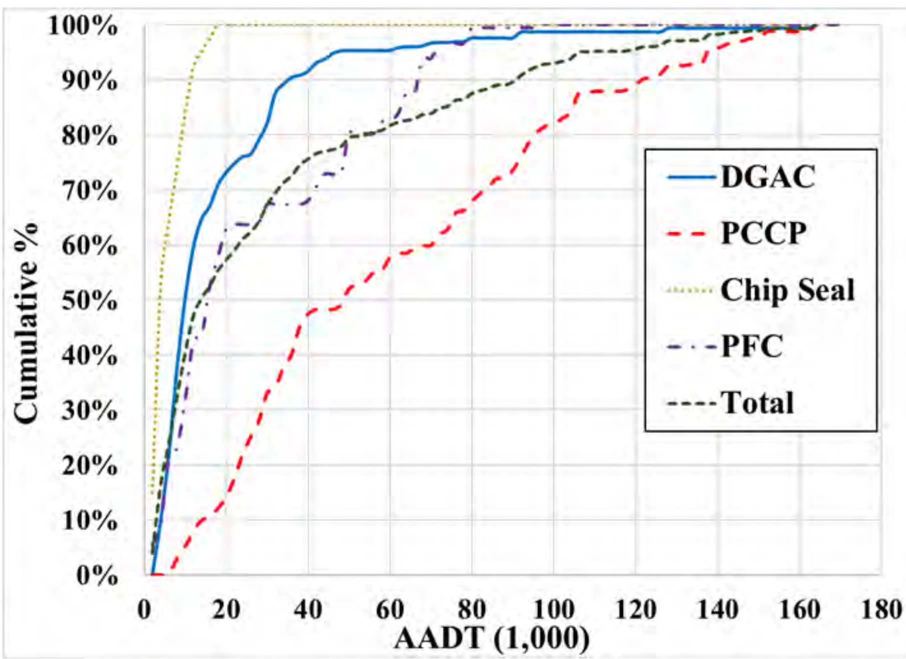


Figure 13. Graph. Distribution of AADT by pavement type.

2.2.10 Study Preliminary Data Analysis – Pavement Data

Figure 14–Figure 17 show typical histograms of the SCRIM readings, MPD, radius of curvature, and gradient of the data, separating the data distributions by pavement type. Table 13 lists the average friction and texture averages and standard deviations for the different pavement types.

Based on Figure 14 and the data in Table 13, the various pavement types have similar average friction values but different distribution shapes. All pavements have average friction SR between 45 and 55, whereas the distributions for the macrotexture or MPD are lower for DGAC and PCCP and higher for chip seal and PFC (Figure 15). The shape of the distribution of the chip seal pavement type is clearly made up of two distributions, as it shows two peaks around the mid-30s and the mid-70s (Figure 14).

In this State, chip seal pavements were found to be represented in two very different conditions, raveled and in good condition. It was challenging to determine which condition predominates because they were found next to each other, sometimes less than 1,000 ft apart. Upon further consultation with State personnel, it was concluded that older chip seals suffer aggregate loss and thus they exhibit very different properties many times over the same 0.1-mi section. It was also observed that nearly all pavement types have several sections with SR values less than 30.

Figure 16 and Figure 17 present the histograms of the horizontal radius of curvature and gradient. The distributions shown in both plots, with the exception of different segment counts, are very similar for all pavement types. Figure 16 shows that very few segments (approximately 4 percent or 354 [35.4 mi]) have horizontal curves with radii less than 2,000 ft, and only 1.2 percent have a radius less than 1,000 feet. Figure 17 shows that the majority (90 percent) of sections for each pavement surface type have gradient less than 2.5 percent.

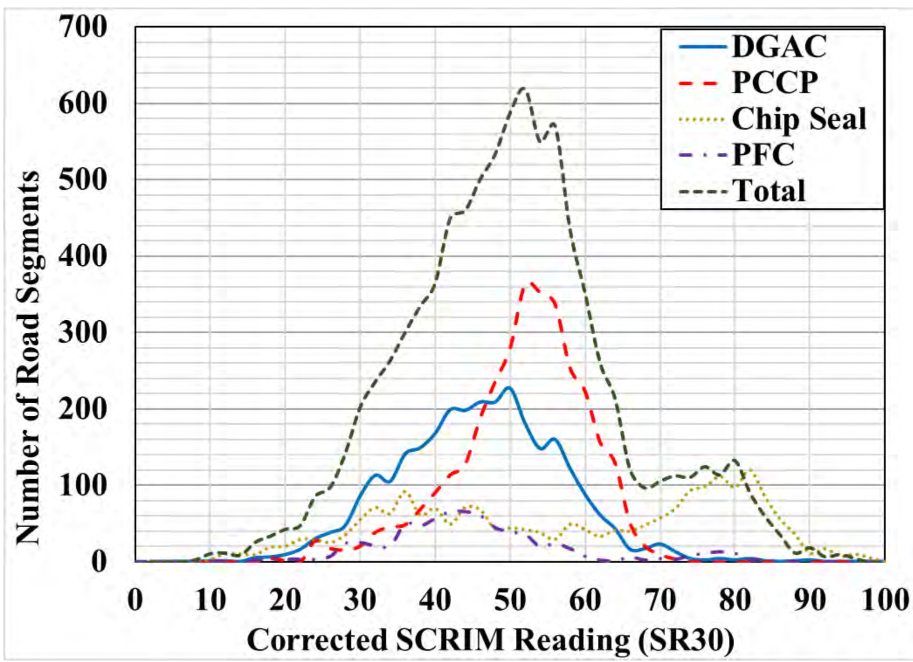


Figure 14. Graph. Typical distribution of SR30 by pavement type.

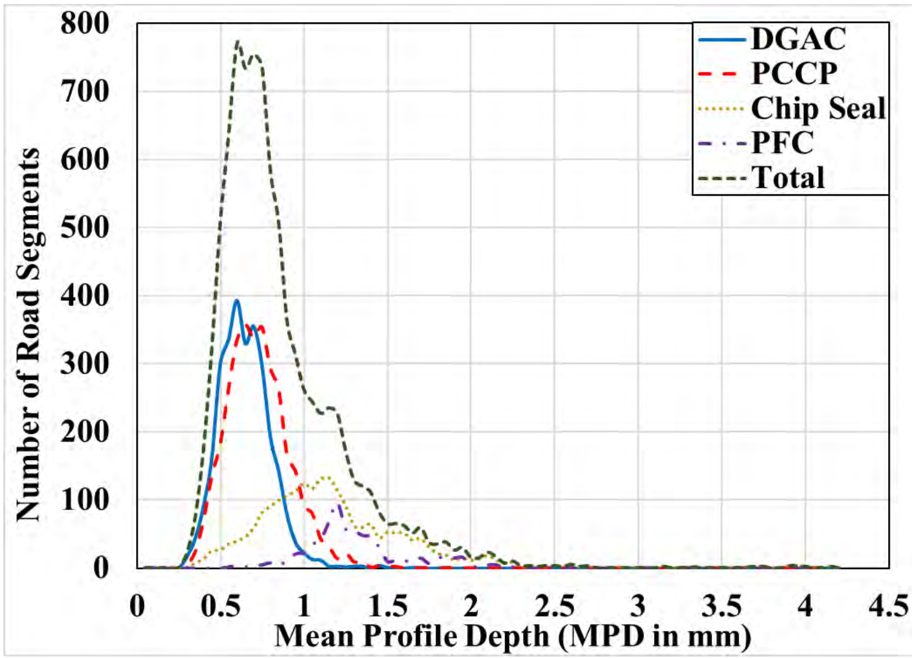


Figure 15. Graph. Typical distribution of macrotexture by pavement type.

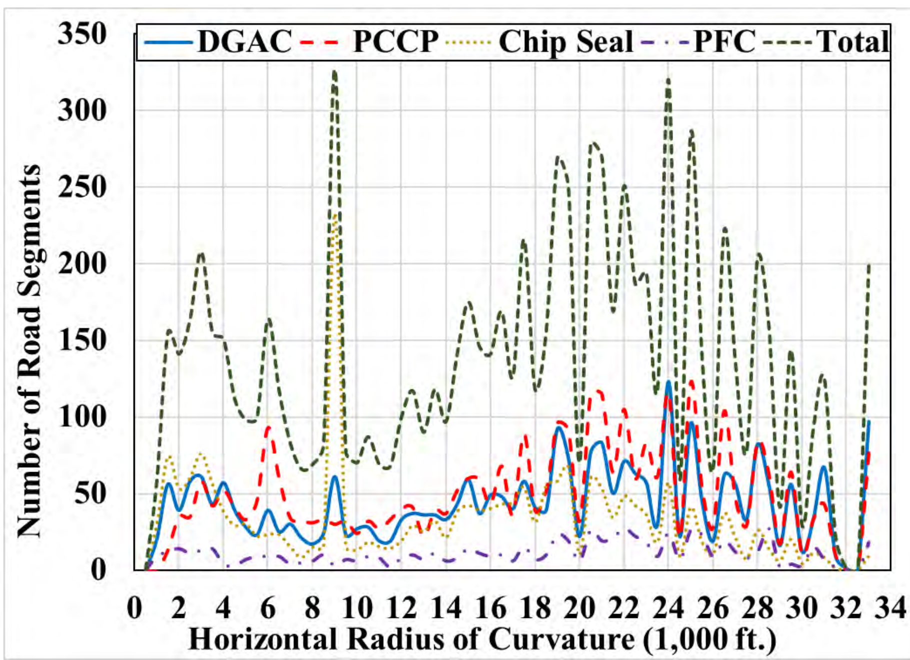


Figure 16. Graph. Typical distribution of horizontal radius of curvature by pavement type.

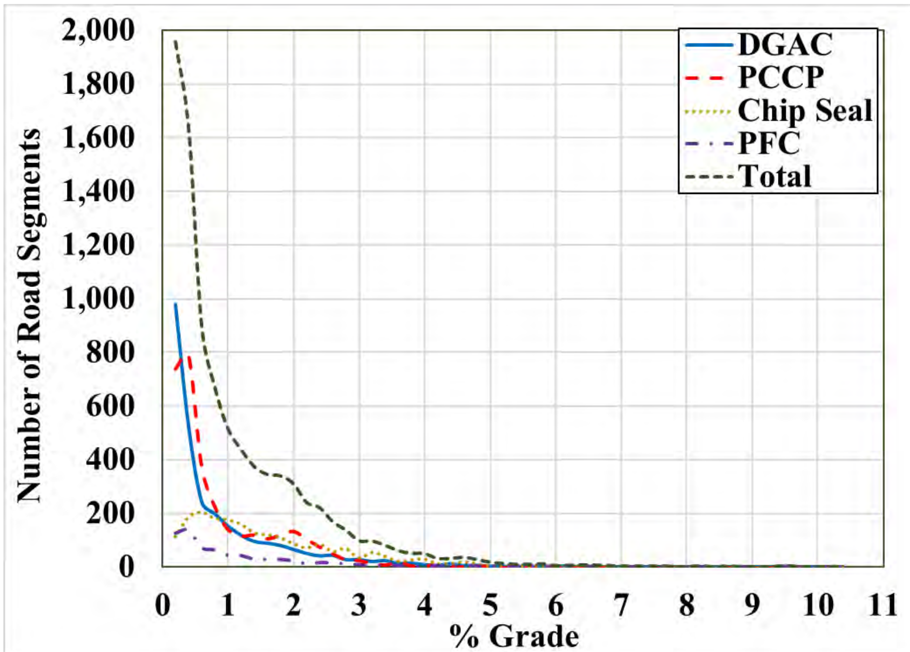


Figure 17. Graph. Typical distribution of gradient by pavement type.

Table 13. The mean and standard deviation for the SR and macrotexture.

Pavement Type	Mean SR	SR SD	Mean Macrotexture	Macrotexture SD
DGAC	44.9	10.7	0.62	0.16
PCCP	50.5	8.7	0.70	0.19
Chip Seal	55.0	21.3	1.15	0.47
PFC	44.4	12.6	1.30	0.31
Total	49.3	14.2	0.83	0.38

2.2.11 Crash Risk Calculation

According to the FHWA *Highway Safety Improvement Program Manual*, the safety of a roadway can be measured using crash rates. Crash rates are used in this manual to convey the current risk for a crash with a specific severity (e.g., fatality, serious injury, etc.) occurring along a segment of roadway (or intersection) due to exposure. The manual also acknowledges that the use of crash rates can be misleading because it implies that crashes and traffic are proportional. However, research has shown that crashes increase with AADT but in a nonlinear fashion (Herbel et al., 2010). Having said that, equation 1 presents the formula used to calculate the crash count (*R*) at a segment of roadway, with a specified length (*L*) occurring after every 100 MVMT (Golembiewski & Chandler, 2011).

$$R_i = \frac{10^8 \times C_i}{365 \times Y \times AADT_i \times L}$$ [Eq. 1]

where:

	R_i	=	Crash count per 100 million MVMT for segment *i*;
	C_i	=	Observed crash count for segment *i*;
	Y	=	Number of years in the study period,
	$AADT_i$	=	Average annual daily traffic for segment *i*;
	L	=	Roadway segment length (in miles).

2.2.12 Crash Data Selection and Assessment

The overall goal for a safety improvement program is to reduce crashes, especially crashes with severe outcomes (i.e., fatalities and serious injuries). An effective safety improvement program can make use of crash rate formulas and crash prediction modeling to assess the current or expected risk associated with a segment of road. Crash prediction models (see section 2.5 for additional information) determine the average estimated expected number of crashes as a function of collected data (e.g., AADT, surface friction, macrotexture, etc.). These regression models rely on the number of observations (crashes). For greater precision, a large number of observations is necessary.

Table 14 lists the crashes in one study State by surface condition and crash severity. In earlier sections, it was explained that the risk for friction-related crashes is greater on slippery pavement (e.g., wet, snow/ice, etc.). For this study State, wet crashes made up approximately 14.2 percent of all the crashes occurring on the study tested network. Furthermore, for combined wet and dry surfaces, fatality and serious injury crashes made up around 2.5 percent of the total number of crashes. For this study, in order to acquire an appropriate number of observations (i.e., crash counts) for the regression analysis, the *total* number of crashes (combining all crash severities) at each road segment was used. But more importantly, research has shown that the risk for both wet and dry crashes increases as pavement friction decreases (Najafi et al., 2017; Wu et al., 2014; Pratt et al., 2014).

Table 14. Crashes separated by surface condition and severity.

Crash Severity	Wet Obs.	Wet % of Total	Dry Obs.	Dry % of Total	Wet + Dry Obs.	Wet + Dry % of Total
Fatality (K)	24	0.35%	199	0.48%	223	0.47%
Serious Injury (A)	129	1.91%	828	2.02%	958	2.00%
Other Injury (B & C)	1,729	25.49%	11,242	27.39%	12,971	27.12%
PDO (O)	4,902	72.26%	28,778	70.11%	33,680	70.41%
(K) + (A)	153	2.26%	1,027	2.50%	1,180	2.47%
Total	6,785	-	41,047	-	47,832	-

The data obtained in this study show that both wet and dry crashes increase when pavement friction decreases, as shown in Figure 18 and Figure 19 (around SR30 = 42). These data are SPF-EB analysis estimated crashes that are an aggregation of all the crash sites and associated SR30 friction measurements. SPF-EB is presented in section 2.4.

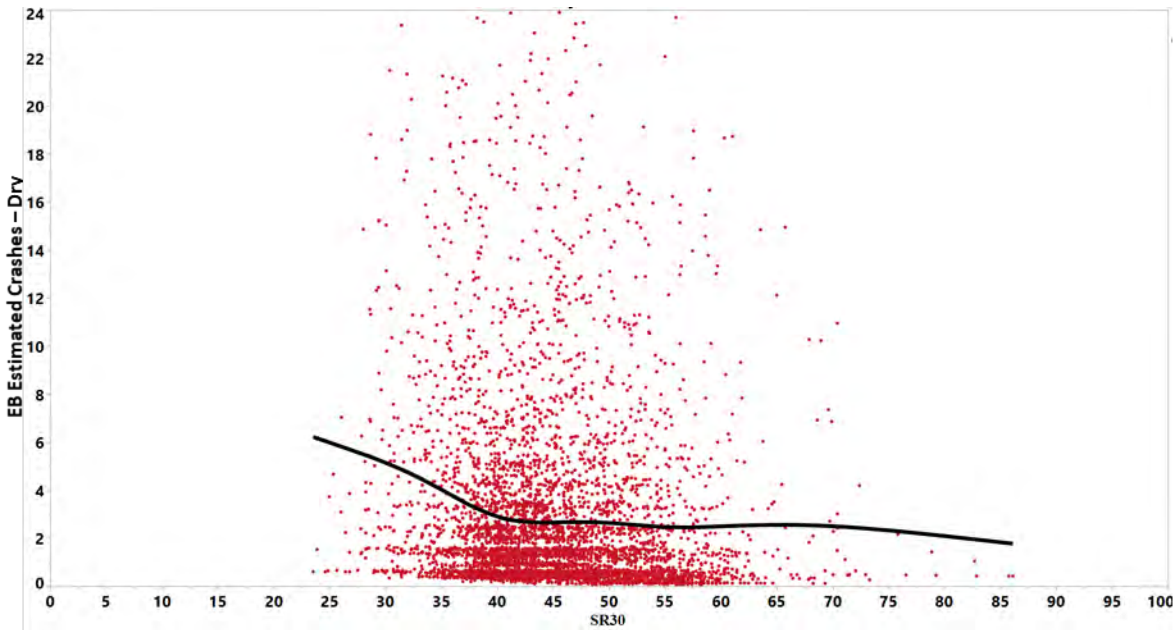


Figure 18. Graph. Illustration of estimated crash counts (EB) versus friction for dry crashes.

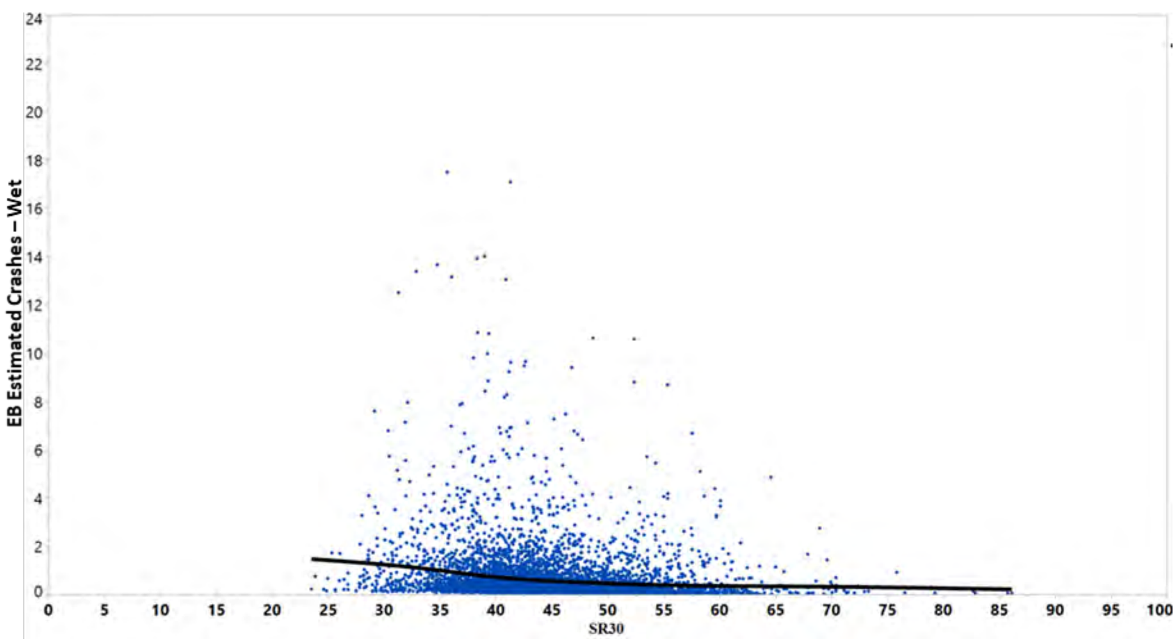


Figure 19. Graph. Illustration of estimated crash counts (EB) versus friction for wet crashes.

2.2.13 Historical LWST Friction Threshold Analysis using the AASHTO GPF

For two of the States studied, a detailed analysis of their historical LWST data was conducted using the three methods outlined in AASHTO GPF section 3.2.3, Network-Level Data Analysis, for establishing friction threshold levels. The purpose of this analysis was to determine the suitability and effectiveness of the GPF methods using LWST data to identify friction thresholds. GPF section 3.2.2, Network-Level Data Collection – Testing Protocol, states that the LWST is the most appropriate testing method at the network level. Investigatory friction threshold levels are threshold values of friction that identify locations where friction may be at a level that may increase the risk of a crash. These levels trigger the need for an investigation to determine if remedial action is warranted.

Following data filtering and reduction into 0.1-mi segments, the data were further divided into friction demand categories as recommended by the AASHTO GPF. Based on the data available for this study and the factors perceived as having the most influence on the friction-crash relationship, several levels of analysis were attempted with LWST data in each State, such as pavement type (DGAC, chip seal, PCCP, and PFC pavements), different levels of traffic, and possible friction demand categories such as the occurrence or non-occurrence of an "event." An event was defined as a road section having one or more of the following conditions: intersections (cross-road, junction, interchange on-/off-ramp, or access drive entrance/exit), excessive grade (>5 percent), and sharp horizontal curves (radius ≤ 2,000 ft).

In the United States, most PMS consider LWST measurements as representative of the friction on each of 0.1-mi of roadway under analysis, but this is an incorrect assumption. As previously presented, friction can vary considerably, especially in high friction demand locations, thus the discrete measurements of the LWST cannot consistently provide a representative friction for a 0.1-mi section for crash analysis. Furthermore, as was explained in section 2.2.5.1, most States normally only obtain one or two FN values per mile and then would have to interpolate the values in between, which is also not representative of the real friction on the road. Because the LWST value only represents a 60-foot measurement, it is common that the lack of friction data where crashes have occurred disconnects the relationships that can exist using crash analysis methods with LWST data at the network level. An example of each of the three GPF methods using the LWST is discussed below.

GPF Method 1 – Establishing Thresholds Using Historical Pavement Friction Data Only. For each friction demand category, plot the historical LWST friction data versus pavement age. Figure 20 shows an example of the data from a State for a friction demand category using Method 1. Although this plot shows a decrease in friction over time, the rate of friction loss does not have a demonstrable significant increase at a certain point in time. This analysis was completed for two study States, and none of the plots resulted in a demonstrable significant increase in friction loss over time as would be evidenced by inflection points in the graphs. On many of the plots, the friction shows an increase over time, which is not the normal behavior. This method cannot identify the risk associated with any section as it lacks the comparison to its particular crash history, not making it justifiable to increase the friction of a particular section.

The complete analysis of method 1 for the two study States is included in the appendices.

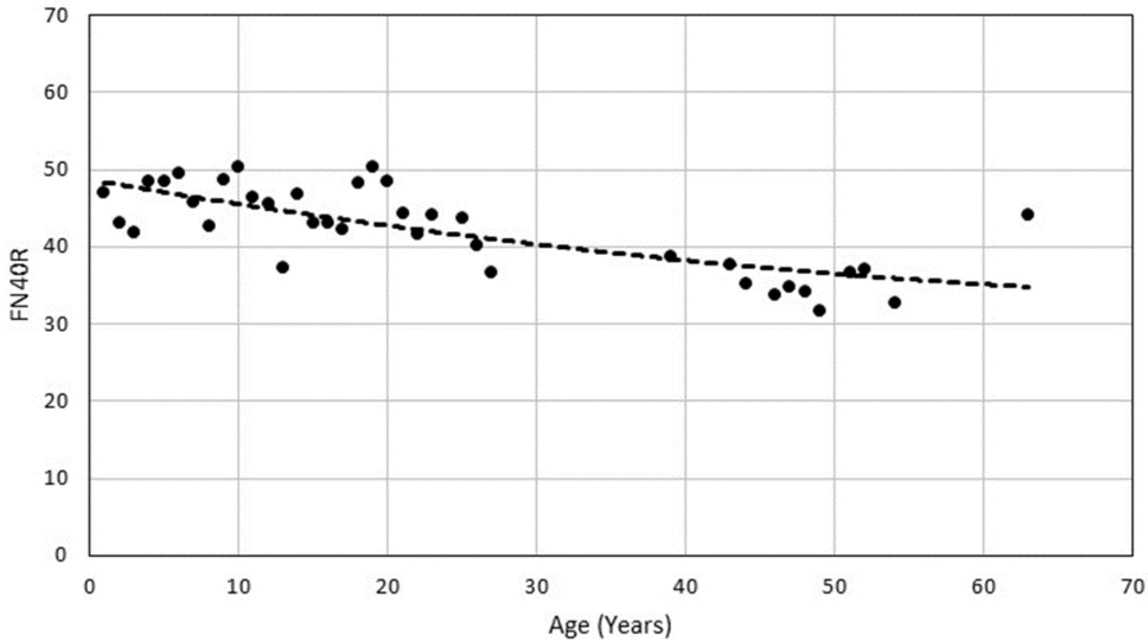


Figure 20. Graph. LWST friction versus pavement age for divided, non-event friction demand segments (GPF method 1).

GPF Method 2 – Establishing Thresholds Using Both Historical Pavement Friction Data and Crash Data. Per friction demand category, plot the historical LWST friction data and pavement age to determine the IL, which is set at a point that corresponds to a large loss in friction. This is a similar concept to GPF method 1. In addition, plot crash data (e.g., crash rates, wet-to-dry crash trends) on the same graph. A problem associated with this method is confronted when there are zero dry crash counts, which makes the ratio undividable.

An IL may be set where there is a significant increase in crashes. Figure 21 shows the data from a study State for one friction demand category. Although this plot shows a decrease in friction over time and an increase in crash rate over time, the rate of change for each is based on average FNs and crash rates that cannot identify the potential risk of a particular section, which also does not show a demonstrable significant increase at a specific point in time. None of the other plots in the appendices resulted in a demonstrable significant increase in friction loss or crash rate over time. The complete method 2 analysis of the two study States is included in the appendices.

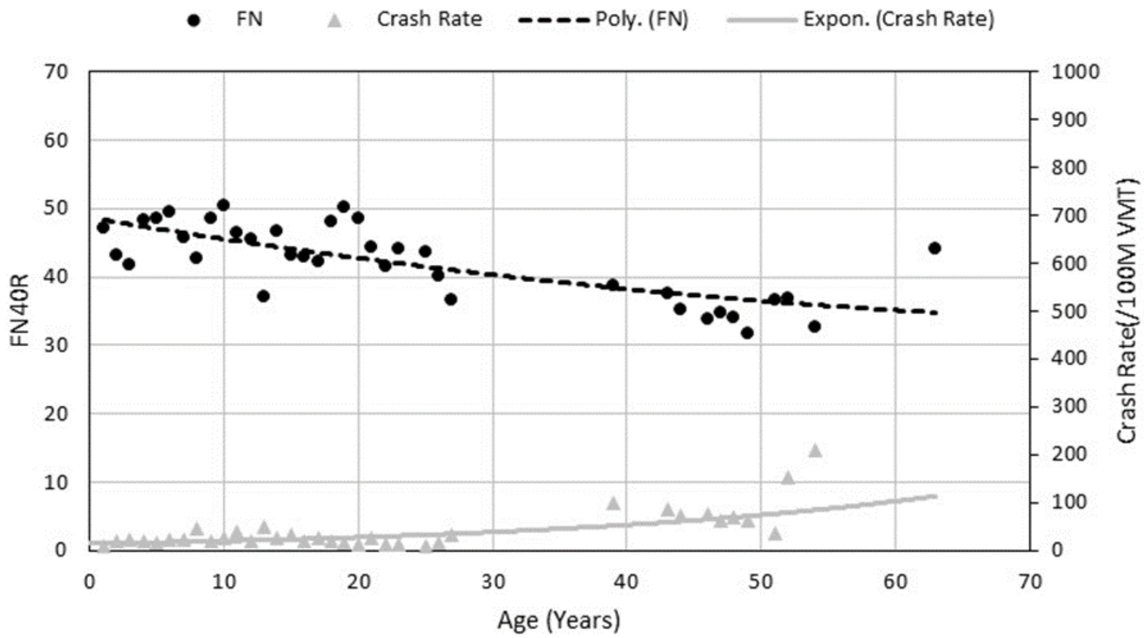


Figure 21. Graph. LWST friction versus pavement age for divided, non-event friction demand segments (GPF method 2).

GPF Method 3 – Establishing Thresholds Using Pavement Friction Distribution and Crash Rate – Friction Trend. Per friction demand category, plot the histogram of all the LWST friction measurements and plot the wet-to-dry crash rate for each friction bin. However, when there are zero crash counts, the ratio is undividable, which is similar to the problem in method 2. A potential solution to the zero-ratio problem is to use the wet-to-(wet+dry) ratio.

Set the IL as the mean friction less “x” standard deviations, where “x” standard deviations is where the crash rate begins to increase considerably. Figure 22 shows the data from a study State for one friction demand category. An IL cannot be identified as there is no significant increase in crash rate due to the fact that the ratios represent averages from all of the individual locations represented with a weighted crash rate, which is not representative of the risk at all individual locations having the same FN. This analysis was completed for two study States and none of the plots resulted in a demonstrable significant increase in crash rate. The complete method 3 analysis of the two study States is included in the appendices.

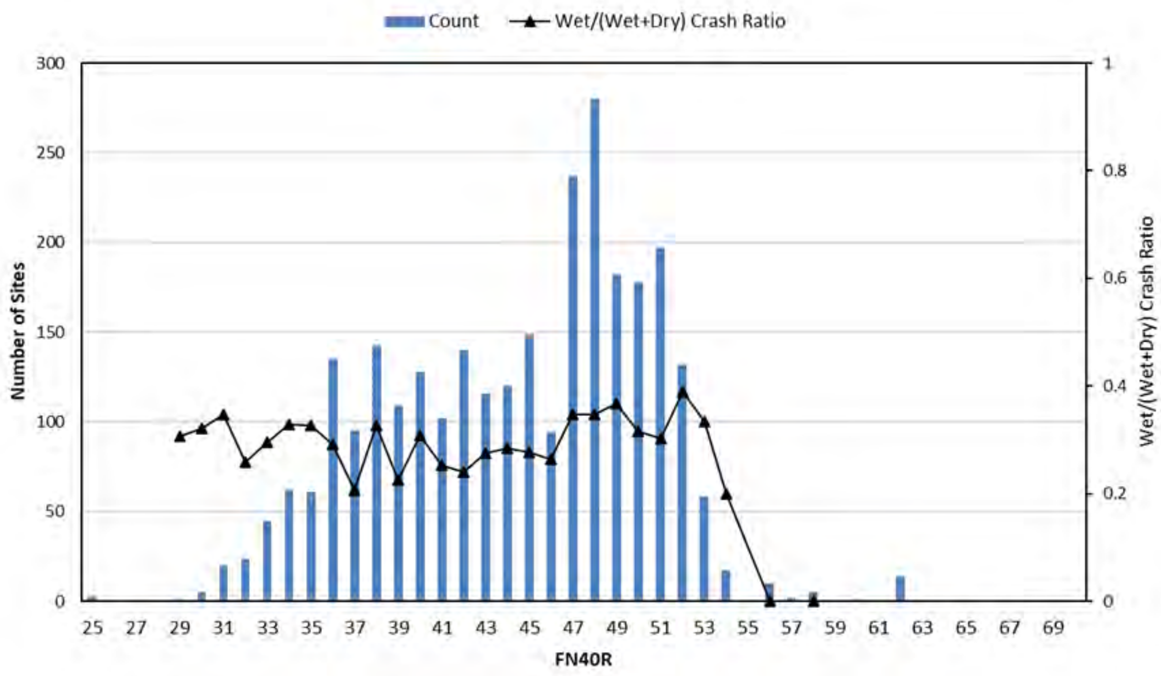


Figure 22. Chart. LWST friction distribution and wet/(wet+dry) crash ratio for divided, non-event friction demand segments (GPF method 3).

2.2.13.1 Findings, Conclusions, Recommendations, and Observations

The analysis to determine the probability of identifying friction thresholds as described in the three AASHTO GPF methods using LWST data was not successful in establishing investigatory friction threshold levels. The primary reason suspected is that the LWST's discrete measurements are not representative of the friction of interest for crash analysis in a 0.1-mi section of road because of the variability in friction throughout the 0.1-mi section. Due to the variability in the location of the discrete measurements with LWST, it is not possible to always match crash locations with skid measurements (i.e., LWST measurements are done at fixed 0.5-mi or 1.0-mi separations). The lack of friction data where crashes have occurred disconnects the relationships that can exist using any crash analysis methods with LWST data.

Based on the findings from this analysis, it is recommended that further evaluation of LWST data and the AASHTO GPF methods in establishing friction threshold levels be conducted. Section 2.2.3 presented information that friction can vary significantly along the road and particularly in areas of high friction demand. The testing resolution of LWST does not appear to be adequate to consistently identify potential friction issues on road sections. This is expected to be even more pronounced in high friction demand locations, such as curves and intersections, which can be very challenging to test with an LWST. As highlighted by Kummer and Meyer (1967) in NCHRP Report 37, it is important to measure high friction demand locations "because the intensity of the polishing process increases markedly with tread element slip, all other factors being equal, the lowest friction levels are found on high-speed roads, curves, and approaches to intersections; in short, in locations at which high friction values are needed most."

2.2.13.2 Study Investigatory Friction Threshold Analysis using the CFME Data

ILs can vary per friction demand category depending on highway characteristics, such as functional classification, geometry and the presence of intersections, ramps, etc. ILs can be selected using either a subjective or objective approach. A subjective approach may be conducted in different ways. This study recommends visually selecting the threshold using a plot that compares crash risk (per unit of traffic volume over a specific measure of distance), where the threshold is the value below which crash risk increases. An objective approach involves using a regression analysis method called constrained least squares (CLS) to directly compute the threshold. CLS uses linear regression modeling to fit two lines of crash risk data that intersect at a single point, which is regarded as the IL.

The CLS method is described by Boyd (2017). The parameters for CLS are estimated using equation 2, where β is the estimated parameter for the vector containing skid resistance, and y is the response vector containing crashes. (Note: Z is a Lagrange multiplier, and the value is not of interest in the analysis.) The point where the two regression lines (equation 3[a]) intersect (x_i) is defined by the constraint (C) in equation 3(b).

$$\begin{bmatrix} \hat{\beta} \\ z \end{bmatrix} = \begin{bmatrix} 2A^{T}A & C^{T} \\ C & 0 \end{bmatrix}^{-1} \begin{bmatrix} 2A^{T}y \\ 0 \end{bmatrix}$$

[Eq. 2]

$$y(x) = \begin{cases} a_1 x + b_1, & x \leq x_i \\ a_2 x + b_2, & x > x_i \end{cases}$$

[Eq. 3a]

$$C = \begin{bmatrix} x_i & 1 - x_i & -1 \end{bmatrix}$$

[Eq. 3b]

The optimum point of intersection (i.e., the IL) is the value of x_i that minimizes the mean squared error (MSE). Figure 23 shows an example of the standard application of CLS for intersections (and ramps) on DGAC surfaces on divided primary routes in one of the States in the study. The lines intersect along the *x*-axis at 51.

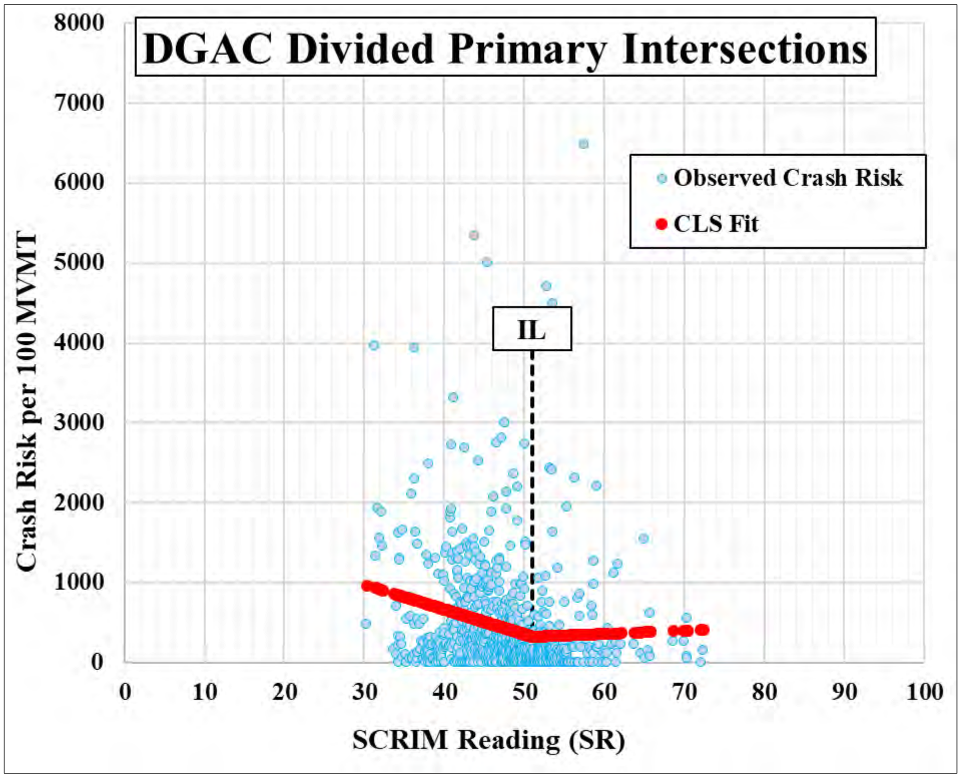


Figure 23. Graph. IL determined with CLS regression.

In this study, the data samples were not as robust as necessary to establish statistically sound values for the ILs of friction, thus illustrative levels are shown in Table 15.

Table 15. Illustrative State ILs of friction for different friction demand categories.

Friction Demand Categories	State A	State B	State C	State D
Interstate Nonevents	N/A	30-35	40-45	30-35
Divided Primary Nonevents	N/A	35-40	40-45	30-35
Undivided Nonevents	N/A	40-45	N/A	50-55
All Nonevent	35-40	N/A	N/A	N/A
Horizontal Curves	N/A	50-55	N/A	50-55
Intersections, ramps, etc.	45-50	50-55	N/A	55-60

2.3 HIGHWAY CRASH ANALYSIS

2.3.1 Crashes

A crash is defined in the Highway Safety Manual (AASHTO, 2014) as the combination of events on a roadway that result in the collision of one or more vehicles. Within this context, an event refers to the movement of one or more vehicles. At any point in time, the combination of events results in a low to high risk for a crash. In general, most events combine to form a low level of risk, and, for this reason, crashes are rare. In addition to being rare, crashes are also complex to model since the factors responsible are related to the roadway, the environment, the driver(s), and the vehicle(s). Highway engineers are primarily interested in controlling roadway characteristics. The remaining three factors are considered when selecting treatments but are primarily managed by other agencies.

2.3.2 Negative Binomial Regression

Crash counts are essential for evaluating highway safety, and they are reported as non-negative, integers (y). The extra variability related to the random factors is accounted for using negative binomial (NB) regression to estimate the average expected number of crashes as a function of roadway characteristics. The NB model uses a Poisson-gamma distribution parameterized with the inverse link function shown in equation 4 (AASTHO, 2010; Lord and Mannering, 2010; Srinivasan and Bauer, 2013).

$$E[y] = \lambda_i = \exp\left(\beta_0 + \sum_{j=1}^{k} \beta_j N_{ij}\right) \qquad \text{Eq. 4}$$

where:

	λ_i	=	Expected average number of crashes for section *i*;
	β_0	=	Intercept parameter;
	β_j	=	Parameters for *j* independent variables;
	N_{ij}	=	Value of predictor variable *j* for section *i*.

For NB regression, the variance of the random variable, $V[y]$, can be larger than λ [equation 5].

$$V[y] = \lambda + \alpha\lambda^2 \qquad \text{Eq. 5}$$

2.3.3 Safety Performance Functions (SPF) and Empirical Bayes (EB) Methodology

The FHWA uses the NB model to generate SPFs in highway safety management practice as a network-level screening process to identify sites or segments that have elevated crash risk and to assess the potential benefits of surface treatments. The FHWA uses SPFs to predict the average expected number of crashes per year on a road segment of length L, as a function of AADT and other additional roadway characteristics specified by an agency (Srinivasan & Bauer, 2013). An example of an SPF model is given in Table 16.

Table 16. Final coefficients of the SPF for the SCRIM in one study State.

Model Variable	Regression Coefficient	Model Variable	Regression Coefficient
Intercept	-6.9139	Route ID *(ref. group = State Route 10 (SR 10)*	-
ln(AADT)	0.8618	SR 1431	-1.0297
Lane Count	0.0805	SR 16	-0.8810
Friction (SR30)	-0.0134	SR 29	-1.2586
Divided	0.2456	SR 281	-1.7851
County Region (*ref. group = AAA*)	-1.0946	SR 290	-1.3767
Pavement Surface Type *(ref. group = Chip Seal)*	-	SR 21	-2.4989
DGAC	1.2286	SR 95	-1.0045
PCCP	1.0152	SR 969	-0.6320
PFC	0.3268	SR 20	-0.9659
Gradient	0.0627	SR 80	-1.3420
Cross-Slope	-0.0310	SR 1035	-1.5193
Horizontal Radius of Curvature (1/mi)	0.0981	SR 2304	-1.2962
SR30*Divided	0.0164	SR 620	-0.8136
SR30*ACP	-0.0171	SR 12	-1.3645
SR30*PCCP	-0.0155	SR 183	-1.1629
SR30*PFC	-0.0028	SR 45	0.1081
		SR 362	0.1063
		SR 290	0.2446
		SR 149	-0.4648
		SR 105	0.6003
		SR 146	0.2754
		SR 2004	-0.3983
		SR 2035	0.2184
		SR 2004	-0.3983
		SR 35	0.2184
		SR 518	0.8254
		SR 225	0.0113
		SR 59	-0.2287
		SR 762	0.0216
		SR 1090	0.1335
		SR 6	0.2951
		SR 90	-0.1395
		SR 610	-0.0296
		SR 1093	0.76666

Model selected criterion, such as Akaike information criterion (AIC), can be used to select additional roadway characteristics for the model. When using AIC, the model with the lowest AIC has the lowest fit (Akaike, 1978). The EB method is used to improve the strength of the estimated average expected crash count. EB combines the observed crash count (y) and the SPF estimated count into a weighted average using the function in equation 6a. The weighted term (W), in equation 6b, varies depending on the size of the over-dispersion parameter (α), where large over-dispersion may indicate a potentially less reliable SPF. If the SPF is less reliable, then

W will be smaller, and the resulting EB estimate will be closer to y. If over-dispersion is small, then W will be larger and the resulting EB estimate will be closer to the SPF (AASHTO, 2010).

$$EB_i = W_i \times \lambda_i + (1 - W_i) \times y_i \quad \text{[Eq. 6a]}$$

$$W_i = \frac{1}{1+\lambda_i \alpha} \quad \text{[Eq. 6b]}$$

where W_i = Weight term for road segment i
λ_i = Predicted number of crashes per year for road segment i
α = Over-dispersion parameter for the SPF
EB_i = EB estimate for road segment i
y_i = Observed crash count for road segment i

2.3.4 Selection and Prioritization of short-and-long term restoration treatments

Cost-benefit analysis can be used to identify sites that have high crash risk and that could potentially benefit from a surface treatment to improve friction. Sites identified in the analysis are then further investigated with a detailed site investigation. This section offers an example to illustrate the suggested cost-benefit analysis. The example uses cost data from a State highway agency on DGAC and PCCP. Although this example focuses on improving friction, the procedure could also apply to surface texture.

When an SPF is used to compute the average expected crash count as a function of treatable pavement surface characteristics (e.g., friction), it is then possible to use the EB method to estimate the potential effectiveness of various friction-improvement surface treatments (i.e., expected crash count reduction).

2.3.5 Step 1: Identify Potential Friction Enhancement Treatment Options

To illustrate the approach, evaluations can be made on the potential safety improvement. For this example, taken from one of the State's surveyed network in 2015, there are two friction-enhancement treatment options for each pavement type. For each pavement type, the highest level of friction enhancement treatment is an HFST. The other options for DGAC and PCCP are an asphalt overlay (HMA-OL) and conventional diamond grinding (CDG), respectively. The cost of treatment per 0.1-mi lane-segment is $5,152.81 for HMA-OL, $7,019 for CDG, and $14,784 for HFST. The potential benefit of each treatment is quantified as a function of the expected improvement to friction, although for this particular State the decision was to limit the use of HFST to interstate roads for this analysis.

For this example, the estimated SR30 friction for HMA-OL is 55, for CDG it is 60, and for HFST it is 80. If the current SR30 for a segment is higher than the values in Table 17, the segment is considered to have adequate friction values and no treatment is considered. Another approach could be evaluating all pavement sections with friction below the estimated improvement provided by surface treatment with the SPF-EB method. It is noted again that these values are adopted for illustrative purposes only and should be verified with a larger sample size.

Table 17. Network-level segment selection criteria for potential treatment.

Road Category	HFST *(interstate only)*	Resurfacing/CDG
Curves	SR30 < 45	SR30 < 45
Tangents	SR30 < 40	SR30 < 40

2.3.6 Step 2: Determine Comprehensive Average Crash Costs

The process of determining the costs associated with different crash types or the costs to reduce the risk of crashes with a specific severity (e.g., injury or fatality) can involve a complex evaluation of various econometric studies. The U.S. Department of Transportation (U.S. DOT) quantifies the economic benefit of reducing "the expected number of fatalities by one" using a measurement called the Value of a Statistical Life (VSL; U.S. DOT, 2015). Furthermore, the U.S. DOT uses an Abbreviated Injury Scale (AIS), shown in Table 18, which is based on the Maximum Abbreviated Injury Scale (MAIS), introduced by the Association for the Advancement of Automotive Medicine, to estimate the cost of different injury crashes (Herbel et al., 2010). The AIS rates the losses resulting from different types of injury crashes by severity using a scale called quality-adjusted life years (QALYs; U.S. DOT, 2015). Most states, however, still use the KABCO five-level scale.

Table 18. Relative disability factors by injury severity level (AIS).

AIS Level	Severity	Fraction of VSL
AIS 1	Minor	0.003
AIS 2	Moderate	0.047
AIS 3	Serious	0.105
AIS 4	Severe	0.266
AIS 5	Critical	0.593
AIS 6	Not survivable	1.000

NHTSA evaluates the societal impacts of crashes (i.e., comprehensive costs) using economic impacts (e.g., productivity losses, medical costs, property damage, etc.) and lost quality-of-life (e.g., physical pain, disability and emotional) impacts (Blincoe et al., 2015). The total number of crashes and their associated comprehensive costs for 2010, reported by NHTSA, are listed in Table 19.

According to NHTSA, "approximately 60% of PDO crashes and 24% of all injury crashes are not reported to the police" (Blincoe et al., 2015). Furthermore, since the crashes that are police-reported are frequently more severe than non-police-reported crashes (i.e., vehicles require towing and/or occupants requiring hospitalization), the effectiveness of safety countermeasures is often analyzed using police-reported crashes only). Therefore, the police-reported crashes and the associated costs from Table 19 are used to estimate the comprehensive costs for crashes.

Table 19. NHTSA comprehensive costs for 2010 (after Blincoe et al., 2015).

Crash Severity	Police-Reported Crashes	Police-Reported Comprehensive Cost ($ million)	NHTSA Cost/Crash (Police-Reported)
Fatality	30,296	$301,809	$9,962,008
Non-Injury/Injury (MAIS0:MAIS5)	1,791,572	$400,435	$223,510
PDO	4,255,495	$45,297	$10,644
Total	6,077,362	$747,541	-
Note: In the cited NHTSA technical report, Table 1-3, 1-12, and 1-13 provide the listed crash counts and comprehensive costs, respectively.			

Since States report crashes using the KABCO scale and NHTSA reports injury crashes using MAIS, the costs reported for each MAIS level were combined to form a single cost for all injury-related police-reported crashes ($223,510). Next, the total comprehensive costs of fatalities, injuries, and PDO crashes were computed using Cost/Crash from Table 19 and the total crash counts in Table 20. The average comprehensive cost of each crash considering all severity types in 2010 dollars is approximately $118,921 ($10,993,671,036 ÷ 92,445).

Table 20. Comprehensive crash costs for a surveyed network (2010 $).

Crash Severity	Crash Count (2012-2014)	NHTSA Cost/Crash (Police-Reported)	Comprehensive Costs
Fatality (K)	430	$9,962,008	$4,283,663,520
Injury (A, B, C)	26,921	$223,510	$6,017,123,864
PDO (O)	65,094	$10,644	$692,883,652
Total	92,445	-	$10,993,671,036

In 2015, FHWA published a new report, Harmon et al. (2018), with recommended average crash costs per crash for 2016. The recommended costs should be considered for calculating the average cost using the number of crashes for a future network of interest.

2.3.7 Step 3: Calculate the Potential Crash Reduction

For each candidate, the potential reduction in crash estimates is computed using the SPF and EB values predicted with the values of friction for the recommended friction treatments. The crash estimate of the SPF for the friction treatment is calculated using the same model developed for the existing pavement, with the new value of SR30 that would be achieved if the recommended friction treatment were applied. Next, the EB crash estimate is computed using equation 7.

$$EB_{HMA-OL,i} = \frac{\lambda_{HMA-OL,i}}{\lambda_i} \times EB_i \qquad \text{[Eq. 7a]}$$

$$EB_{CDG_i} = \frac{\lambda_{CDG,i}}{\lambda_i} \times EB_i$$

[Eq. 7b]

$$EB_{HFS,i} = \frac{\lambda_{HFS,i}}{\lambda_i} \times EB_i$$

[Eq. 7c]

Last, the benefit of the treatment is quantified as the money saved by reducing the number of crashes. The potential crash reduction is calculated as the difference between the existing (EB) and the achievable reduction in crashes (new EB). The difference is then multiplied by the average cost per crash to acquire the cost of crash reduction.

2.3.8 Step 4: Cost-Benefit Analysis

The final step in the economic analysis is to use benefit-cost (B/C) to choose candidate sites that yield the best return on investment. The B/C is calculated by dividing the monetary benefit of the treatment (B) by the cost of applying the treatment (C). Candidate sites are then selected for detailed site investigation if the B/C is greater than 1 and where the total savings (B – C) are, for example, greater than $0.5 million.

2.3.9 Prioritizing Treatment Options

Decision-makers can prioritize treatment options, calculating the savings that any treatment on any section can produce based on the potential crash reduction (CR) for each segment i as seen in equations 8(a), (b), and (c).

$$CR_{HMA\text{-}OL,\ i} = EB_i - EB_{HMA\text{-}OL,\ i}$$ [Eq. 8a]

$$CR_{PCCP\text{-}CDG,\ i} = EB_i - EB_{PCCP\text{-}CDG,\ i}$$ [Eq. 8b]

$$CR_{HFS,\ i} = EB_i - EB_{HSF,\ i}$$ [Eq. 8c]

The savings of each treatment option can then be calculated in terms of the potential costs saved from the prevented crashes (Crash $Savings_i = CR_i \times$ \$118,921). The total savings from each treatment can be estimated for each segment by subtracting the Crash Savings from the Treatment Costs.

Next, the segments are ordered for each treatment from the highest savings to the lowest. For each segment, the Total Savings CR is calculated for each treatment option by subtracting the Treatment Costs from the Crash Savings. Each selected segment is prioritized for treatment if the savings are greater than or equal to the costs. Finally, for each treatment option, segments can be arranged from highest to lowest priority using CR (i.e., the larger the CR, the greater the priority).

2.4 EXAMPLE RESULTS OF THE SPF-EB COST-BENEFIT ANALYSIS

The SPF-EB analysis presented evaluates possible friction-enhancement treatments and selects the one based on the highest possible total savings accrued when the treatment costs are lower than the projected savings based on potential crash reductions computed using SPF-EB estimates. Sometimes an increase in friction does not result in any savings based on the projected number of crashes predicted. In this case, no friction treatment is recommended.

The following is an example analysis from a data set of 8,911 0.1-mi sections of which 2,849 are DGAC, 3,237 are PCCP, 2,111 are chip seals, and 714 are PFC pavements. From these pavement types, 919 DGAC, 388 PCCP, and 63 PFC pavement sections have a B/C greater than 1. Chip seals were not included in the analysis because there were noticeable recurring sections with aggregate raveling. Table 21 presents the results for the 3-year period, potential economic savings at various levels ranging from greater than \$3 million each to less than \$0.5 million each on DGAC pavements. Table 22 and Table 23 present the results for the PCCP and the PFC pavement sections analyzed, respectively, according to the SPF and EB methodology described in section 2.3.2.

There is also an associated predicted number of crashes in each of these sections that has been estimated. Thus, for the first savings level, greater than \$5 million in the PCCP pavements (Table 22), the predicted crash reduction is 113. The second savings level is 201, etc. In total, in 388 sections (388 CDG) the potential crash reduction is 1,491. The cost to achieve all of the potential crash reductions by treating 388 sections of all 3,237 PCCP sections is about \$10 million, resulting in economic savings from the reduction in the cost of the crashes of about \$167 million. However, this would require treating all 388 sections. Another approach that could be taken is to focus on only those sections that have savings greater than \$0.5 million. This reduces the number of sections to be treated by CDG to 90 at a cost of about \$2.6 million, resulting in a predicted crash reduction of 1,019 with economic savings of about \$119 million.

Table 21. DGAC sections with B/C > 1 with potential predicted crash reductions.

Savings per Sections >	Total	Resurfacing	HFS	Pred. crash reductions	Total Costs	Total Savings	Average B/C
\$3.0 M	1	1	0	40	\$15,458	\$4,778,900	310
\$2.0 M	9	9	0	186	\$200,960	\$21,928,530	113
\$1.0 M	24	24	0	302	\$463,753	\$35,399,822	81
\$0.5 M	75	75	0	448	\$1,396,412	\$51,892,494	42
< \$0.5 M	810	810	0	784	\$12,150,326	\$81,047,980	8
TOTAL	919	919	0	1,760	\$14,226,909	\$195,047,727	14

Table 22. PCCP sections with B/C > 1 with potential crash reductions.

Savings per Sections >	Total	CDG	HFS	Pred. crash reductions	Total Costs	Total Savings	Average B/C
\$5.0 M	2	2	0	113	\$63,170	\$13,431,221	216
\$3.0 M	7	7	0	201	\$203,548	\$23,692,423	118
\$2.0 M	6	6	0	20	\$31,585	\$2,394,110	80
\$1.0 M	35	35	0	423	\$1,045,813	\$49,251,012	50
\$0.5 M	40	40	0	262	\$1,249,361	\$29,858,121	26
< \$0.5 M	298	298	0	472	\$7,362,805	\$48,736,181	8
TOTAL	388	388	0	1,491	\$9,956,281	\$167,363,067	17

Table 23. PFC pavement sections with B/C > 1 with potential predicted crash reductions.

Savings per Sections >	Total	Resurfacing	HFS	Pred. crash reductions	Total Costs	Total Savings	Average B/C
$0.5 M	2	2	0	15	$62,862	$1,679,915	28
< $0.5 M	63	63	0	49	$1,964,433	$3,835,059	3
TOTAL	65	65	0	63	$2,027,295	$5,514,974	2.7

Similarly, for DGAC an investment of $2.0 million on 109 sections results in a predicted crash reduction of 976 with economic savings of $114 million. For the PFC pavement type, investing $62,000 on two sections results in a predicted crash reduction of 15 crashes with economic savings of $1.6 million.

Adding up all the predicted crash reductions possible for all projects having more than $0.5 in savings, a total of 2,011 crashes could be reduced. Assuming that the reductions of fatal crashes and serious injuries in the 201 sections are proportional to the total crashes (as shown in Table 14), this would result in a potential reduction of 9 fatalities and 39 serious injuries in the DGAC, PCCP, and PFC networks tested. This represents a potential reduction in fatalities and serious injuries of 4.2 percent in the network tested.

2.5 IDENTIFYING SITES WITH HIGH POTENTIAL SAVINGS

The SPF-EB model developed for the example in section 2.4 also identifies the locations with the highest potential savings benefits. As an example, Table 24, Table 25, and Table 26 highlight the top 10 sites that have the highest estimated potential savings for DGAC, PCCP, and PFC pavements, respectively.

Table 24. Top 10 sections with the highest savings benefit for DGAC pavements.

Rte.	MM	D	DIV	SR30	AADT (10^3)	RAD (10^3 ft)	*y*	SPF	EB	TRT	SPF After	EB After	CR
IH X	1.2	N	YES	36	79	23.0	186	12	174	RSF	9	134	40
SR xxxx	2.5	E	YES	30	33	16.0	81	22	79	RSF	15	55	24
SR yyyy	3.1	N	NO	23	33	16.4	43	5	38	RSF	2	14	23
SR xxxx	4.8	E	YES	35	29	13.3	93	18	90	RSF	14	68	22
US B	5.6	S	YES	33	127	21.9	83	29	81	RSF	21	60	21
SR xxxx	6.3	E	YES	28	33	25.0	68	22	66	RSF	15	45	21
SR xxxx	7.3	E	YES	32	30	12.9	78	20	76	RSF	14	54	21
SR xxxx	8.5	E	YES	29	33	22.2	61	22	60	RSF	15	41	18
SR xxxx	9.4	E	YES	31	30	18.7	65	20	63	RSF	14	45	18
SR G	10.3	E	NO	38	29	3.8	46	8	42	RSF	5	25	17

MM= Mile Marker; D = Travel direction; DIV=Divided; SR30 = SCRIM Reading at 30 mph; Rad = Radius of the horizontal curvature; y = Observed crash count; CR = Potential crash reduction; TRT = Treatment; RSF = Resurfacing

Table 25. Top 10 sections with the highest savings benefit for PCCP pavements.

Rte.	MM	D	DIV	SR30	AADT (10^3)	RAD (10^3 ft)	*y*	SPF	EB	TRT	SPF After	EB After	CR
US B	1.7	S	YES	27	97	18	176	17	169	CDG	12	112	57
IH W	2.6	S	YES	36	136	17	222	35	218	CDG	26	161	56
IH X	3.9	W	YES	26	142	9	96	35	95	CDG	23	61	33
US B	4.1	S	YES	29	78	26	103	14	98	CDG	10	66	32
IH X	5.7	E	YES	30	74	2	100	23	97	CDG	16	66	31
US B	6.4	S	YES	35	90	29	106	16	102	CDG	12	74	27
US B	7.8	S	YES	29	97	28	87	17	84	CDG	11	57	27
US B	8.5	S	YES	35	97	10	100	16	96	CDG	12	70	26
IH X	9.3	E	YES	34	84	6	95	24	93	CDG	17	67	26
IH W	10.0	S	YES	32	94	28	81	23	79	CDG	16	56	23

MM= Mile Marker; D = Travel direction; DIV=Divided; SR30 = SCRIM Reading at 30 mph; Rad = Radius of the horizontal curvature; y = Observed crash count; CR = Potential crash reduction; TRT = Treatment; CDG = Conventional Diamond Grinding

Table 26. Top 10 sections with the highest savings benefit for PFC pavement surfaces.

Rte.	MM	D	DIV	SR30	AADT (10^3)	RAD (10^3 ft)	*y*	SPF	EB	TRT	SPF After	EB After	CR
SR DDD	1.7	S	NO	37	28	12	38	3	30	RSF	2	23	7
SR rrr	2.6	W	NO	36	42	2.3	30	6	27	RSF	4	20	7
SR DDD	3.0	S	NO	40	39	9	20	4	17	RSF	3	13	4
SR DDD	4.4	S	NO	35	40	7	12	4	10	RSF	3	8	3
SR Y	5.4	E	NO	33	19	23	12	2	9	RSF	1	7	3
SR DDD	6.3	S	NO	36	39	2.8	11	5	10	RSF	4	7	3
SR Y	7.1	E	NO	31	17	15	10	2	8	RSF	1	5	3
SR DDD	8.5	S	NO	40	40	10	11	3	10	RSF	3	7	2
SR Y	9.6	E	NO	27	14	24	7	2	6	RSF	1	4	2
SR rrr	10.9	W	NO	37	42	14	7	4	6	RSF	3	5	2

MM= Mile Marker; D = Travel direction; DIV=Divided; SR30 = SCRIM Reading at 30 mph; Rad = Radius of the horizontal curvature; y = Observed crash count; CR = Potential crash reduction; TRT = Treatment; RSF = Resurfacing

2.6 CASE STUDIES

The case studies below discuss the conditions found on some roads that exemplify the deterioration of the microtexture (aggregate polishing), deterioration of the macrotexture, and raveling of chip seal pavements. Although many factors impact crash risk, in these locations the SPF-EB analysis model estimates that a friction-enhancement treatment would reduce the crash risk.

2.6.1 Macrotexture and High-Speed Roads

The lack of sufficient friction between the tire and pavement, especially during wet weather conditions, is one of the factors that can increase crash risk. As explained earlier, friction is a function of two components of the surface texture of the road: microtexture and macrotexture. Microtexture is a function of the surface roughness of the aggregate particles that make up the paving material of the road surface. It is what contacts the rubber of the tire and allows friction from adhesion between the two. The greater the microtexture, the greater the friction and the greater the stopping ability once the rubber of the tire encounters it.

Macrotexture is the texture you can easily see on the surface. When a road is wet and/or experiencing rainfall, macrotexture gives water a place to evacuate when the tire comes along such that the rubber of the tire and the microtexture of the surface can make contact. It does this by providing void channels or space for the water to move to and through. Macrotexture also provides friction from hysteresis, which increases with speed. Thus, macrotexture is increasingly important as travel speeds increase.

Figure 24 shows macrotexture measurements as MPD and friction measurements made with an LWST with a ribbed tire (SN40R) and the SCRIM (SR30) along a 31-mi long section of roadway. Both friction measurements (SN40R and SR30) are indicative of the microtexture of the road, whereas the MPD is a direct measurement of the macrotexture. For the majority of the 31 mi, the MPD is relatively constant around 0.40 mm, except for a 1.3-mi segment (from MM 12.2 to MM 13.7), which represents the only section of the route that was not covered with a new pavement overlay 1.2 years before the friction and texture measurements were made. This 1.3-mi section of the road with the higher macrotexture (average 0.80 mm) is representative of the macrotexture of the pavement that existed before the overlay.

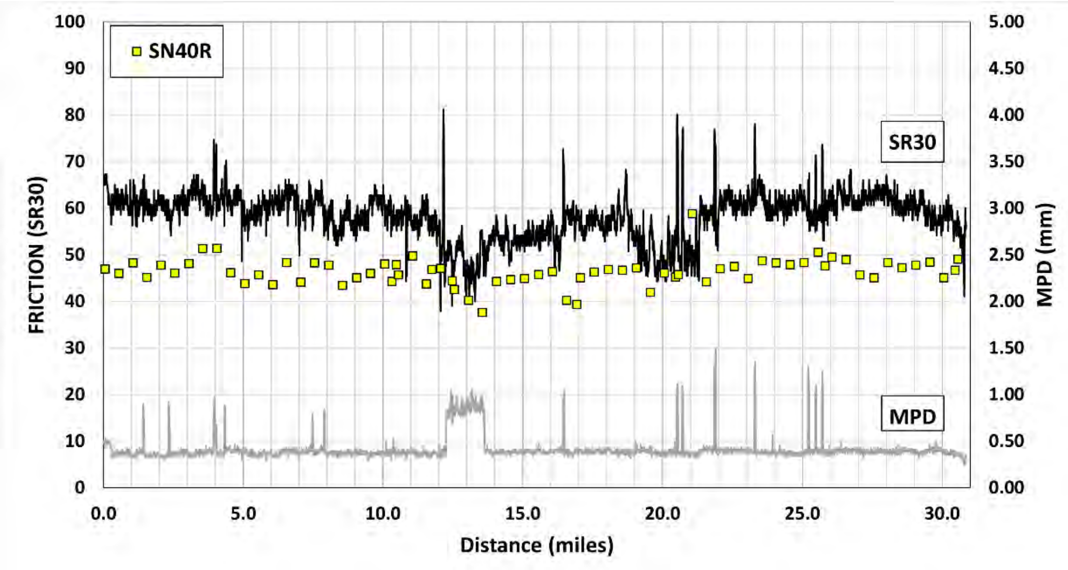


Figure 24. Graph. Macrotexture and friction measurements

A summary of the number of wet weather crashes that occurred in the 3 years prior to the paving of this road and the 1.2 years after paving (the same time as when the friction measurements were taken) are shown below. The results of the analysis are separated by speed limit to better appreciate the effect that low macrotexture has on the crashes, especially as the speed increases (de Leon Izeppi et al., 2017).

Crash Analysis for Sections with Speed Limit = 55 mph

AADT: 15,000–18,000
Total Length: 9.09 mi
Total Crashes: Before = 119, After = 72
Wet Crashes: Before = 33 *(28%)*, After = 21 *(29%)*
Wet/Year/Mile: Before = 1.21, After = 1.91 *(+58%)*
Pavement Surface Mix Type: S9.5C (2015)
Average friction: SR30 = 51.3–57.1
Average Macrotexture: MPD = 0.37–0.40 mm

Crash Analysis for Sections with Speed Limit = 70 mph.

AADT: 15,000–18,000
Total Length: 24.10 mi
Total Crashes: Before = 269, After = 234
Wet Crashes: Before = 112 *(42%)*, After = 157 *(67%)*
Wet/Year/Mile: Before = 1.55, After = 5.38 *(+248%)*

Pavement Surface Mix Type: S9.5C (2015)
Average friction: SR30 = 60.4–60.5
Average Macrotexture: MPD = 0.38–0.40 mm

The data show an increase in the number of wet-weather crashes after the new paving was finished in 2015. The new paving has lower macrotexture values (MPD ~0.4 mm), which could be a reason for the increase in wet-weather crashes in all sections. Furthermore, because higher macrotexture is needed at higher speeds, the lower macrotexture could also be a reason why there is a higher increase in the number of wet-weather crashes in the sections with higher speed limit (58 percent vs. 248 percent).

2.6.2 Macrotexture and Friction at Intersections

The two intersections shown in this example were part of a Road Safety Audit (RSA) conducted as a result of the continuous friction data analysis provided to a study State. The RSA included a multidisciplinary team (law enforcement, safety specialists, traffic operations specialist, and pavement specialists) that used the results of the continuous friction and macrotexture measurements as part of the standard RSA process, including a field site visit.

The route has a 45-mph speed limit. The crash data showed greater than average rear-end crashes in both dry and wet conditions compared to similar intersections in other locations in the district. In the first example, at MM 4.8, there were a total of 100 crashes in the previous 5 years; 86 were dry crashes and 14 were wet crashes. There were 41 dry rear-end crashes and 4 wet rear-end crashes, for a total of 45 rear-end, or 45 percent of the total crashes at the intersection. For the second example, at MM 12.5 (at the first intersection, at the bus stop), there were a total of 51 crashes in the previous 5 years; 43 were dry crashes and 8 were wet crashes. There were 27 dry rear-end crashes and 6 wet rear-end crashes, for a total of 33 rear-end, or 65 percent of the total crashes at the intersection. The RSA team concluded that all rear-end crashes should be considered friction-related crashes. This provides more evidence why dry crashes and not only wet crashes should be considered in the analysis of a PFMP. The RSA team then recommended the installation of an HFST at both sites.

As shown below in Figure 25–Figure 28, the DGAC intersections have macrotexture (MPD) values of 0.24 mm and 0.34 mm, and SCRIM friction values (SR30) of 30.5 and 44.1, respectively. Although the study did not establish recommended ILs for macrotexture, the research team believes that the MPD values found in these two intersections are contributing factors for the high number of rear-end crashes, based on the values recommended in the United Kingdom and in New Zealand (Highways England, 2020; NZTA, 2013).

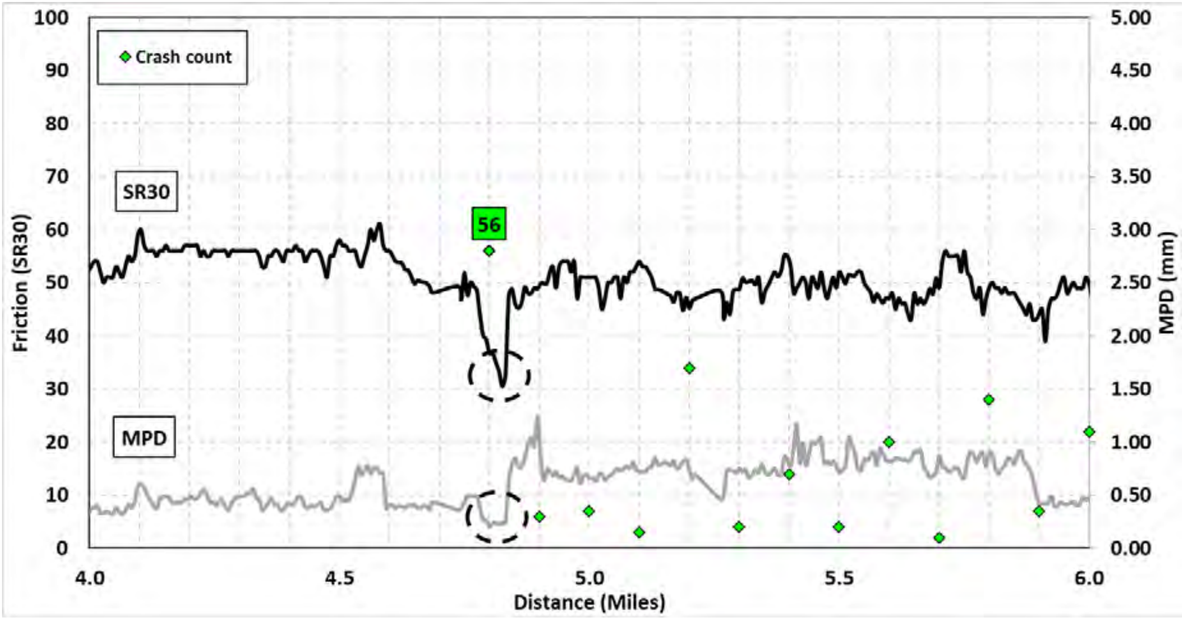


Figure 25. Graph. SR30, MPD, and crash counts for an intersection at MM 4.83.

Source: CSTI

Figure 26. Photo. High crash count intersection at MM 4.83.

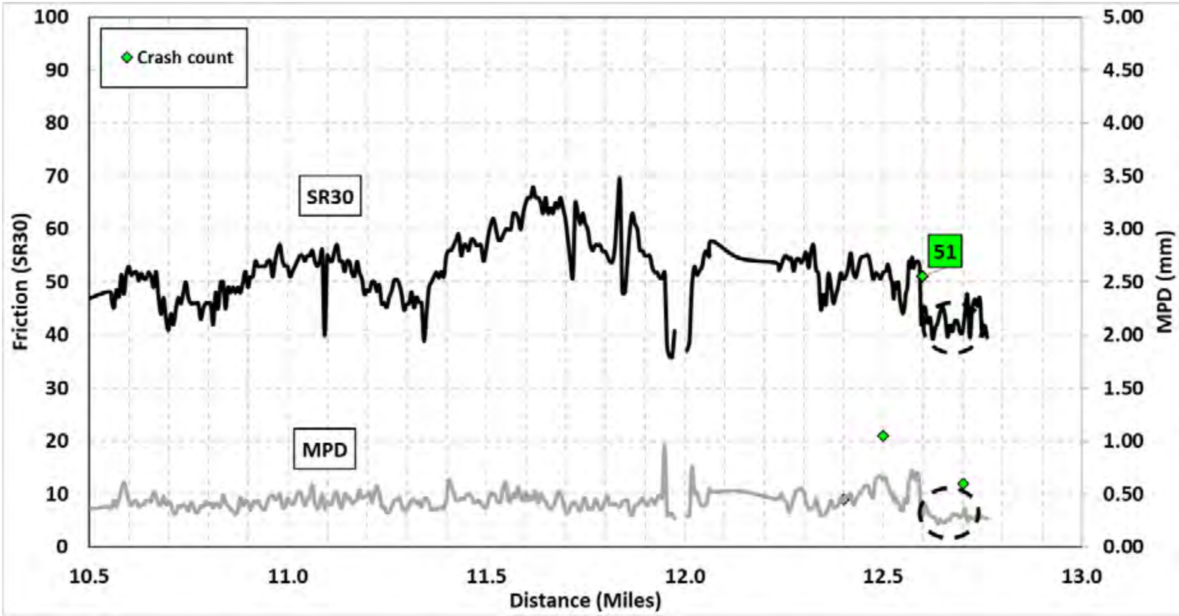


Figure 27. Graph. SR30, MPD, and crash count for intersection at MM 12.55.

Source: CSTI

Figure 28. Photo. Intersection with high crash count at MM 12.55.

2.6.3 PCCP Friction and Macrotexture

The plot in Figure 29 shows the friction and MPD with distance in this 16-mi stretch of PCCP in a study State, where the analysis identified four 0.1-mi sections that are among the top 10 PCCP sections in this State that could benefit from friction-enhancement treatments. The plot in Figure 31 shows the friction and crash counts with distance. There is a higher number of crashes between MM 510.8 and MM 514.0, which coincides with the location of the lowest LWST measurements done with a smooth tire. As expected, the lower LWST measurements are located where the macrotexture values are low as well.

The photos (Figure 30 and Figure 32) show the 0.1-mi values for SCRIM friction and texture at MM 511.7 and MM 518.5, which represent the highest crash counts in this stretch of road. Road standards in both New Zealand and the United Kingdom do not specify values for sections of PCCP pavements. However, these sections have lower values than the illustrative ILs for friction found for non-event sections in this State (SR30 = 45). The research team estimates that the low friction numbers and the low values for texture could be a cause of the high observed crash counts.

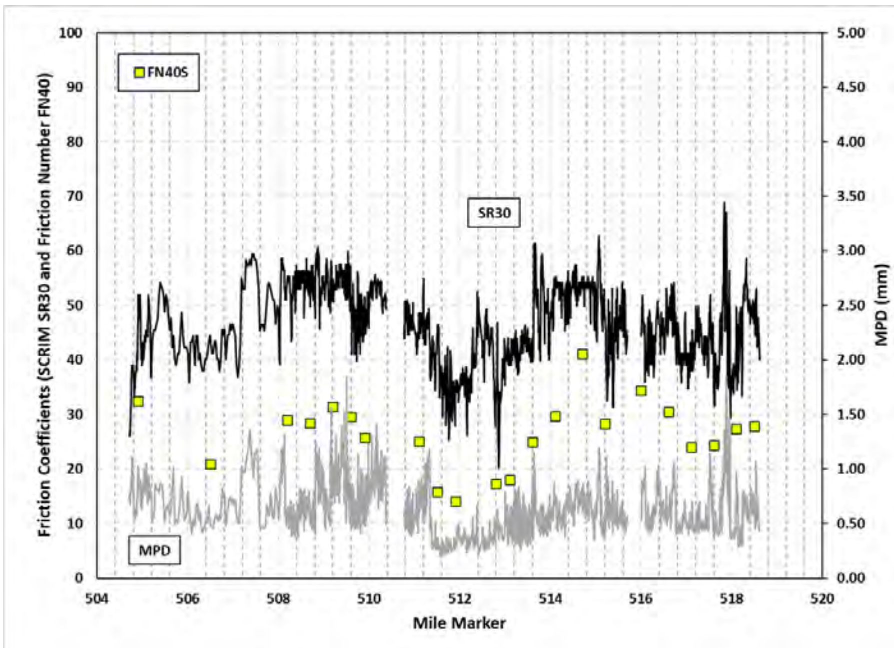


Figure 29. Graph. SR30, FN40S, and MPD for MM 511.7.

Source: CSTI

Figure 30. Photo. PCCP pavement at MM 511.7.

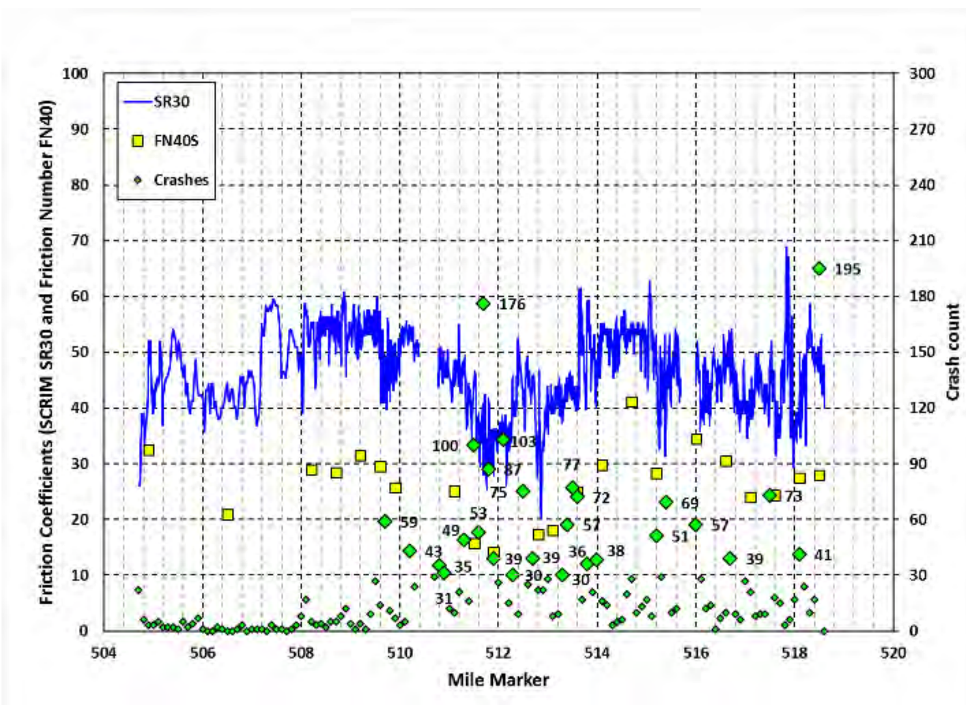
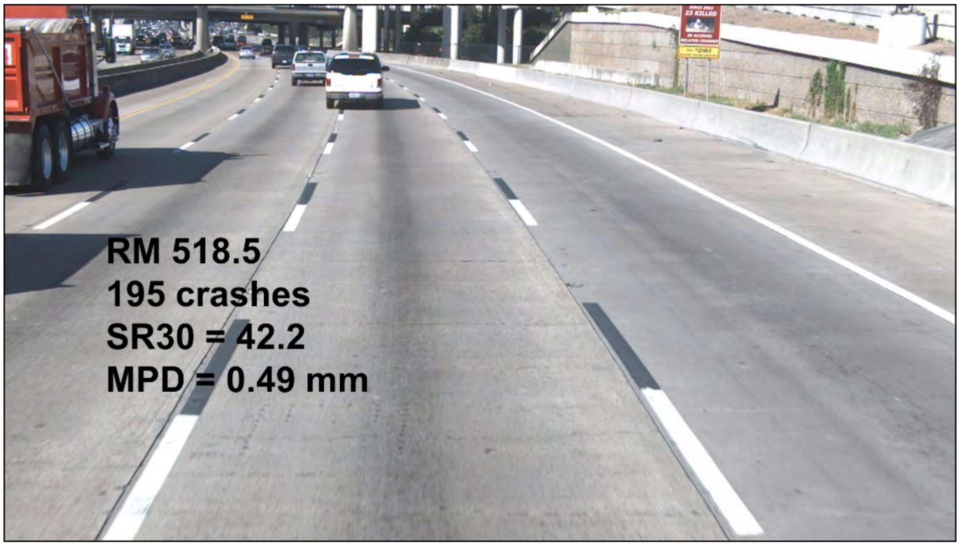


Figure 31. Graph. SR30, FN40S, and crashes for MM 518.5.



Source: CSTI

Figure 32. Photo. PCCP pavement at MM 518.5

2.6.4 Raveling of Chip Sealed Roads

This route has 9 mi (MM 479.5–488.4) of chip seal pavement with different degrees of raveling (i.e., aggregate loss). In Figure 33, the plot shows the whole segment of chip seal pavement. Figure 34 shows a closer look at the first 2 mi of the road where drops in both friction and texture are evident because of the raveling.

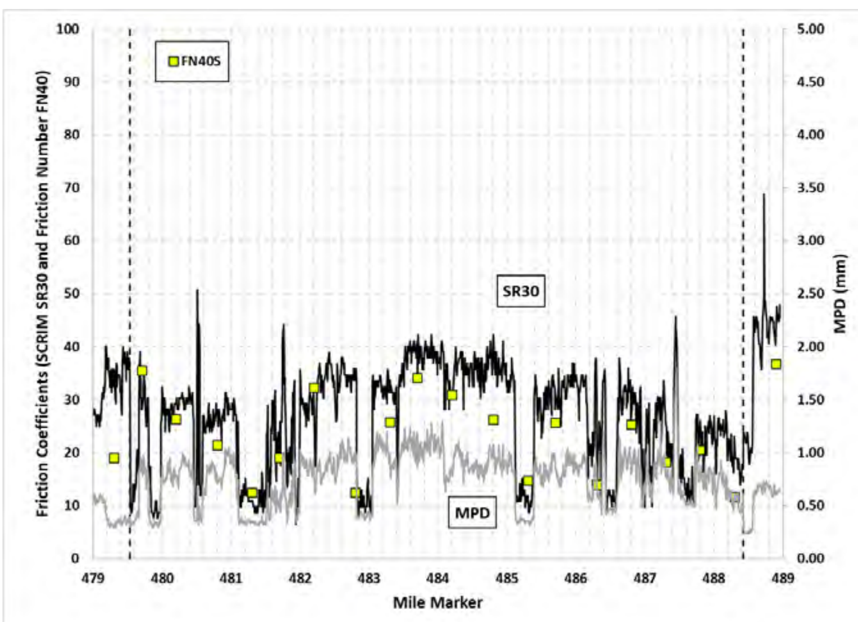


Figure 33. Graph. Friction and texture plots for chip seal roads with raveling between MM 479 and 489.

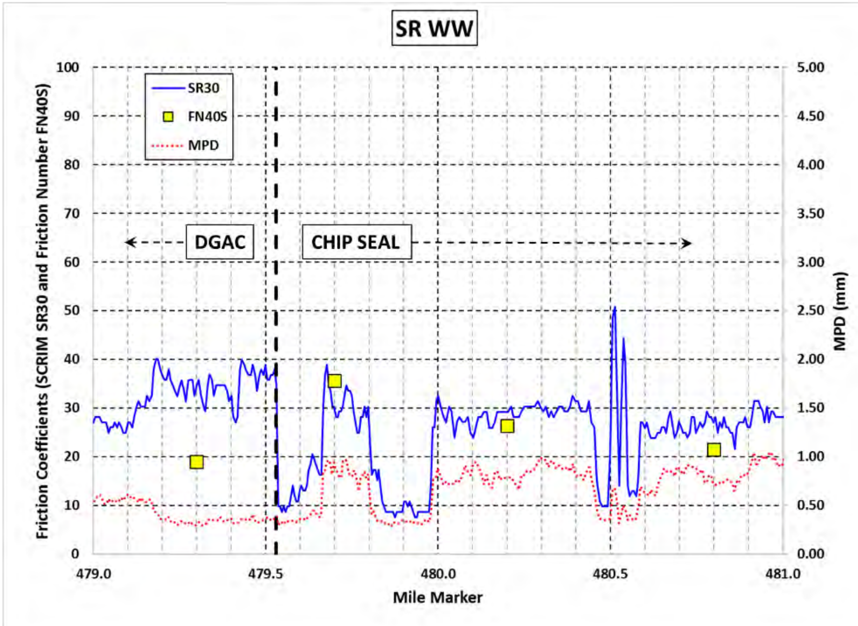


Figure 34. Graph. Friction and texture plots for chip seal roads with raveling between MM 479 and 481.

The photos in Figure 35 and Figure 36 show a less raveled spot at MM 480.0 and a more raveled spot at MM 479.9 (data collection was done in reverse MM order). It is evident by the pictures that the more raveled pavement has a darker color surface where the asphalt has risen to the surface, which is probably the cause for the lower friction and texture measurements. The section that is less raveled shows a lighter color that is characteristic of the aggregate at the pavement surface. It is also interesting to note that all of the LWST results for these two miles represent places where there was not significant raveling, thus showing friction numbers of FN40S > 20, which some agencies select as the investigatory friction threshold for the smooth tire LWST test.

There is a test at MM 479.3 with FN40S = 19, but that is in a segment of road outside the chip seal segment, which is actually a DGAC pavement. Thus, using LWST data and an investigatory threshold of FN40S < 20, this section of chip seal pavement would not have been identified for investigation.

Source: CSTI

Figure 35. Photo. Chip seal road with raveling at MM 480 (SR30 = 32.5, MPD = 0.88).

Source: CSTI

Figure 36. Photo. Chip seal road with raveling at MM 479.9 (SR30 = 8.7, MPD = 0.30).

CHAPTER 3. CONCLUSIONS

The main results of the *Pavement Friction Management* (*PFM*) demonstration project, conducted in collaboration with four State agencies, can be summarized as follows:

- The study confirmed a strong association between crashes and continuously measured frictional pavement properties (friction and macrotexture).
    - Therefore, a proactive PFMP can help reduce the number of crashes and associated fatalities.
- It was possible to identify illustrative ILs for frictional properties using CFME (SR and MPD) measurements for some roadway categories (tangents and curves) and pavement types.
    - The analysis based on the CFME results allowed illustrative ILs for friction to be determined for four friction demand categories and associated with a level of crash "risk."
    - The exception was that it was not possible to identify a threshold when the trend was distorted by other factors, such as chip seal sections with high friction and very high crash rates.
    - Some of the data samples were not as robust as necessary to establish statistically sound ILs for all the friction demand categories.
- The collection of continuous friction and macrotexture data through the adoption of CFME instead of the traditional sampling approach using an LWST can have a significant impact on crash reductions and supports a proactive PFM program.
    - Measuring friction continuously, especially when complemented by macrotexture and road geometry data, provides a more effective method for identifying the most critical sections and allows safety-improvement efforts to be focused on higher-risk locations, such as intersections and curves.
    - Providing an appropriate level of macrotexture is also critical for high-speed roadway segments.
    - The data obtained in this project show that both wet and dry crashes increase when pavement friction decreases.
- An analysis to determine the probability of identifying friction thresholds as described in the three AASHTO GPF methods using LWST data was not successful in establishing investigatory friction threshold levels. The primary reason suspected is that the LWST's discrete measurements are not representative of the friction of interest for crash analysis in a 0.1-mi section of road because of the variability in friction throughout the 0.1-mi

section. Further evaluation of LWST data and the AASHTO GPF methods in establishing friction threshold levels is recommended.

- The application of the SPF-EB analysis method, in conjunction with the continuous measurement of pavement friction, macrotexture, and road geometry, allows the sites with the highest potential payoff for pavement friction improvements to be identified.
    - The analysis of approximately 4,000 mi of tested pavements suggests that if PFM programs can be implemented that determine recommended treatments with CFME data, crashes can potentially be reduced. This, in turn, would result in a reduction of fatalities and serious injuries, with the total investment yielding significant potential economic savings with a very favorable B/C ratio.

APPENDIX A. EVALUATION OF THE AASHTO GUIDE FOR PAVEMENT FRICTION SECTION 3.2.3, METHODS TO ESTABLISH FRICTION THRESHOLD LEVELS USING HISTORICAL LOCKED-WHEEL SKID TRAILER DATA, STATE 1

GPF METHOD 1

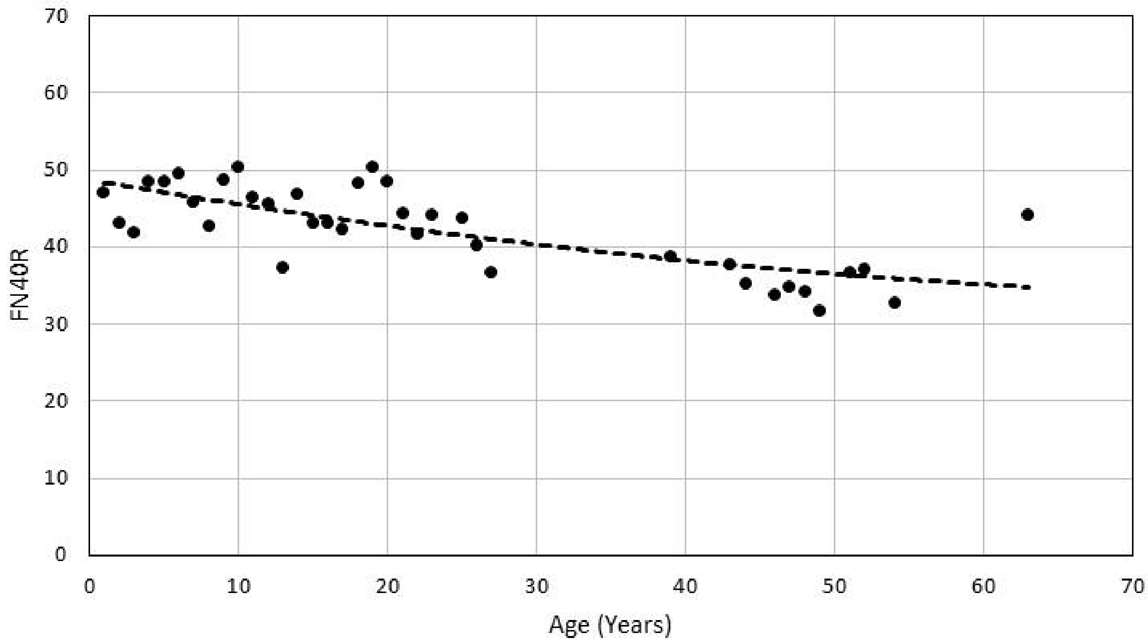


Figure 37. Graph. Friction versus age for divided, non-event segments, all traffic levels.

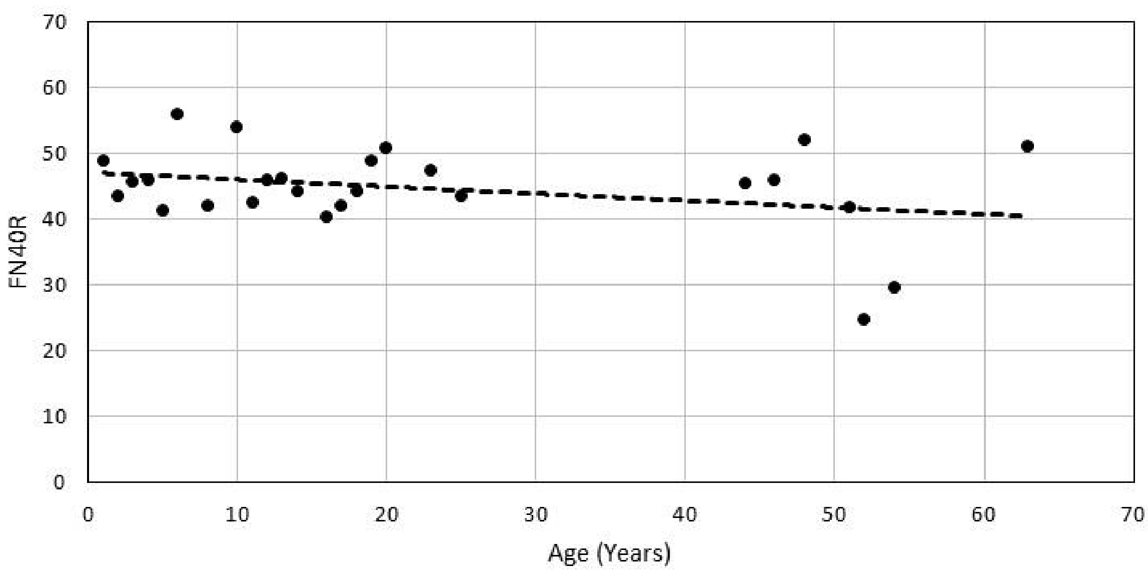


Figure 38. Graph. Friction versus age for divided, event segments, all traffic levels.

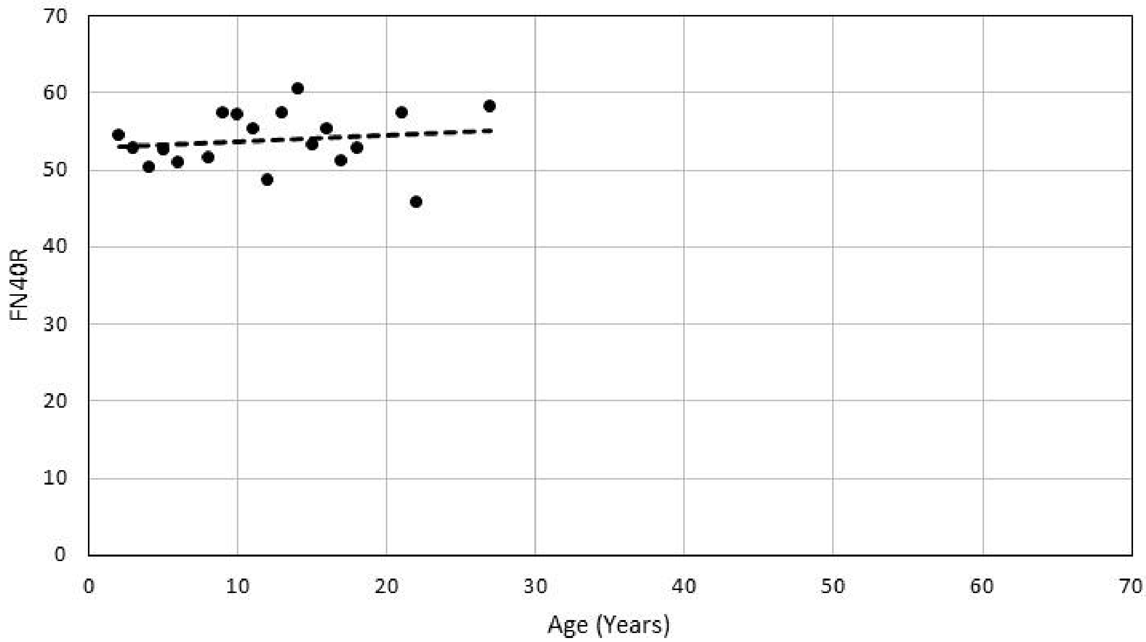


Figure 39. Graph. Friction versus age for undivided, non-event segments, all traffic levels.

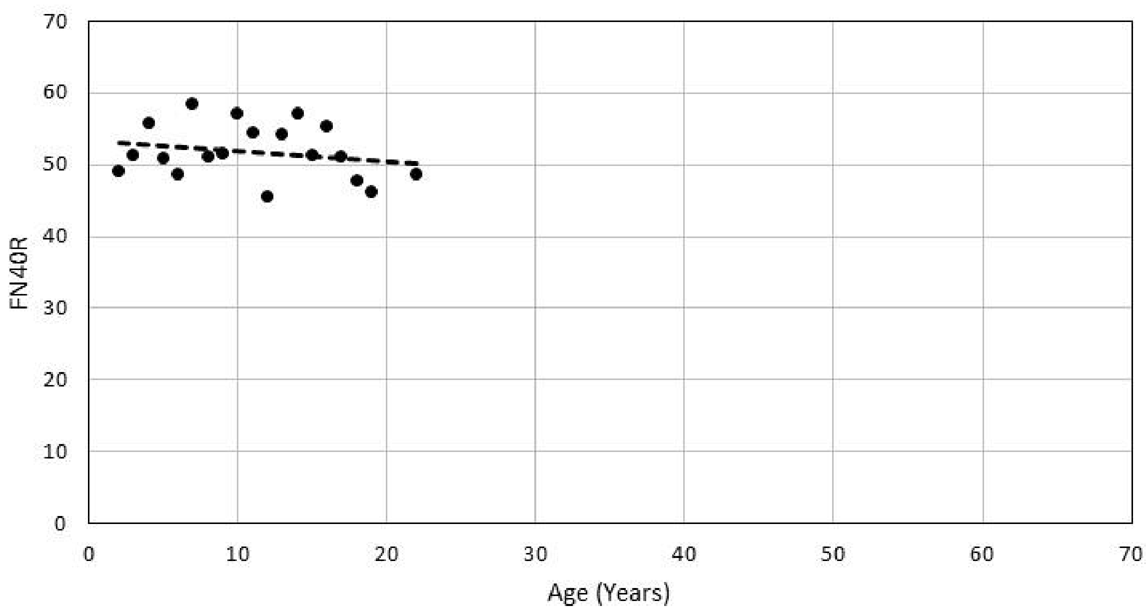


Figure 40. Graph. Friction versus age for undivided, event segments, all traffic levels.

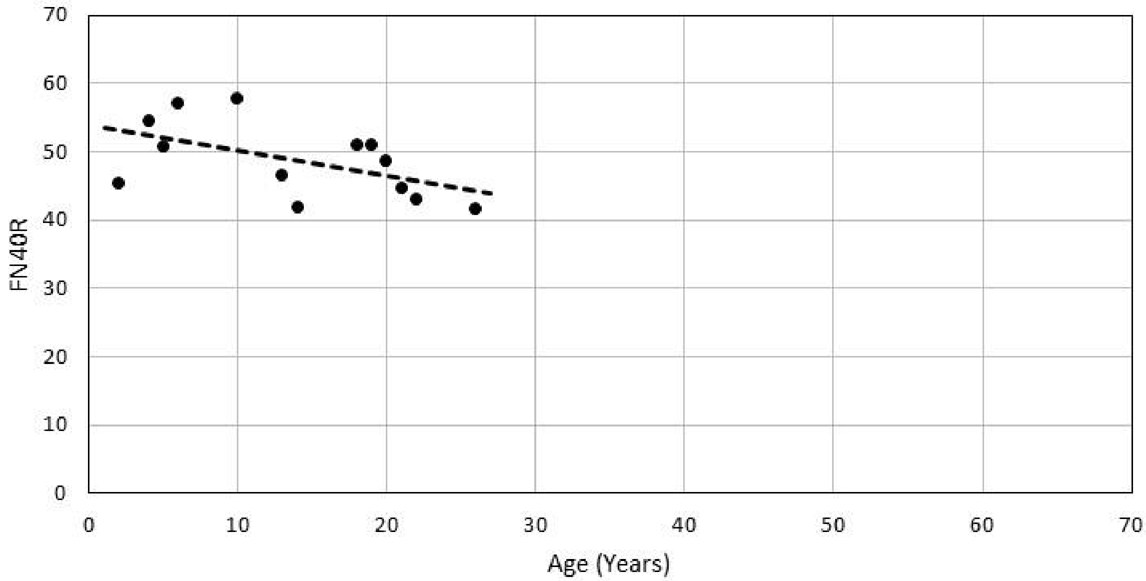


Figure 41. Graph. Friction versus age for divided, non-event segments, low traffic (AADT < 15,000).

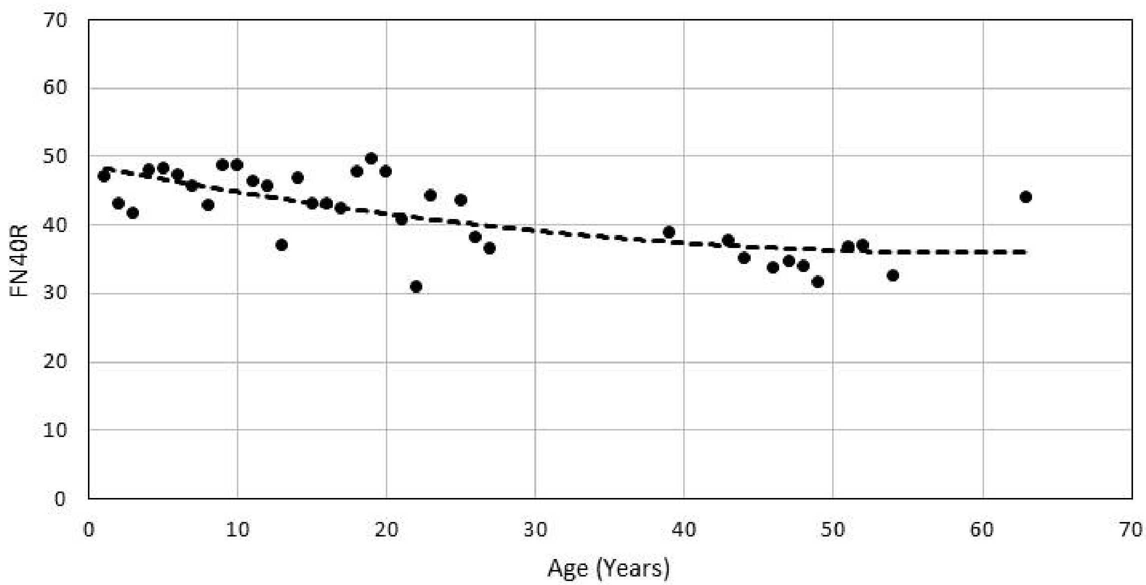


Figure 42. Graph. Friction versus age for divided, non-event segments, high traffic (AADT > 15,000).

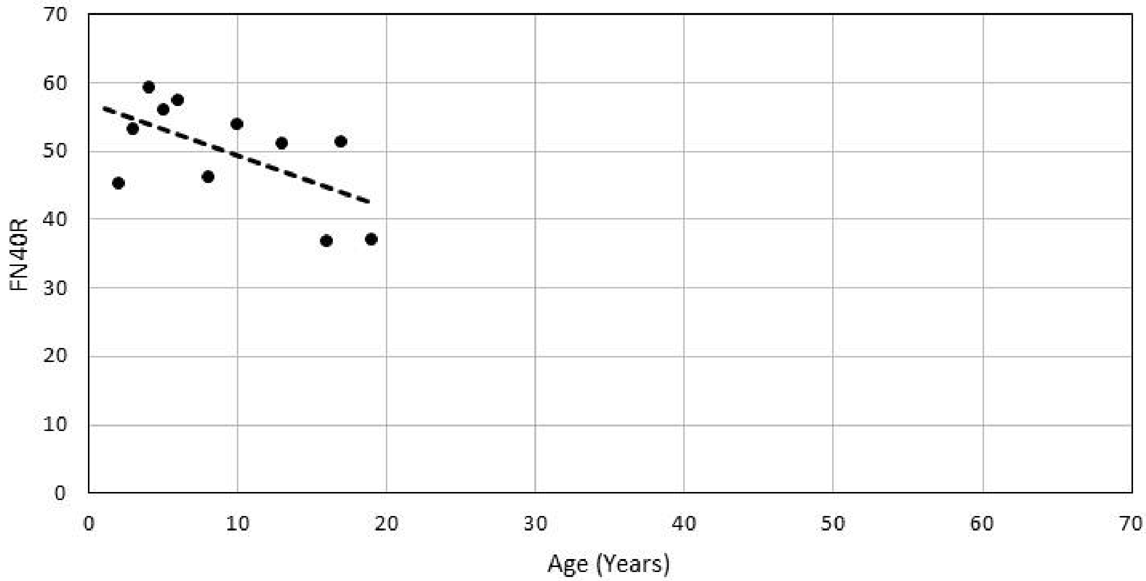


Figure 43. Graph. Friction versus age for divided, event segments, low traffic (AADT < 15,000).

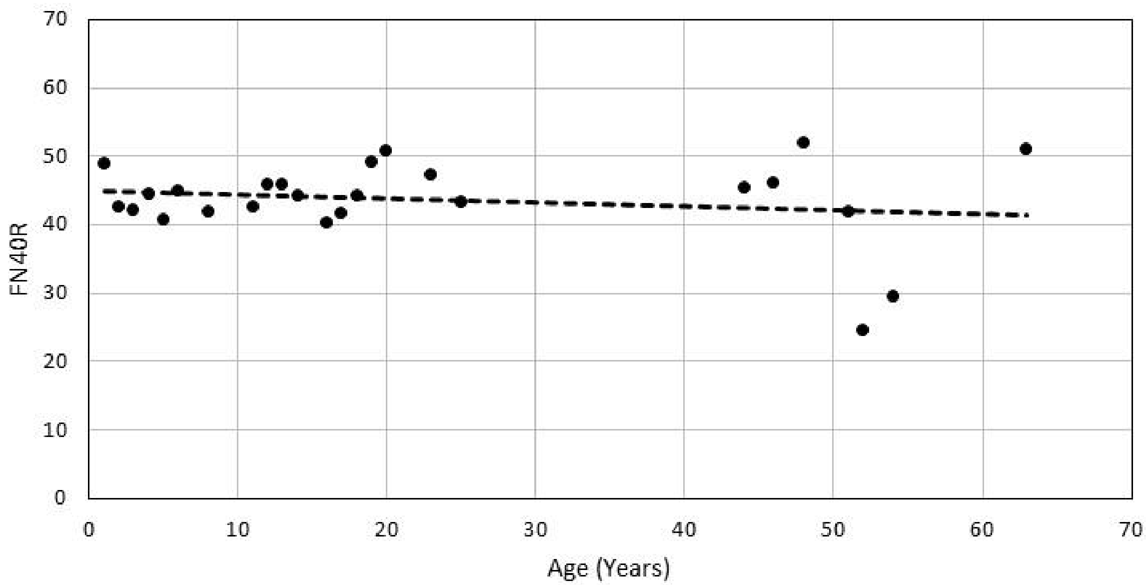


Figure 44. Graph. Friction versus age for divided, event segments, high traffic (AADT > 15,000).

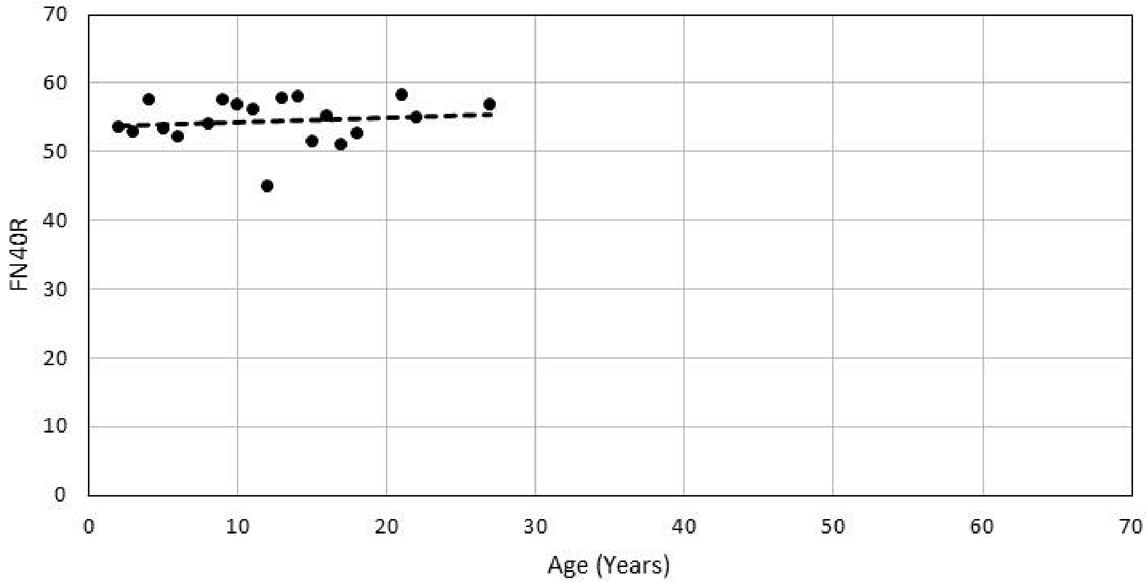


Figure 45. Graph. Friction versus age for undivided, non-event segments, low traffic (AADT < 15,000).

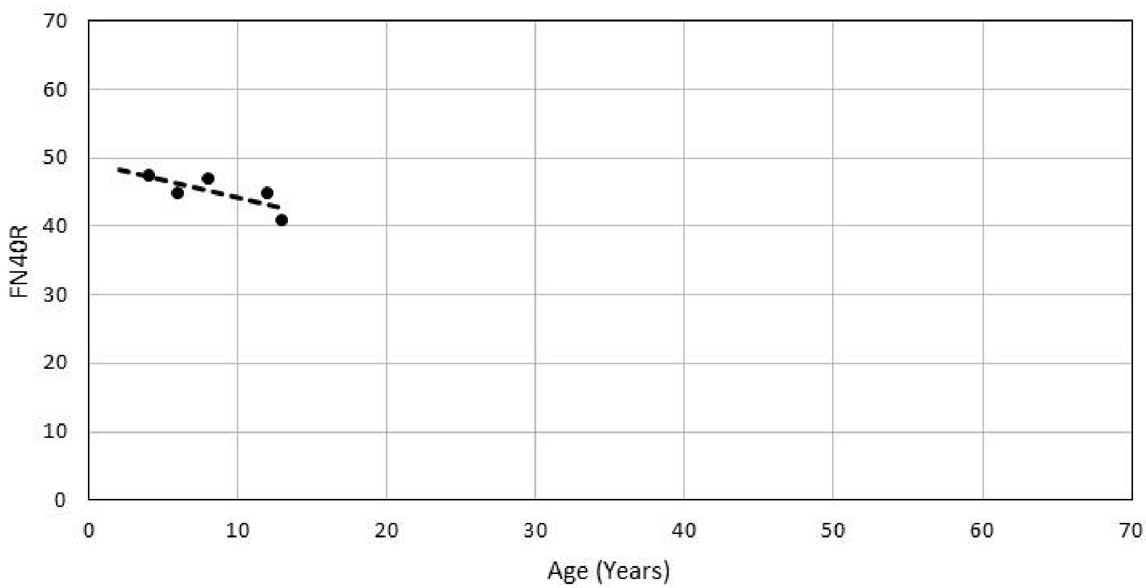


Figure 46. Graph. Friction versus age for undivided, non-event segment, high traffic (AADT > 15,000).

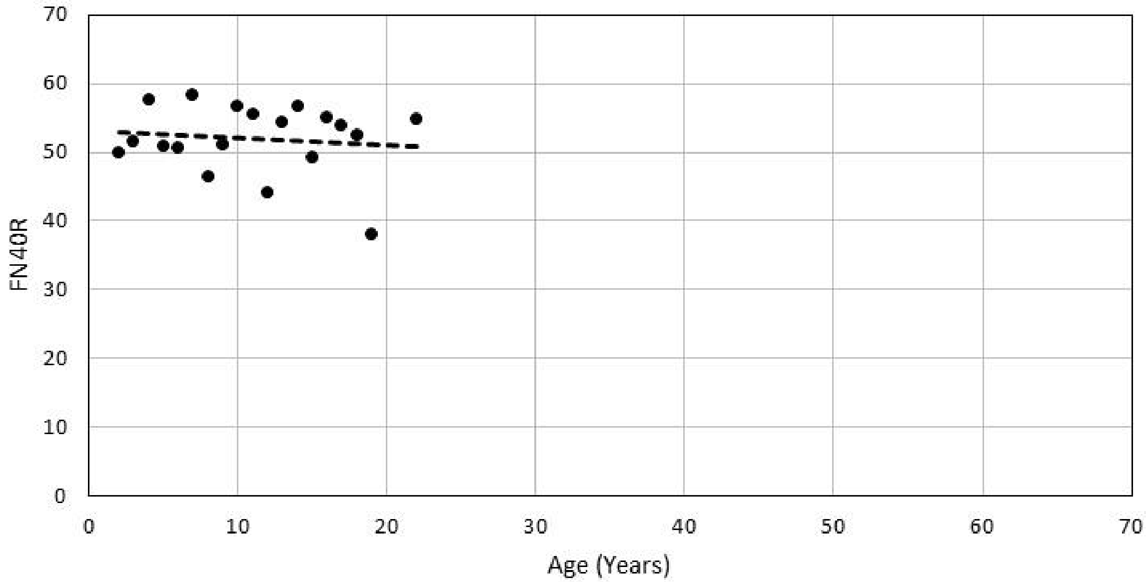


Figure 47. Graph. Friction versus age for undivided, event segments, low traffic (AADT < 15,000).

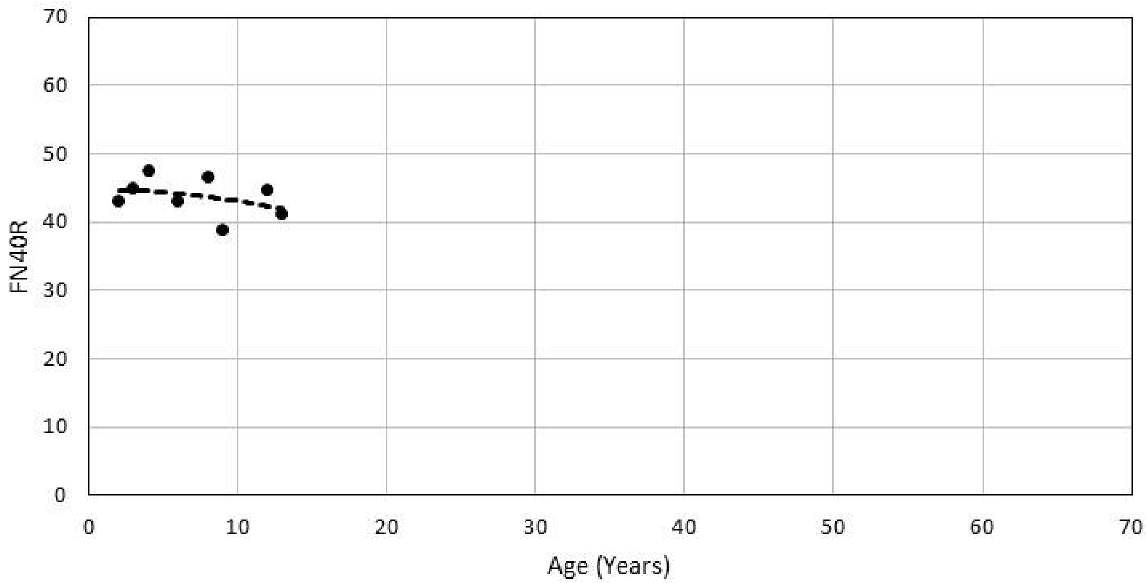


Figure 48. Graph. Friction versus age for undivided, event segment, high traffic (AADT > 15,000).

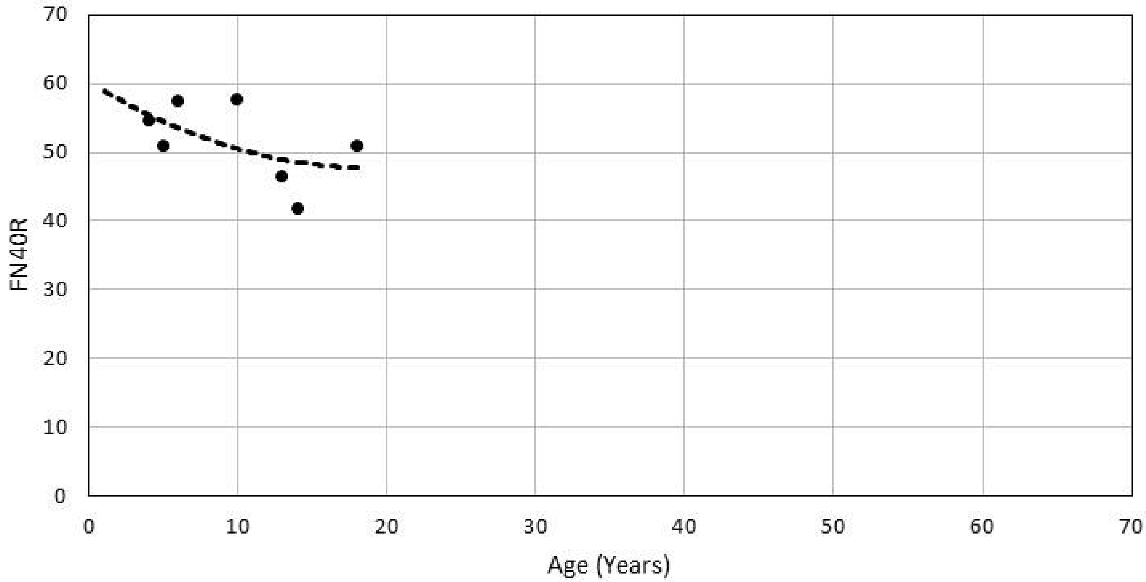


Figure 49. Graph. Friction versus age for divided, non-event segments, low traffic (AADT < 15,000) and DGAC/chip seal pavement.

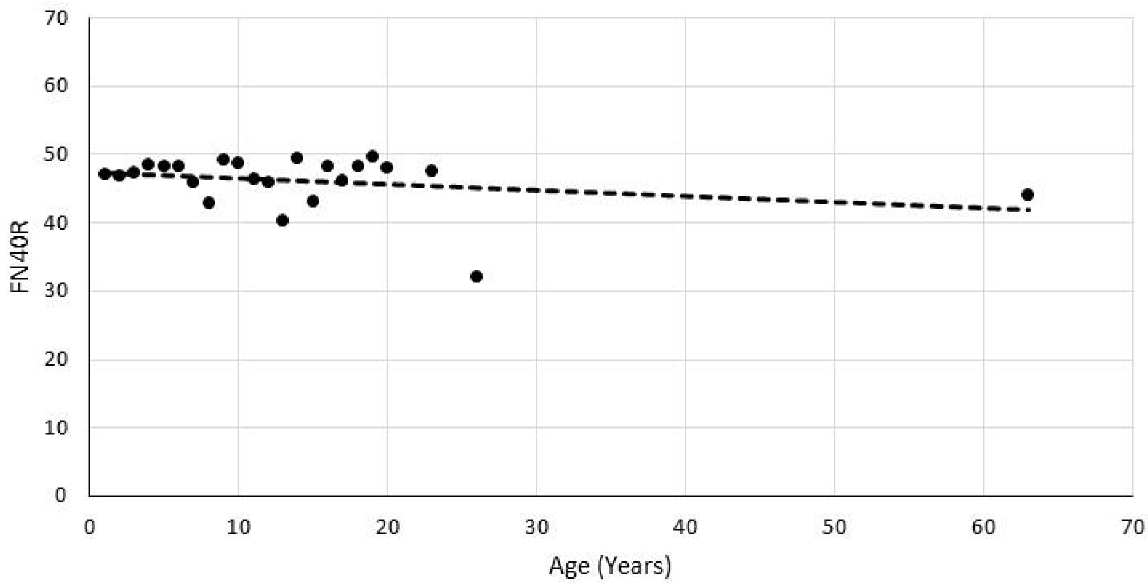


Figure 50. Graph. Friction versus age for divided, non-event segments, high traffic (AADT > 15,000) and DGAC/chip seal pavement.

Note: PCC is Portland Cement Concrete.

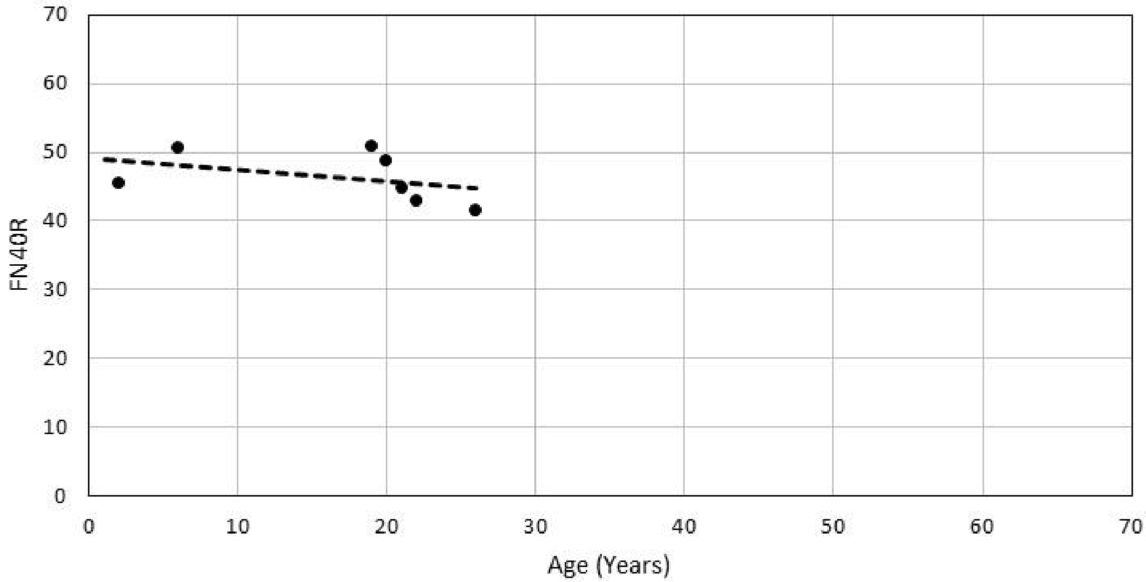


Figure 51. Graph. Friction versus age for divided, non-event segments, low traffic (AADT < 15,000) and PCC pavement.

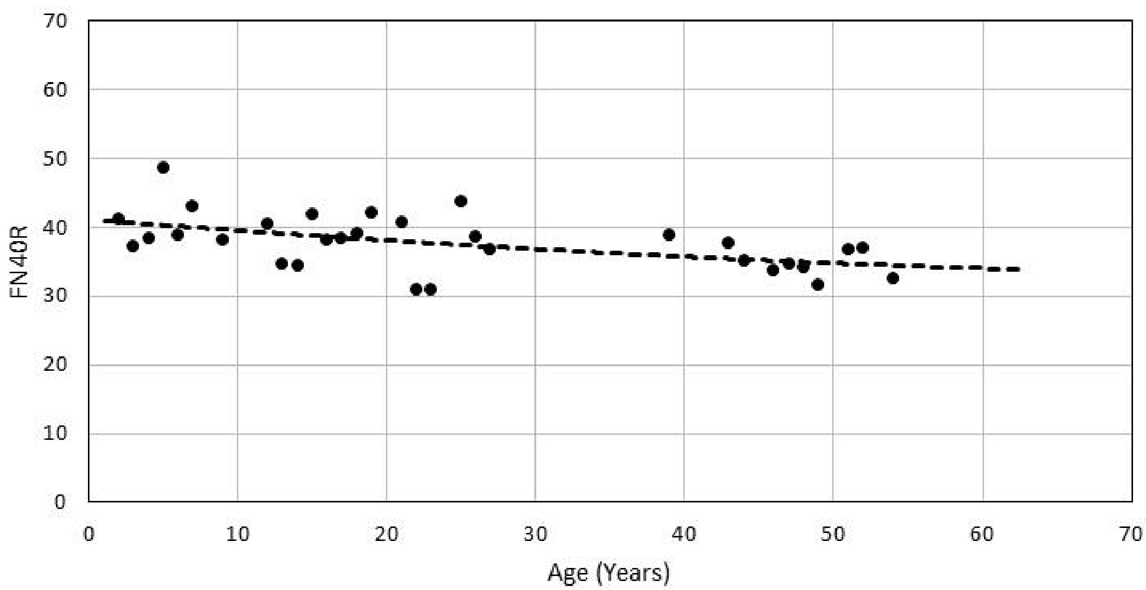


Figure 52. Graph. Friction versus age for divided, non-event segments, high traffic (AADT > 15,000) and PCC pavement.

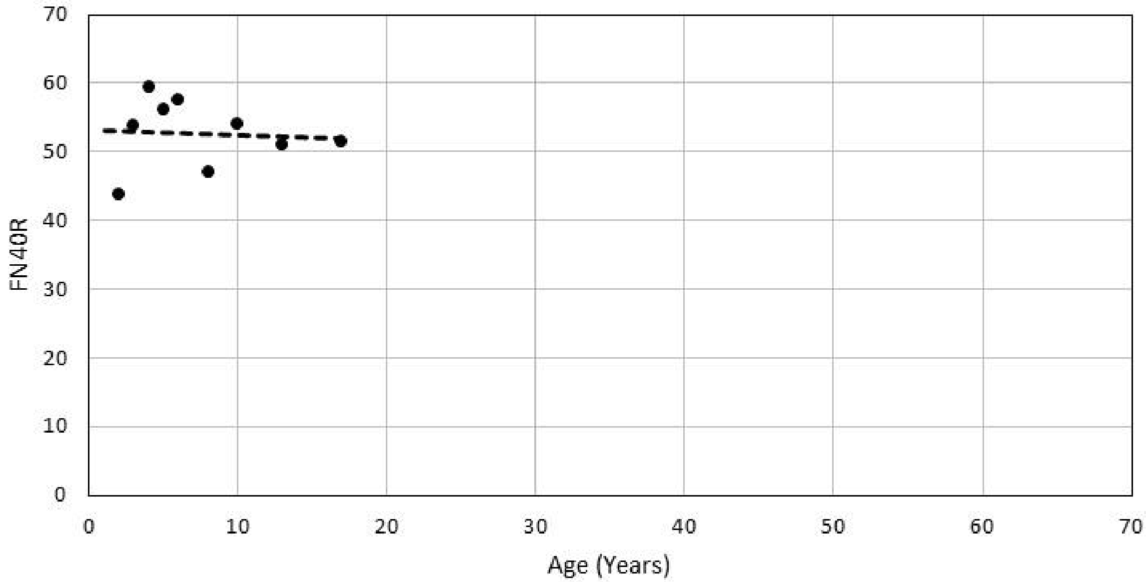


Figure 53. Graph. Friction versus age for divided, event segments, low traffic (AADT < 15,000) and DGAC/chip seal pavement.

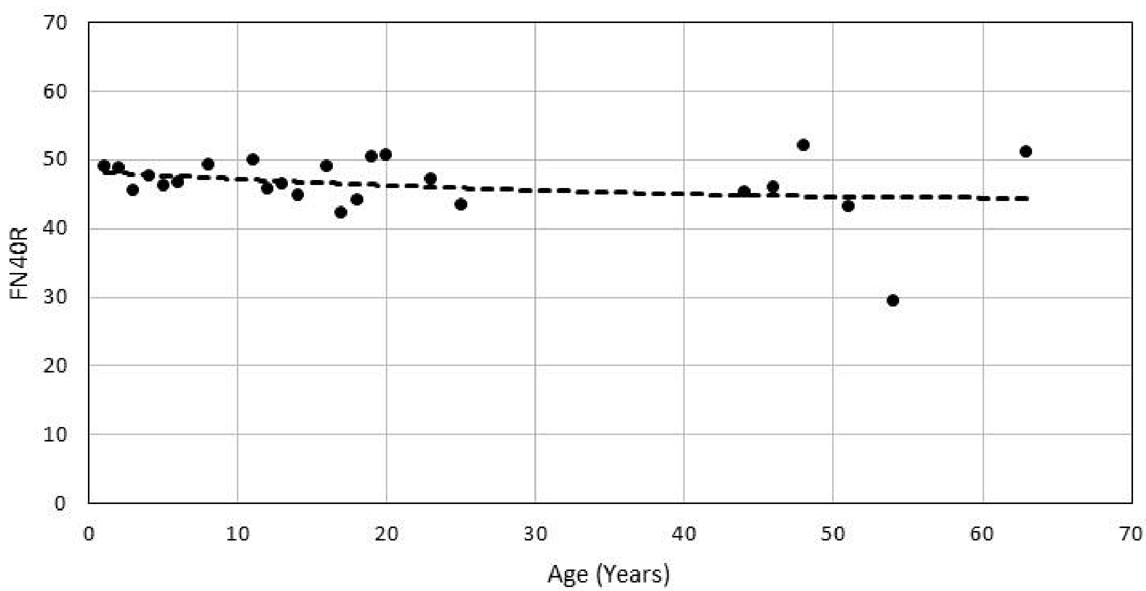


Figure 54. Graph. Friction versus age for divided, event segments, high traffic (AADT > 15,000) and DGAC/chip seal pavement.

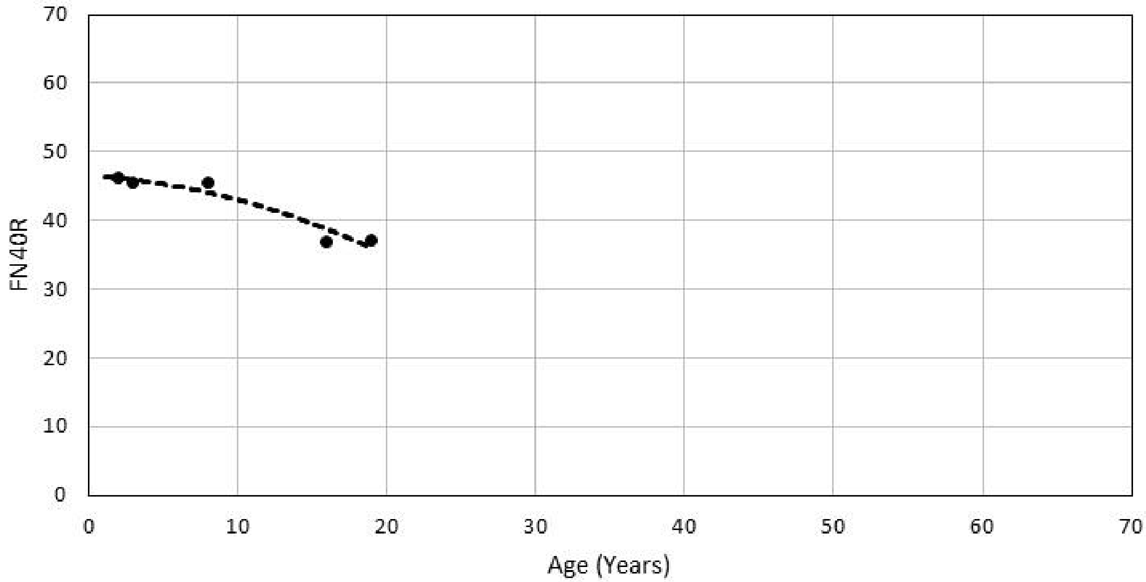


Figure 55. Graph. Friction versus age for divided, event segments, low traffic (AADT < 15,000) and PCC pavement.

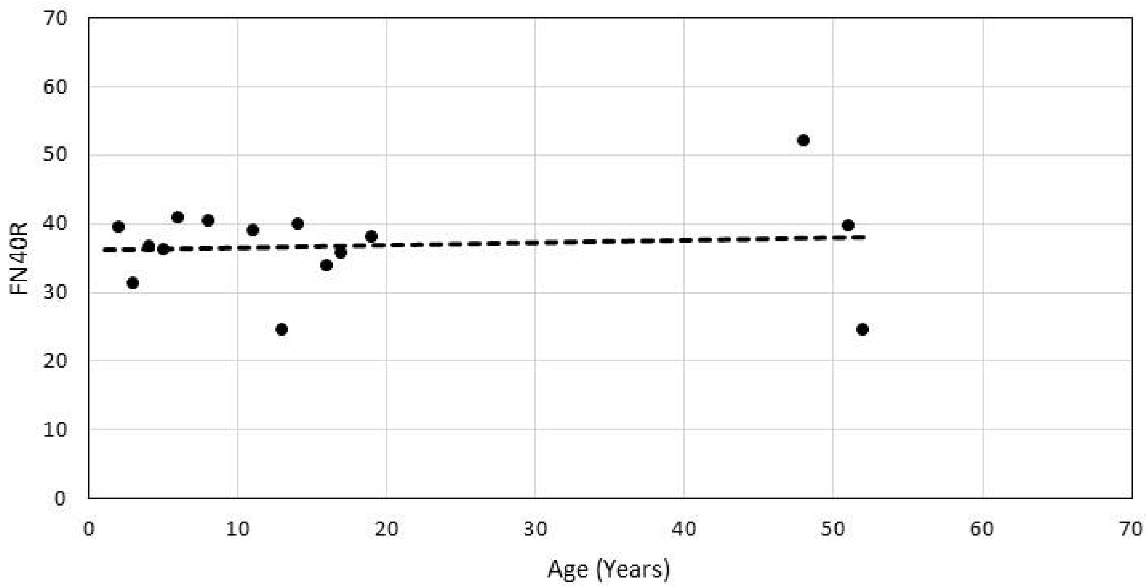


Figure 56. Graph. Friction versus age for divided, event segments, high traffic (AADT > 15,000) and PCC pavement.

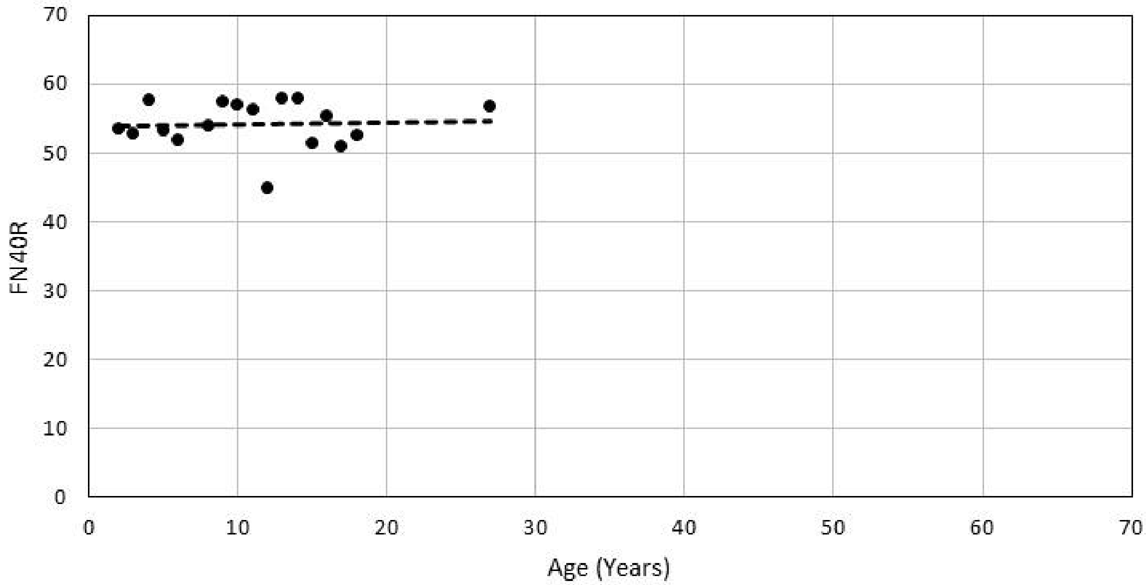


Figure 57. Graph. Friction versus age for undivided, non-event segments, low traffic (AADT < 15,000) and DGAC/chip seal pavement.

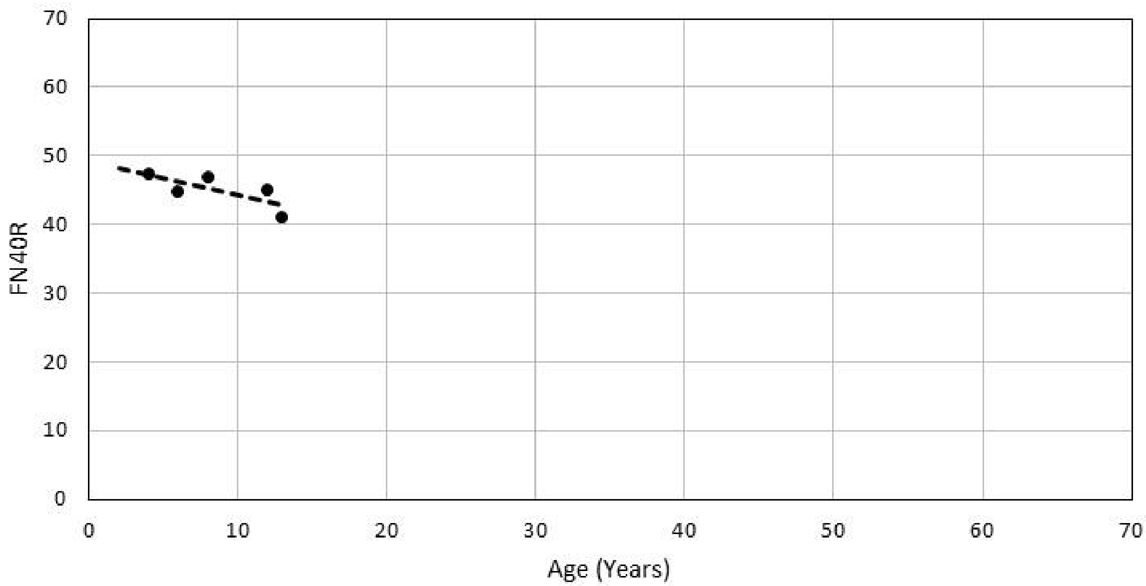


Figure 58. Graph. Friction versus age for undivided, non-event segments, high traffic (AADT > 15,000) and DGAC/chip seal pavement.

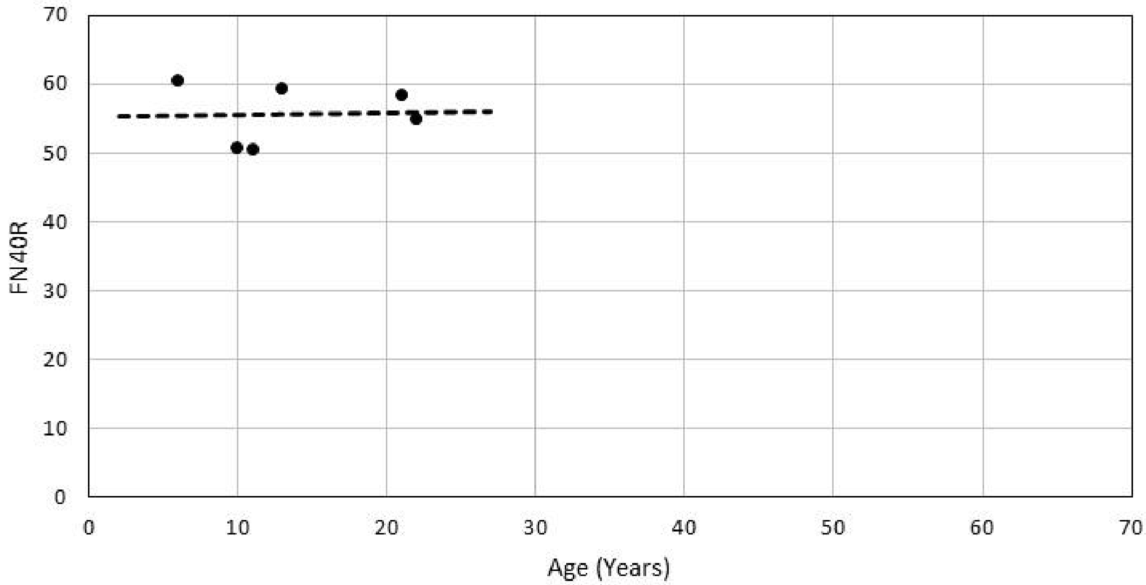


Figure 59. Graph. Friction versus age for undivided, non-event segments, low traffic (AADT < 15,000) and PCC pavement.

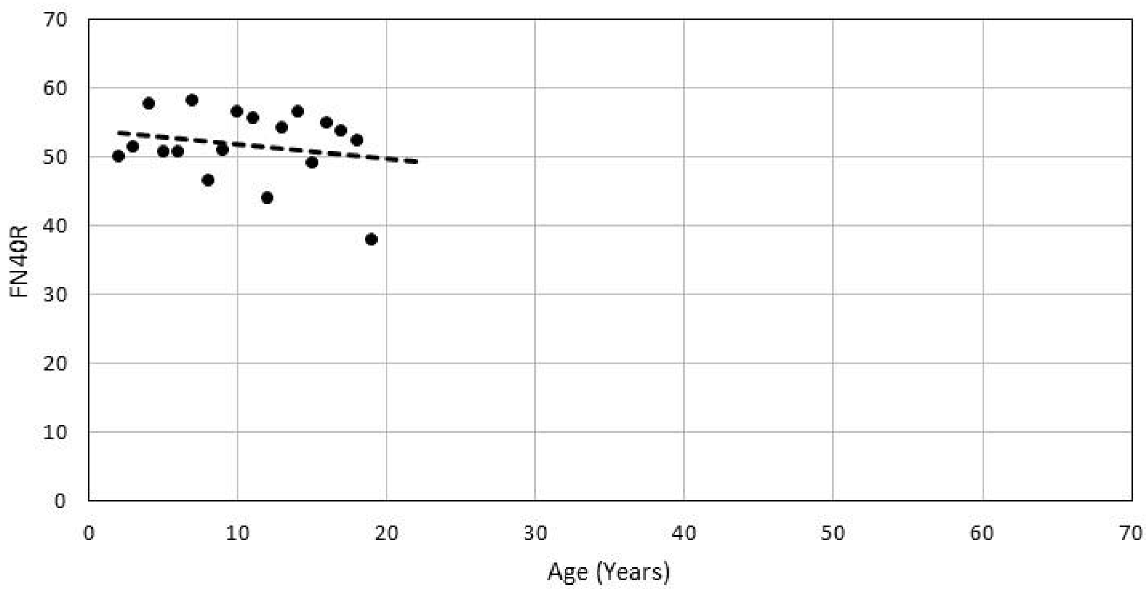


Figure 60. Graph. Friction versus age for undivided, event segments, low traffic (AADT < 15,000) and DGAC/chip seal pavement.

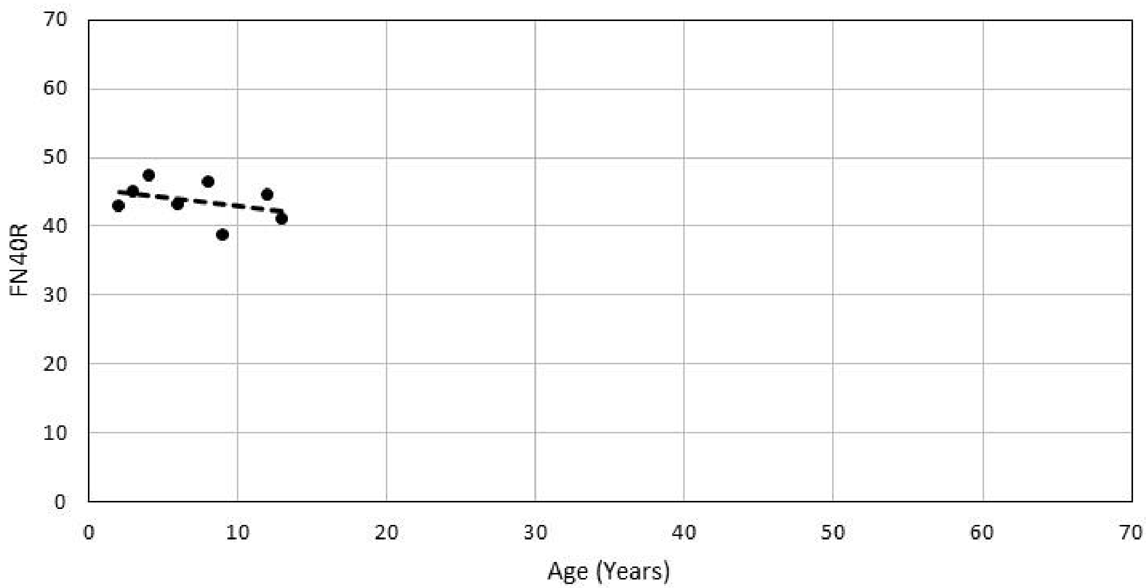


Figure 61. Graph. Friction versus age for undivided, event segments, low traffic (AADT < 15,000) and DGAC/chip seal pavement.

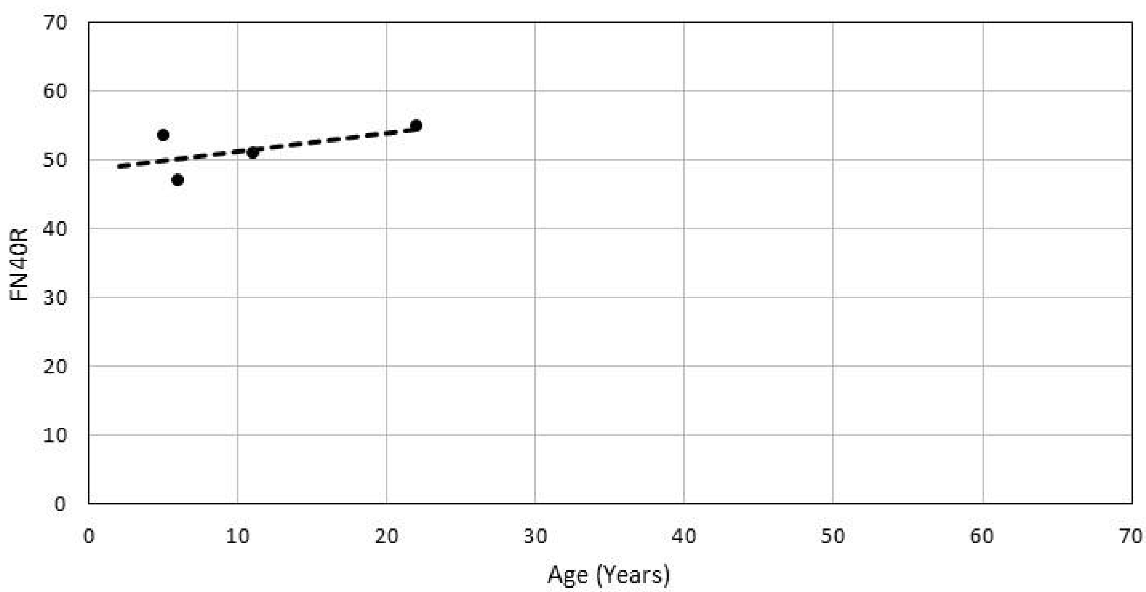
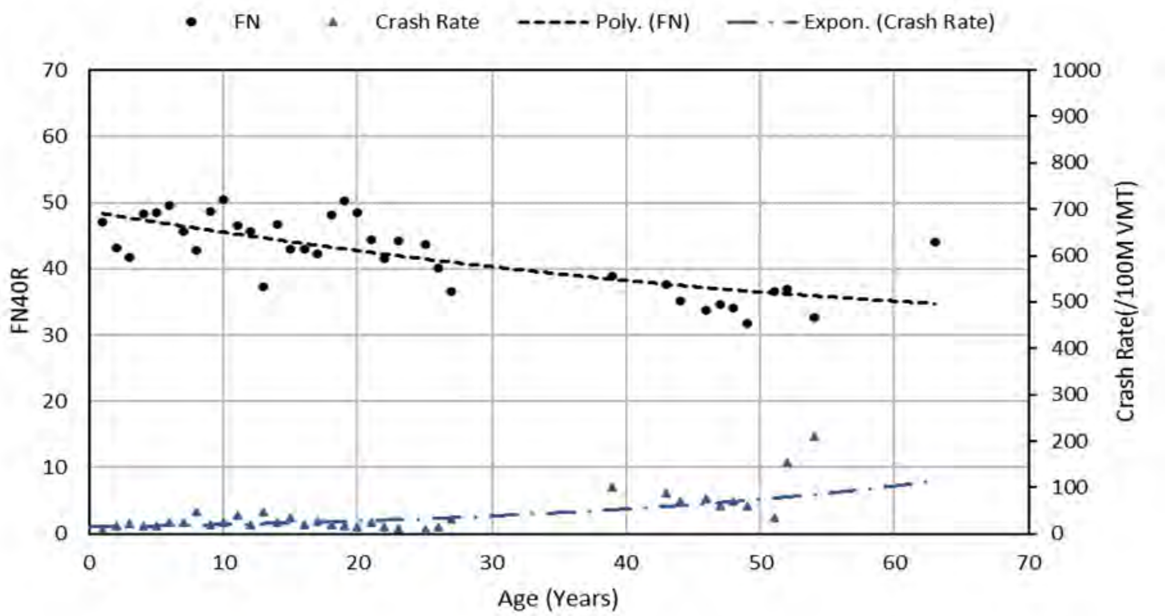


Figure 62. Graph. Friction versus age for undivided, event segments, low traffic (AADT < 15,000) and PCC pavement.

GPF METHOD 2



Note: Crash Rate = crash count/100 million vehicles miles traveled (MVMT).

Figure 63. Graph. Friction and overall crash rate versus age for divided, non-event segments, all traffic levels and DGAC/chip seal and PCC pavements.

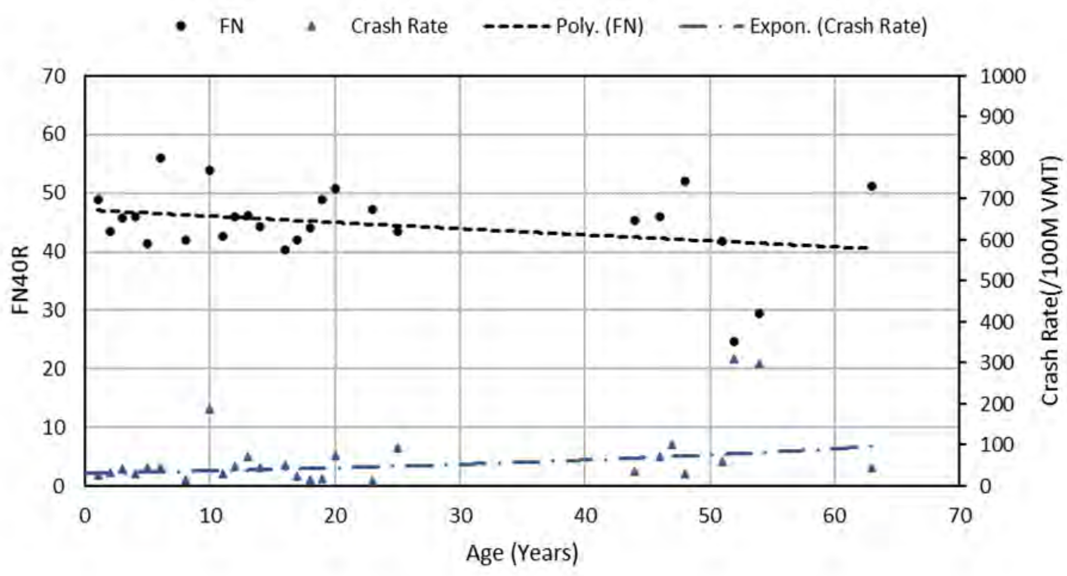


Figure 64. Graph. Friction and overall crash rate versus age for divided, event segments, all traffic levels and DGAC/chip seal and PCC pavements.

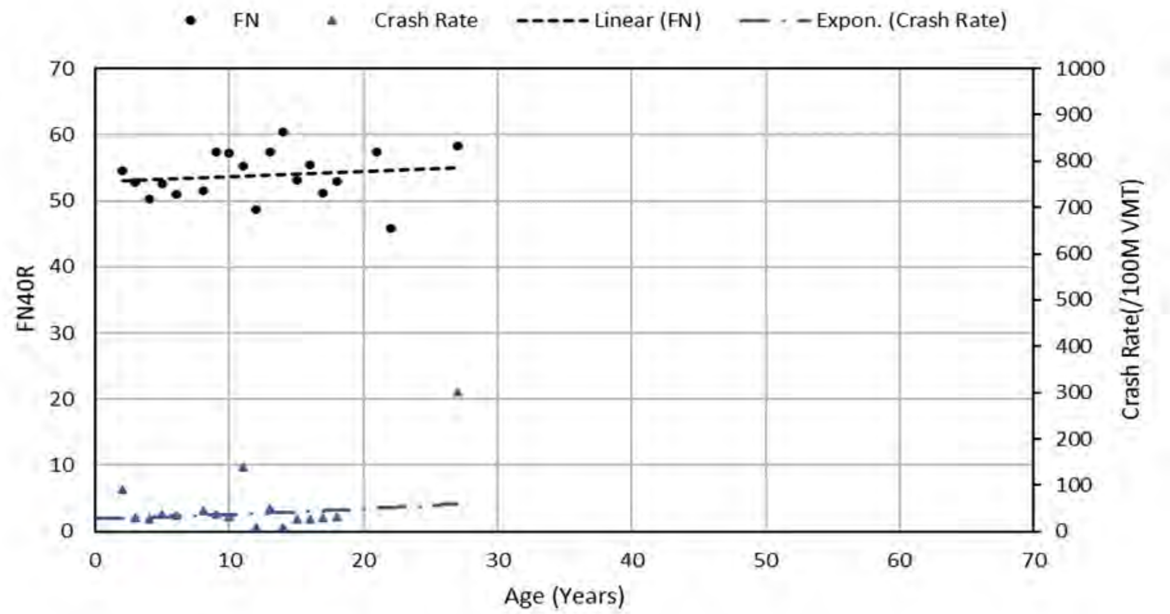


Figure 65. Graph. Friction and overall crash rate versus age for undivided, non-event segments, all traffic levels and DGAC/chip seal and PCC pavements.

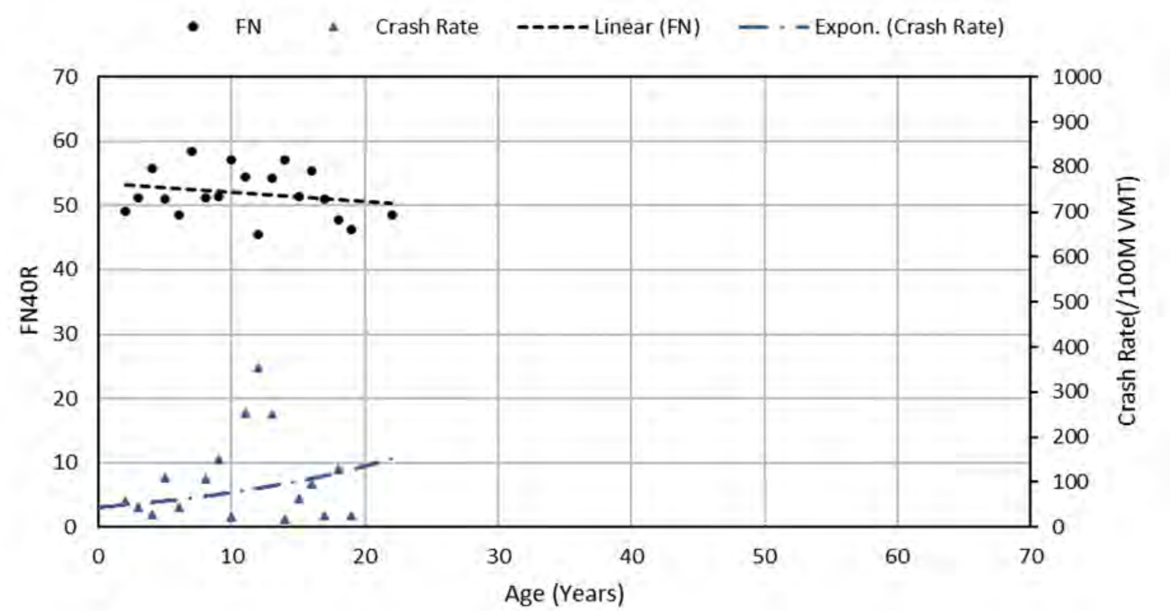


Figure 66. Graph. Friction and overall crash rate versus age for undivided, event segments, all traffic levels and DGAC/chip seal and PCC pavements.

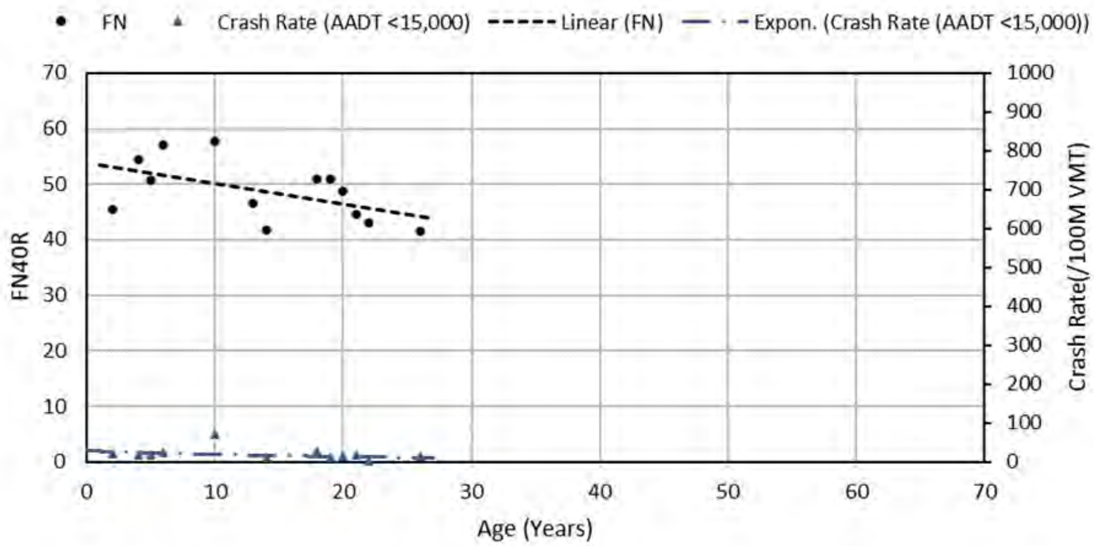


Figure 67. Graph. Friction and overall crash rate versus age for divided, non-event segments, low traffic (AADT < 15,000) and DGAC/chip seal and PCC pavements.

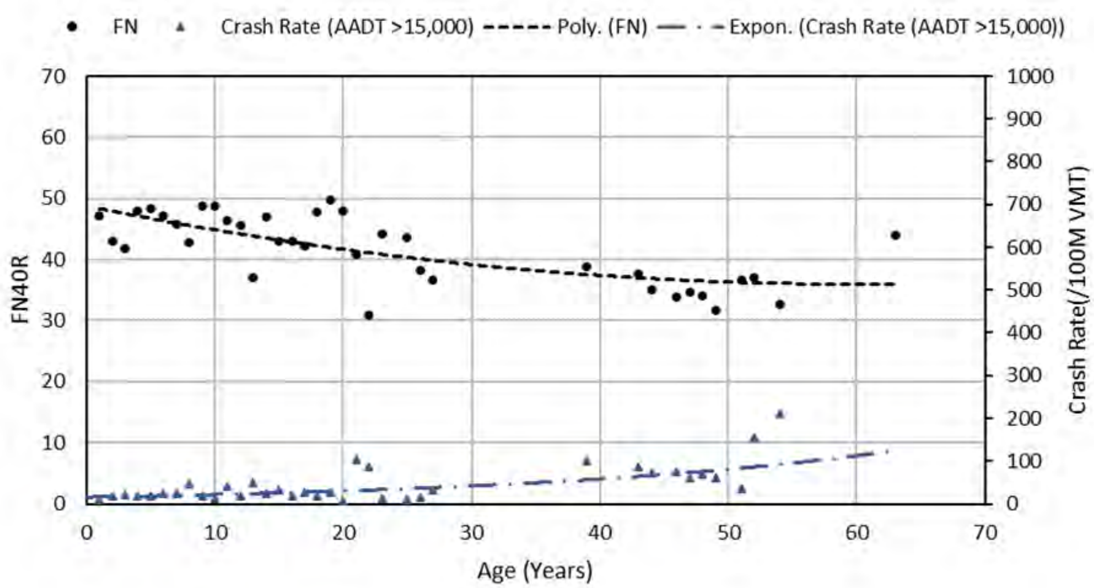


Figure 68. Graph. Friction and overall crash rate versus age for divided, non-event segments, high traffic (AADT > 15,000) and DGAC/chip seal and PCC pavements.

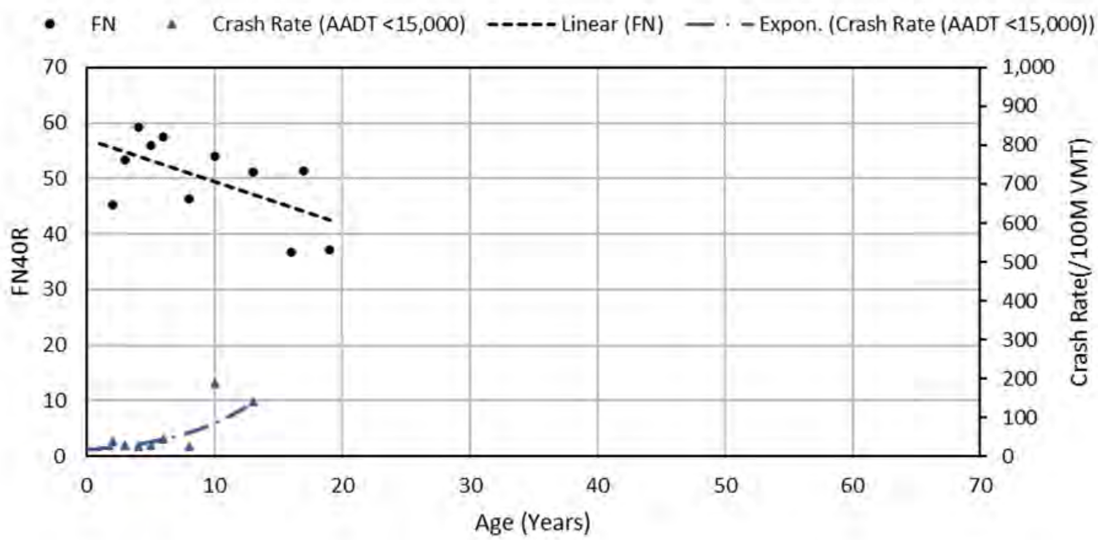


Figure 69. Graph. Friction and overall crash rate versus age for divided, event segments, low traffic (AADT < 15,000) and DGAC/chip seal and PCC pavements.

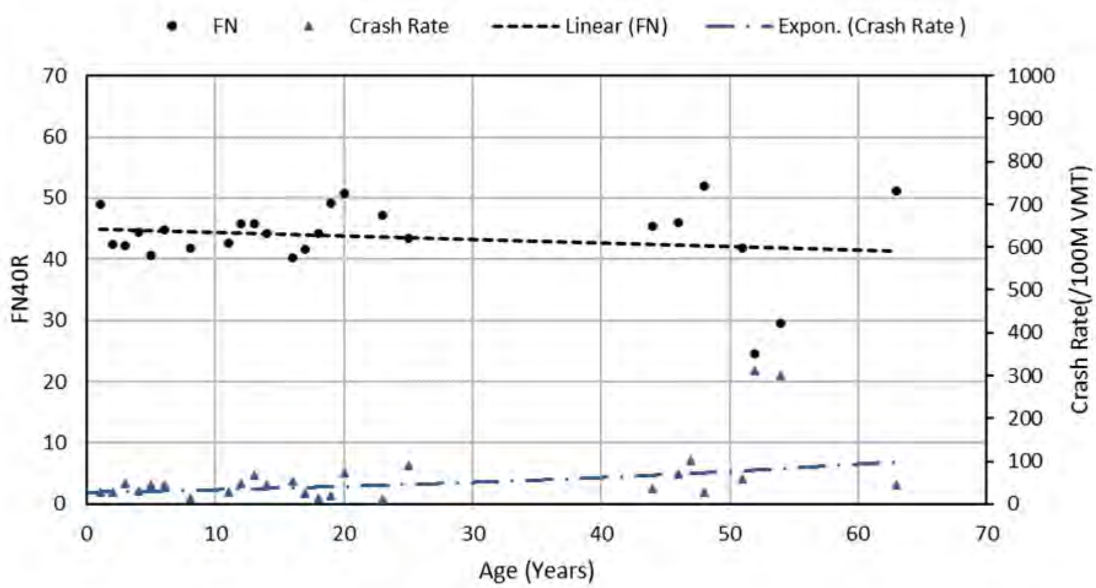


Figure 70. Graph. Friction and overall crash rate versus age for divided, event segments, high traffic (AADT > 15,000) and DGAC/chip seal and PCC pavements.

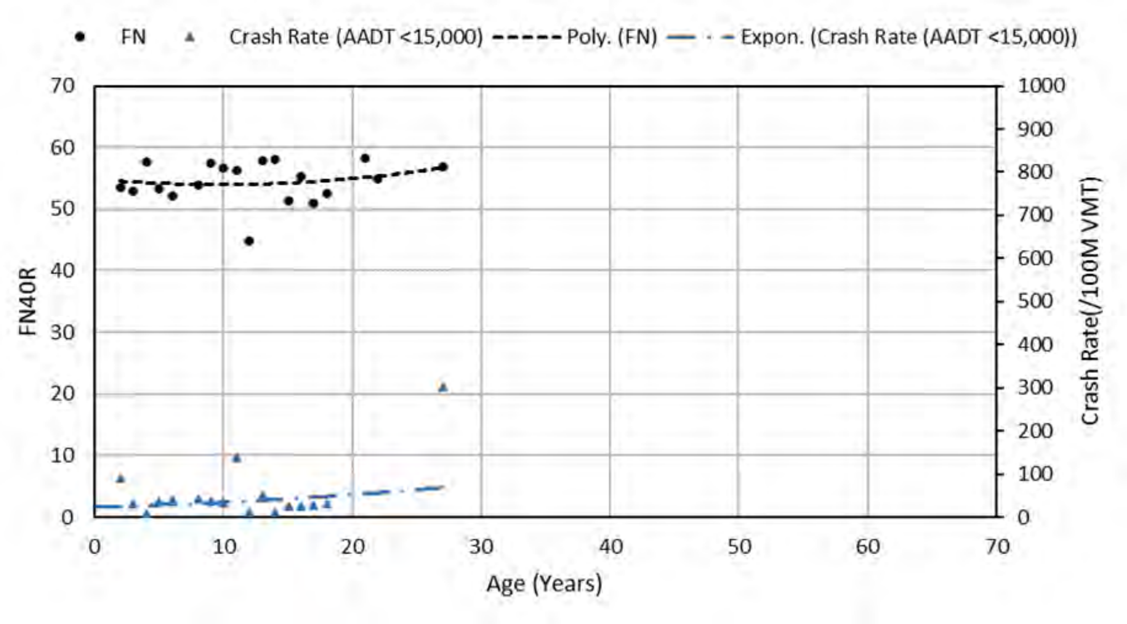


Figure 71. Graph. Friction and overall crash rate versus age for undivided, non-event segments, low traffic (AADT < 15,000) and DGAC/chip seal and PCC pavements.

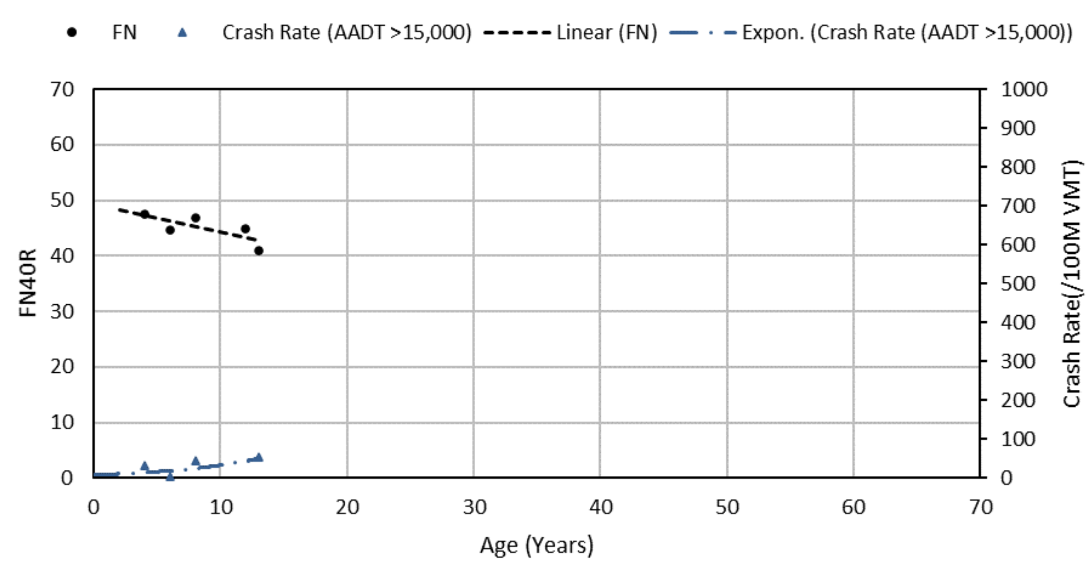


Figure 72. Graph. Friction and overall crash rate versus age for undivided, non-event segments, high traffic (AADT > 15,000) and DGAC/chip seal and PCC pavements.

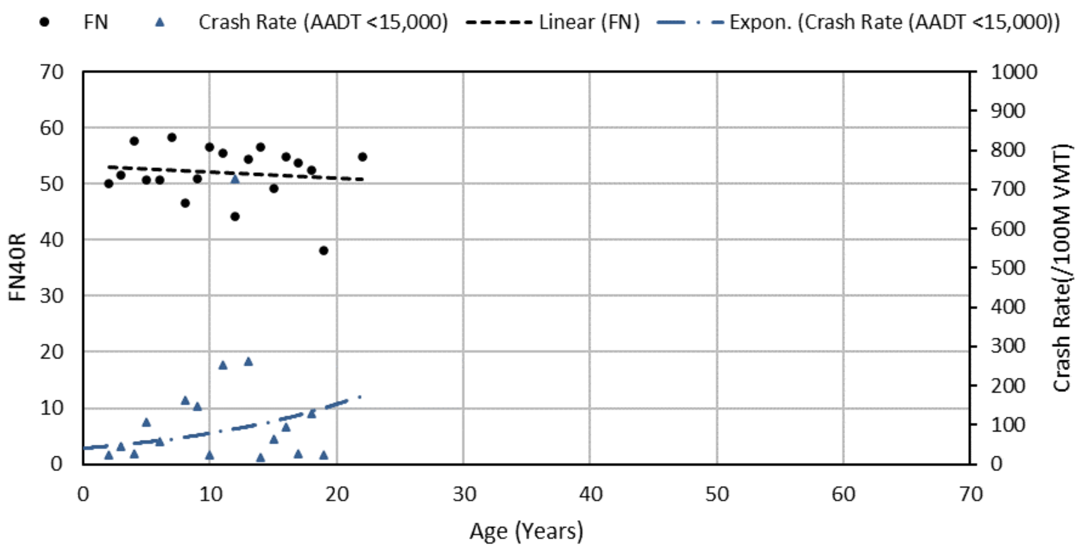


Figure 73. Graph. Friction and overall crash rate versus age for undivided, event segments, low traffic (AADT < 15,000) and DGAC/chip seal and PCC pavements.

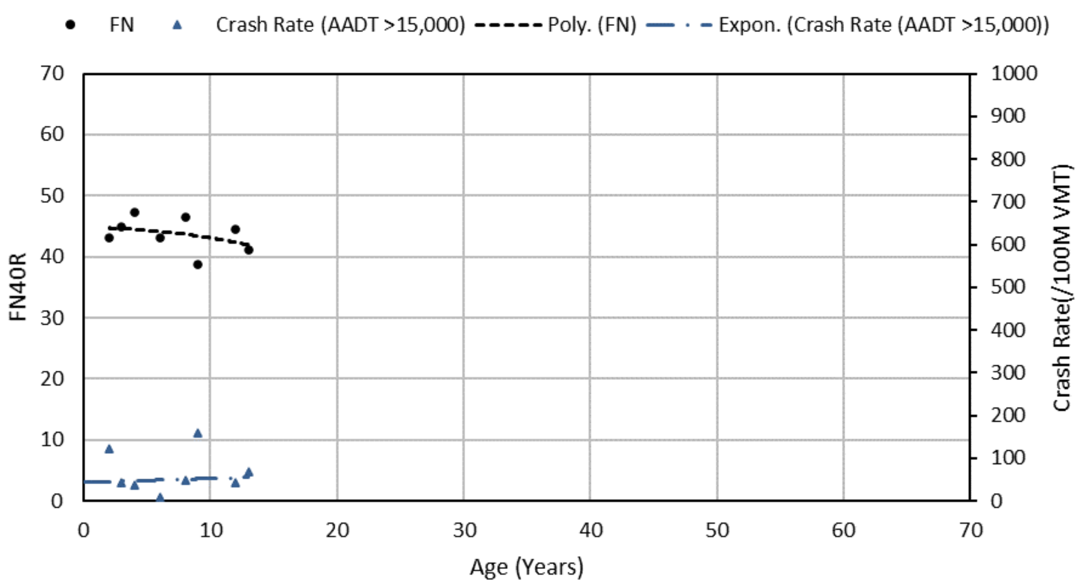


Figure 74. Graph. Friction and overall crash rate versus age for undivided, event segments, high traffic (AADT > 15,000) and DGAC/chip seal and PCC pavements.

GPF METHOD 3

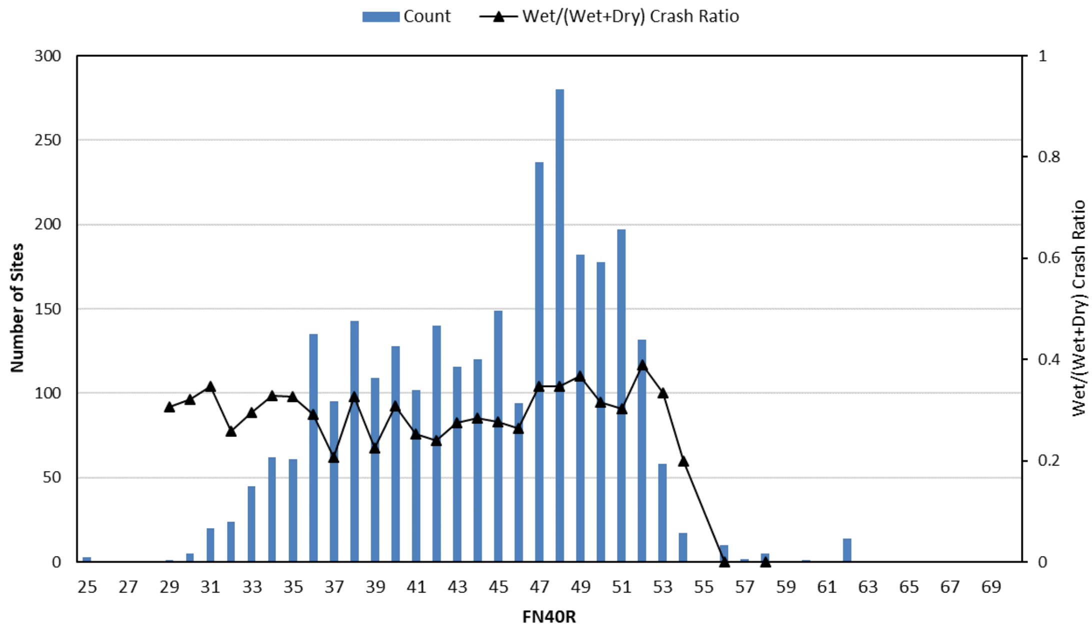


Figure 75. Graph. Friction number distribution and wet/(wet+dry) crash ratio for divided, non-event segments, all traffic levels and DGAC/chip seal and PCC pavements.

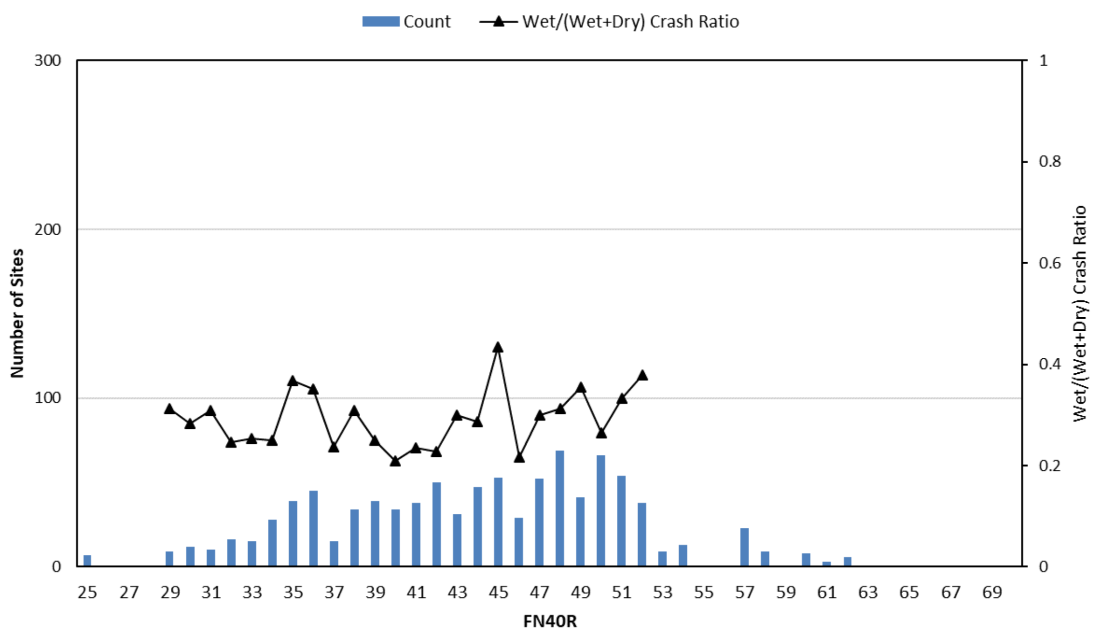


Figure 76. Graph. Friction number distribution and wet/(wet+dry) crash ratio for divided, event segments, all traffic levels and DGAC/chip seal and PCC pavements.

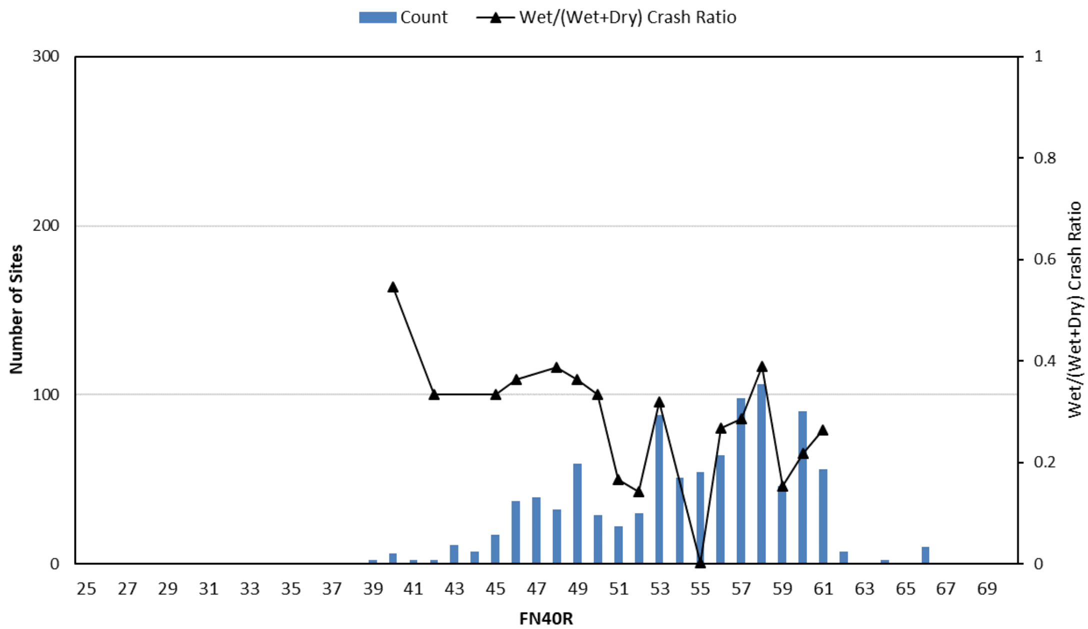


Figure 77. Graph. Friction number distribution and wet/(wet+dry) crash ratio for undivided, non-event segments, all traffic levels and DGAC/chip seal and PCC pavements.

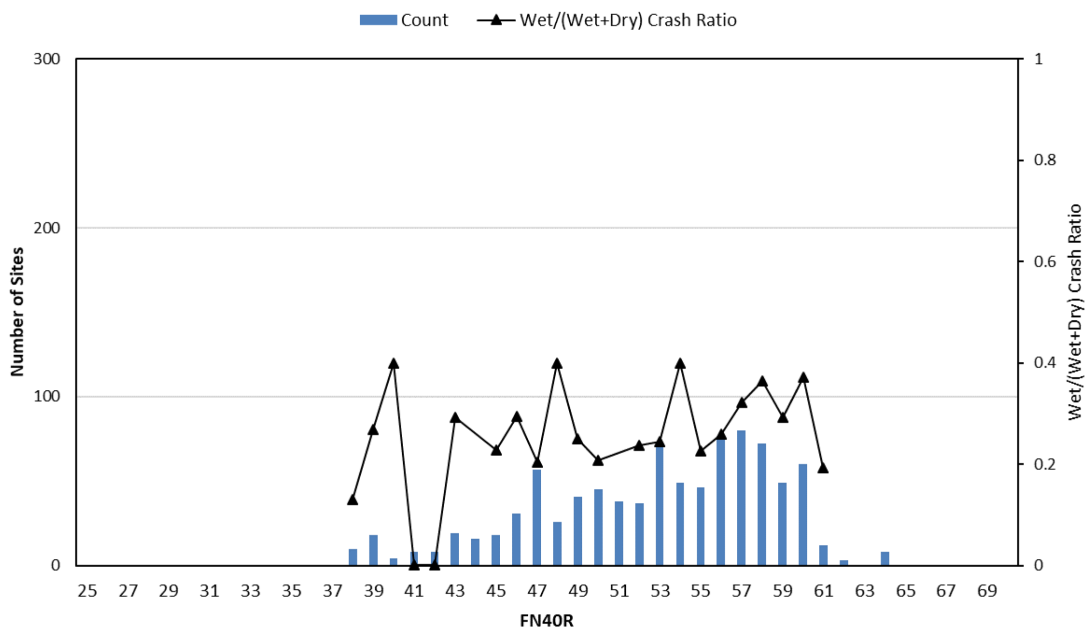


Figure 78. Graph. Friction number distribution and wet/(wet+dry) crash ratio for undivided, event segments, all traffic levels and DGAC/chip seal and PCC pavements.

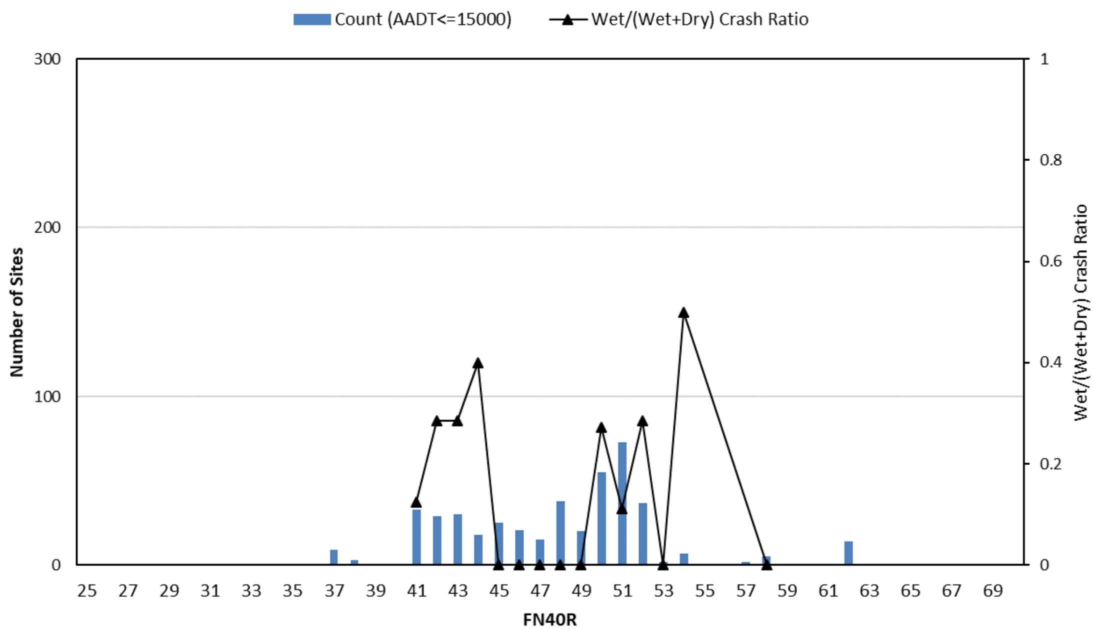


Figure 79. Graph. Friction number distribution and wet/(wet+dry) crash ratio for divided, non-event segments, low traffic (AADT < 15,000) and DGAC/chip seal and PCC pavements.

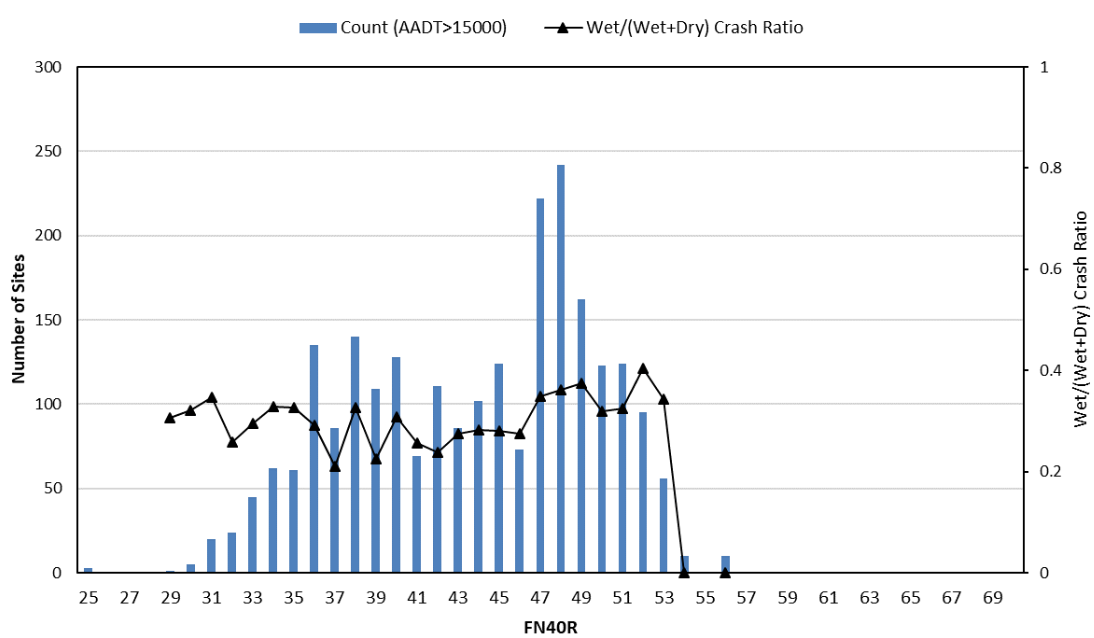


Figure 80. Graph. Friction number distribution and wet/(wet+dry) crash ratio for divided, non-event segments, high traffic (AADT > 15,000) and DGAC/chip seal and PCC pavements.

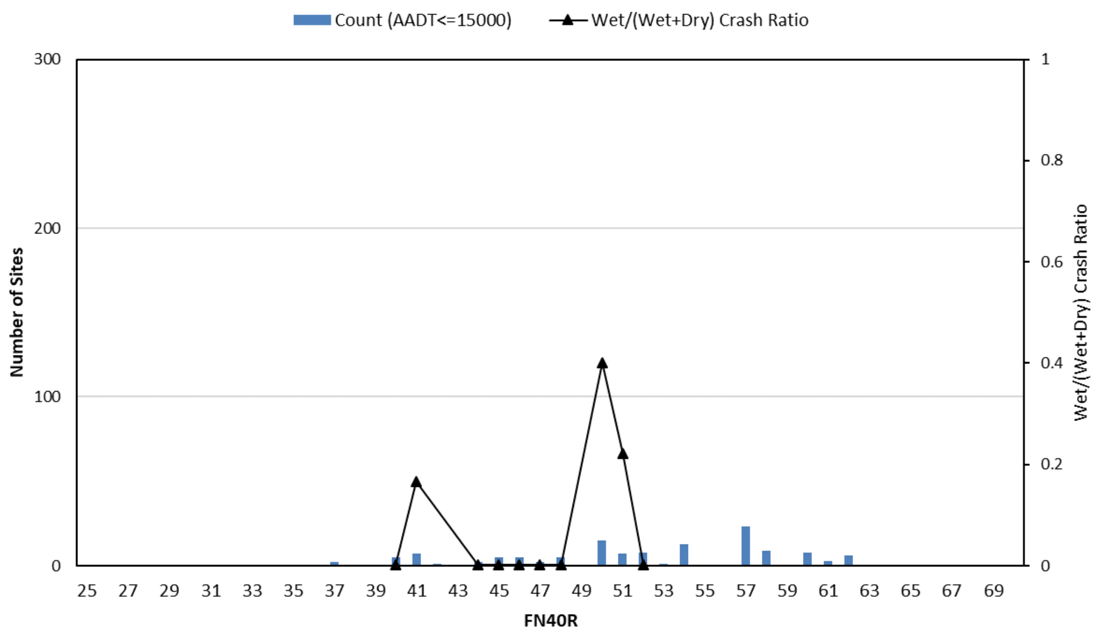


Figure 81. Graph. Friction number distribution and wet/(wet+dry) crash ratio for divided, event segments, low traffic (AADT < 15,000) and DGAC/chip seal and PCC pavements.

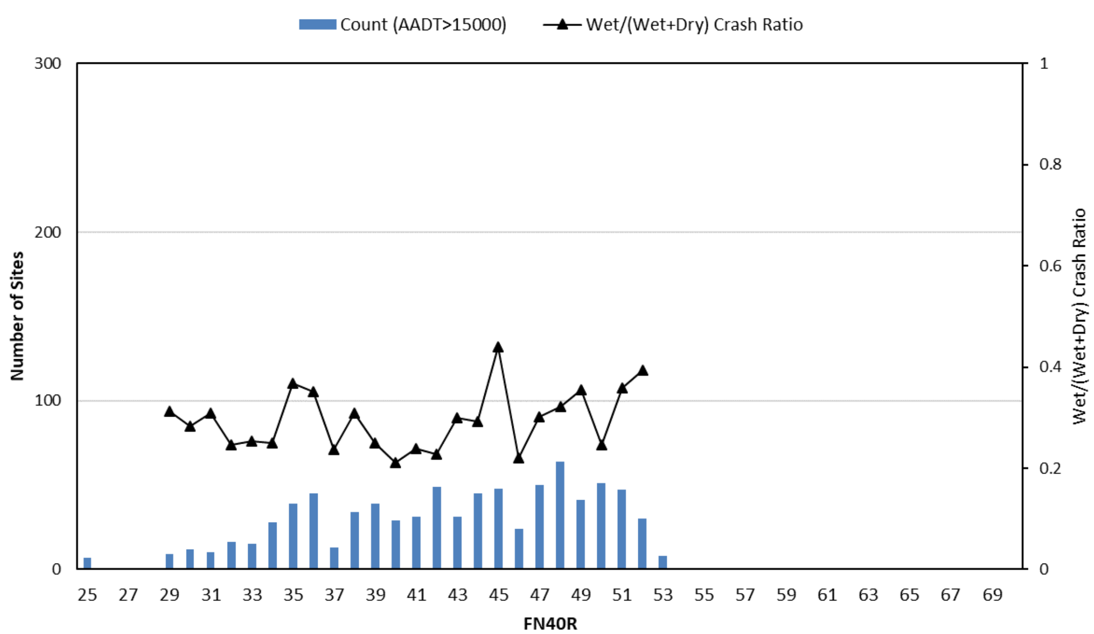


Figure 82. Graph. Friction number distribution and wet/(wet+dry) crash ratio for divided, event segments, high traffic (AADT > 15,000) and DGAC/chip seal and PCC pavements.

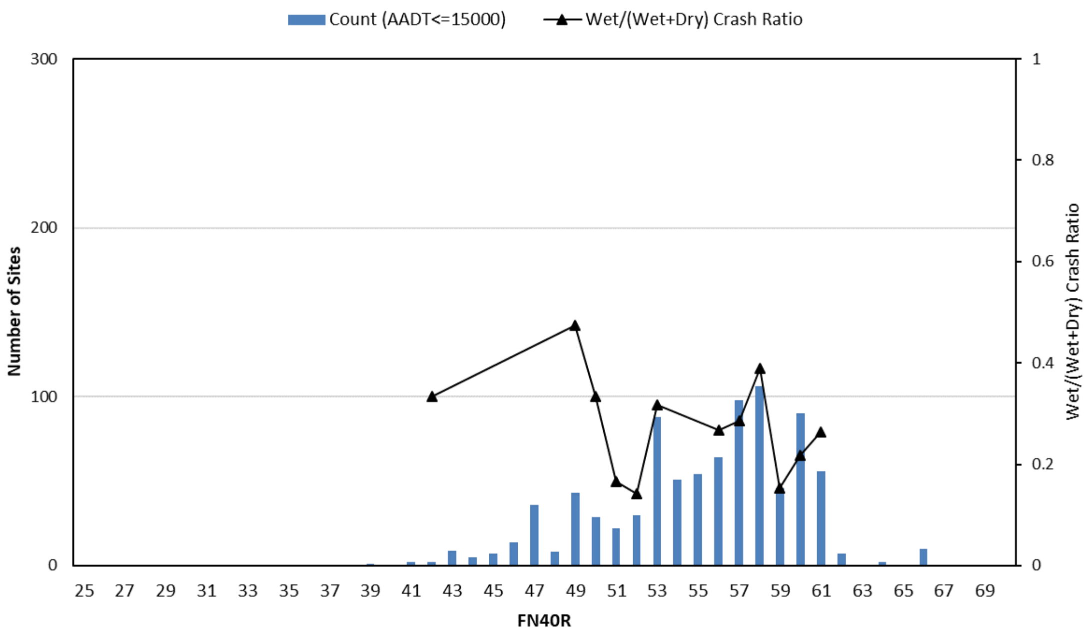


Figure 83. Graph. Friction number distribution and wet/(wet+dry) crash ratio for undivided, non-event segments, low traffic (AADT < 15,000) and DGAC/chip seal and PCC pavements.

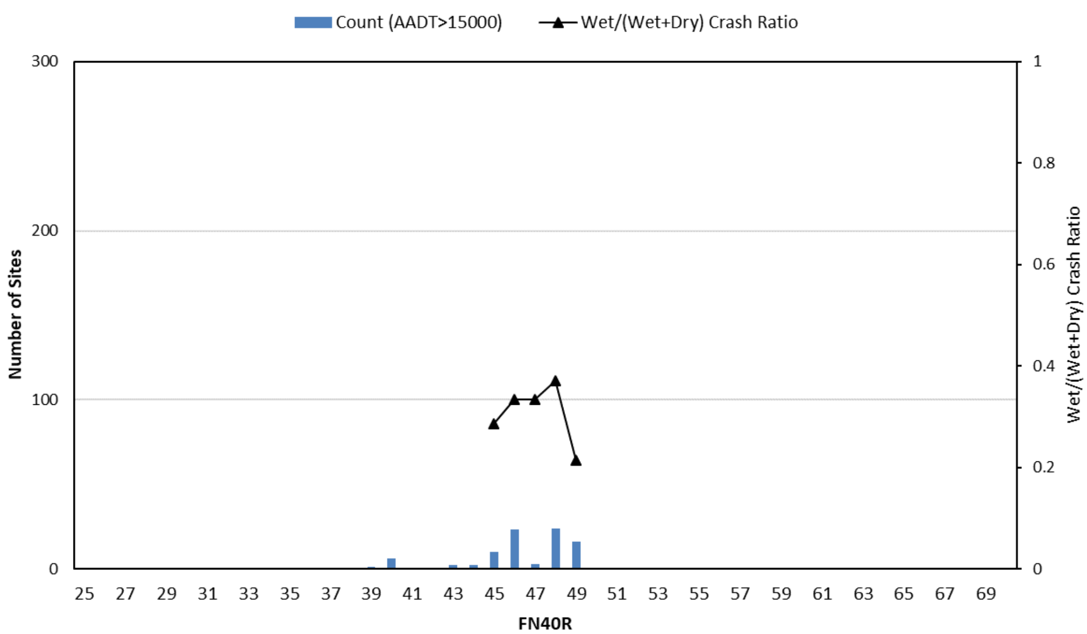


Figure 84. Graph. Friction number distribution and wet/(wet+dry) crash ratio for undivided, non-event segments, high traffic (AADT > 15,000) and DGAC/chip seal and PCC pavements.

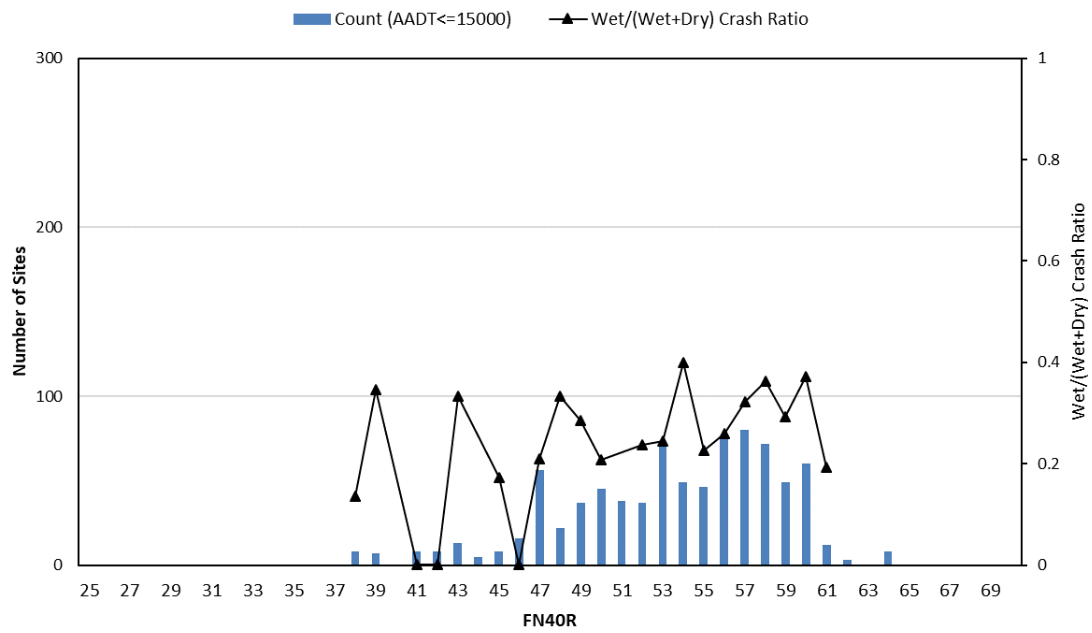


Figure 85. Graph. Friction number distribution and wet/(wet+dry) crash ratio for undivided, event segments, low traffic (AADT < 15,000) and DGAC/chip seal and PCC pavements.

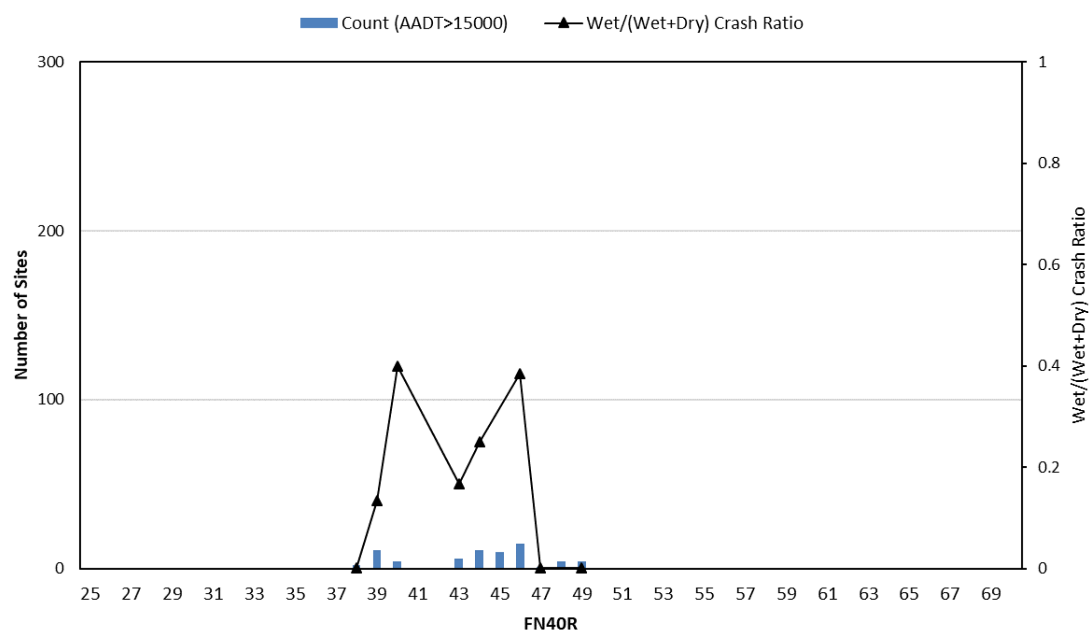


Figure 86. Graph. Friction number distribution and wet/(wet+dry) crash ratio for undivided, event segments, high traffic (AADT > 15,000) and DGAC/chip seal and PCC pavements.

APPENDIX B. EVALUATION OF THE AASHTO GUIDE FOR PAVEMENT FRICTION SECTION 3.2.3, METHODS TO ESTABLISH FRICTION THRESHOLD LEVELS USING HISTORICAL LOCKED-WHEEL SKID TRAILER DATA, STATE 2

GPF METHOD 1

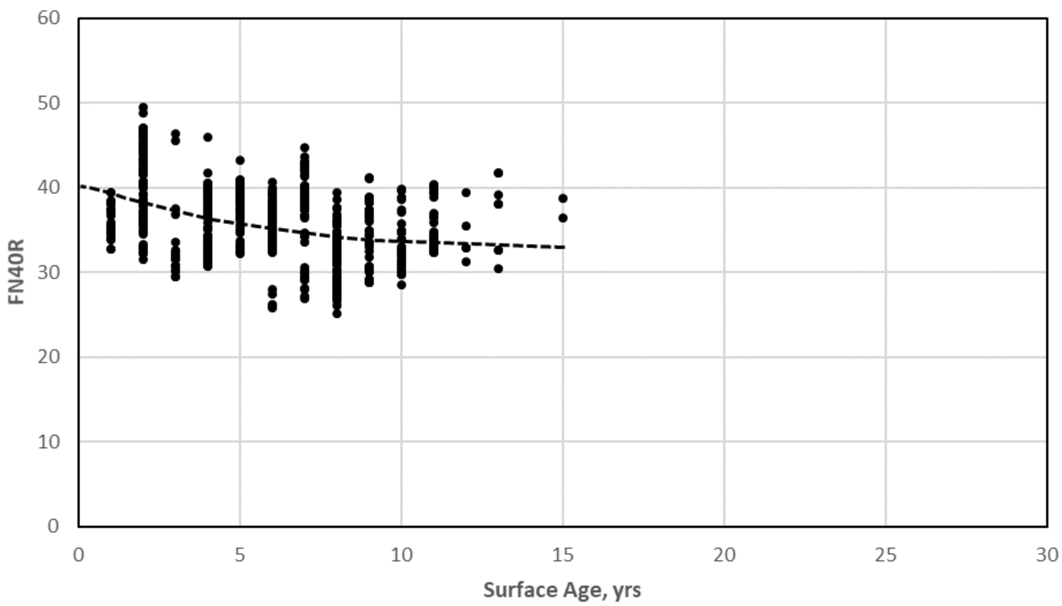


Figure 87. Graph. Friction versus age for interstate, event segments, all traffic levels and PFC surfaces.

[2] Note: PFC is Porous Friction Course; PCC is Portland Cement Concrete.

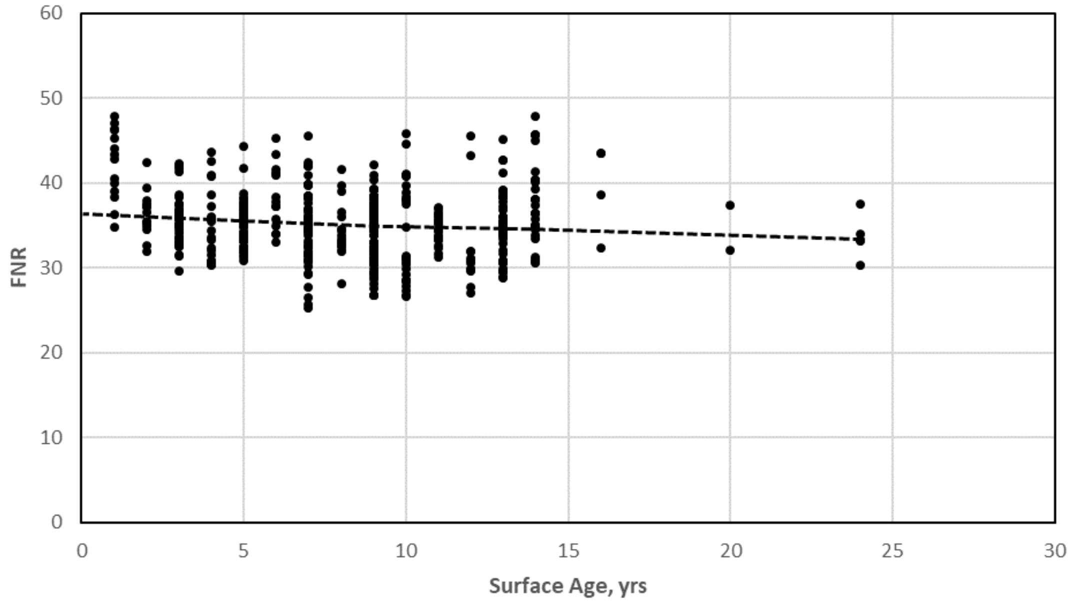


Figure 88. Graph. Friction versus age for interstate, event segments, all traffic levels and PCC surfaces.

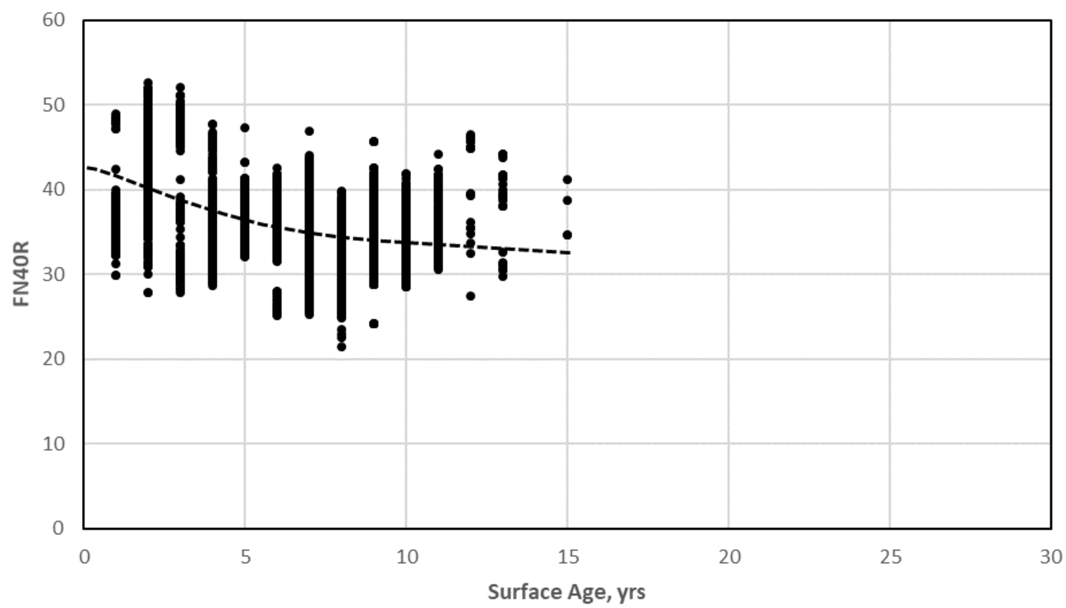


Figure 89. Graph. Friction versus age for interstate, non-event segments, all traffic levels and PFC surfaces.

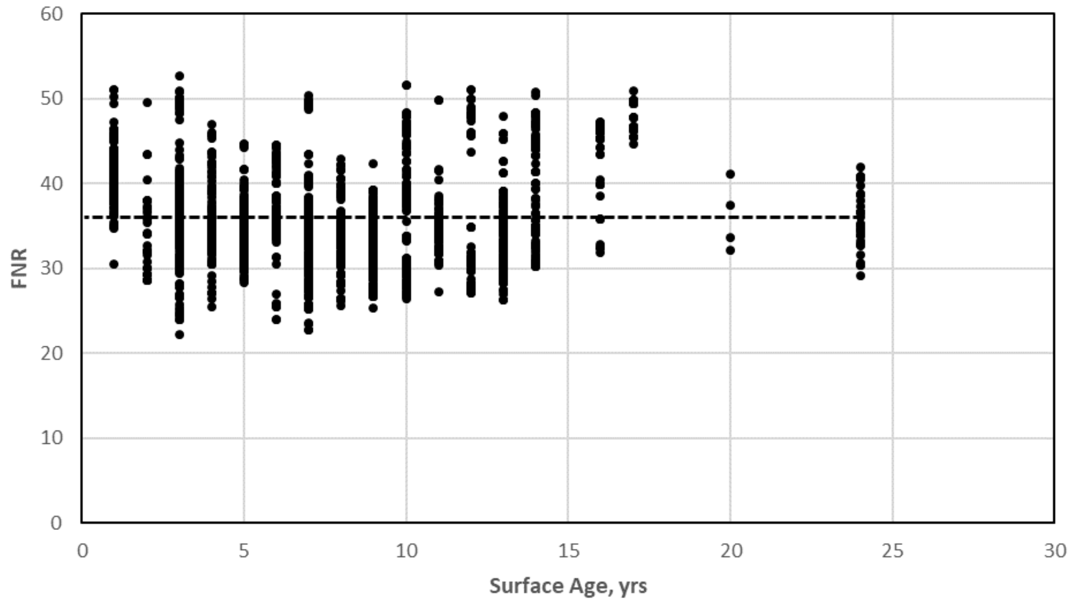


Figure 90. Graph. Friction versus age for interstate, non-event segments, all traffic levels and PCC surfaces.

Note: DGAC is Dense Graded Asphalt Concrete; AADT is Average Annual Daily Traffic.

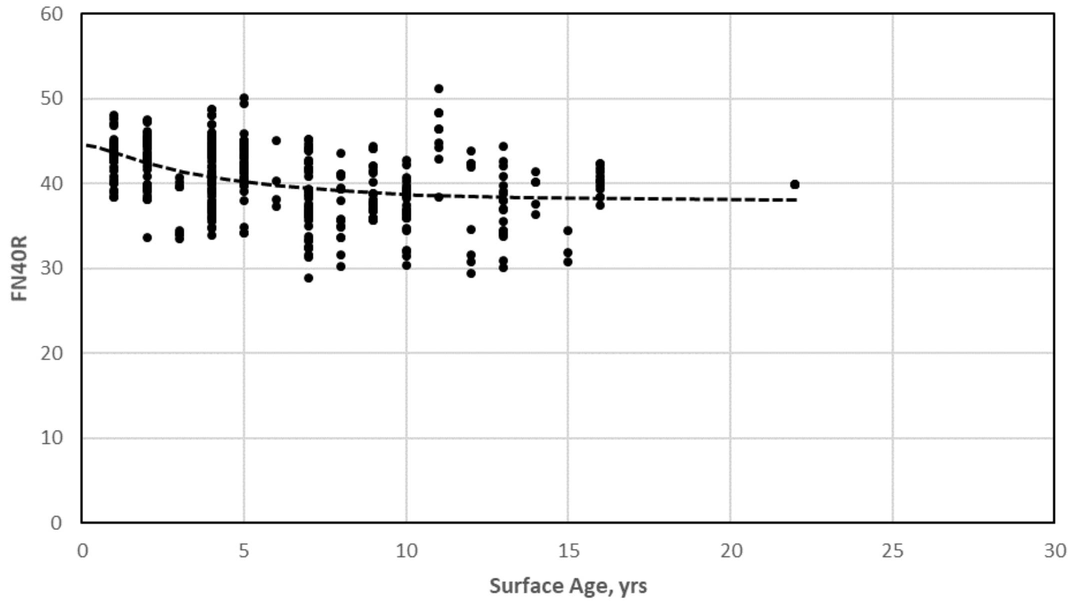


Figure 91. Graph. Friction versus age for divided primary, event segments, low traffic (AADT < 15,000) and DGAC surfaces.

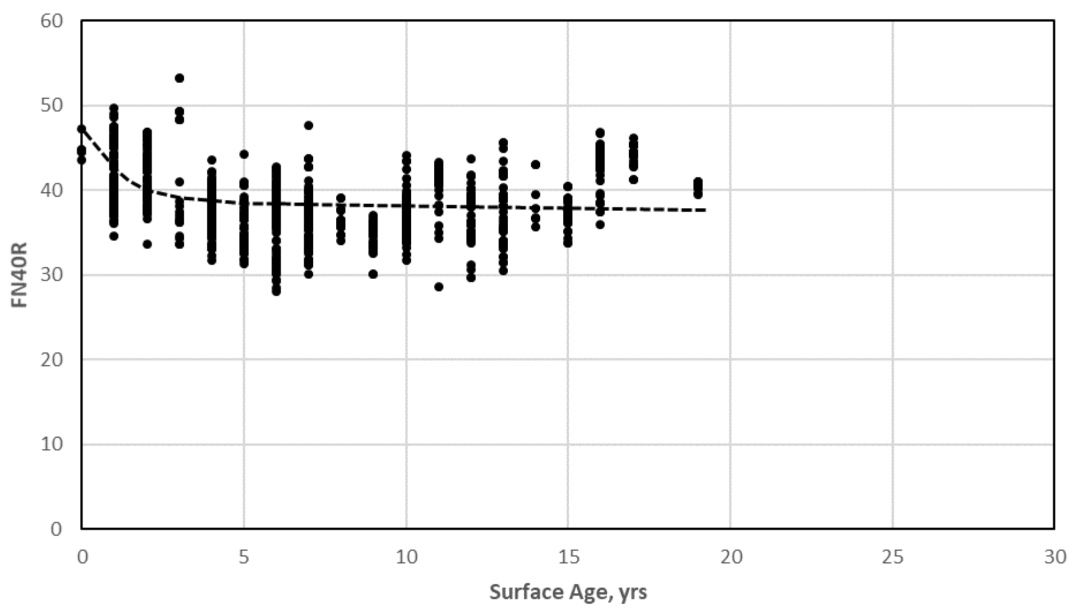


Figure 92. Graph. Friction versus age for divided primary, event segments, low traffic (AADT < 15,000) and PFC surfaces.

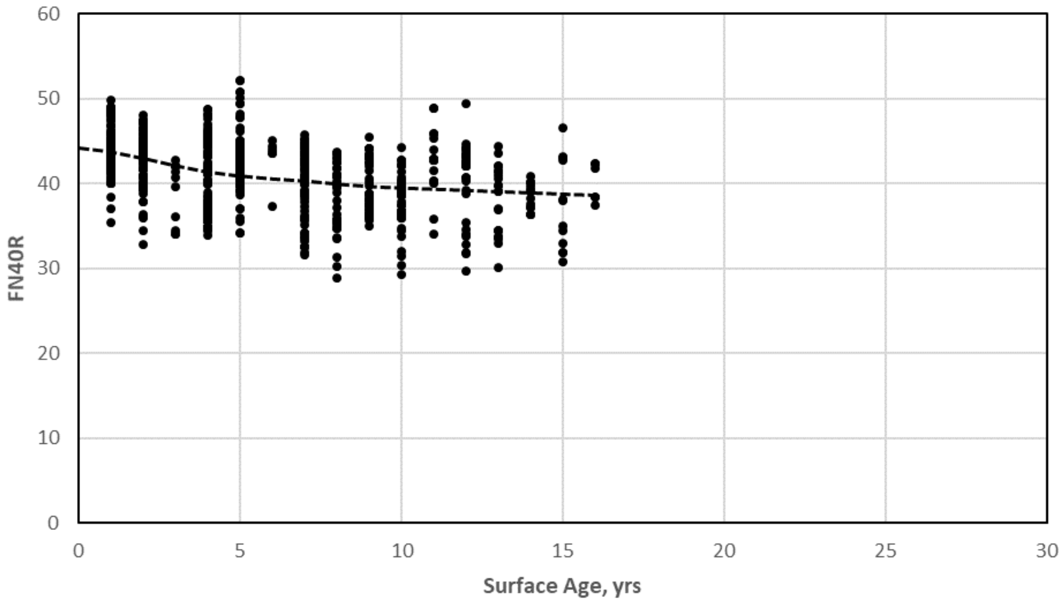


Figure 93. Graph. Friction versus age for divided primary, non-event segments, low traffic (AADT < 15,000) and DGAC surfaces.

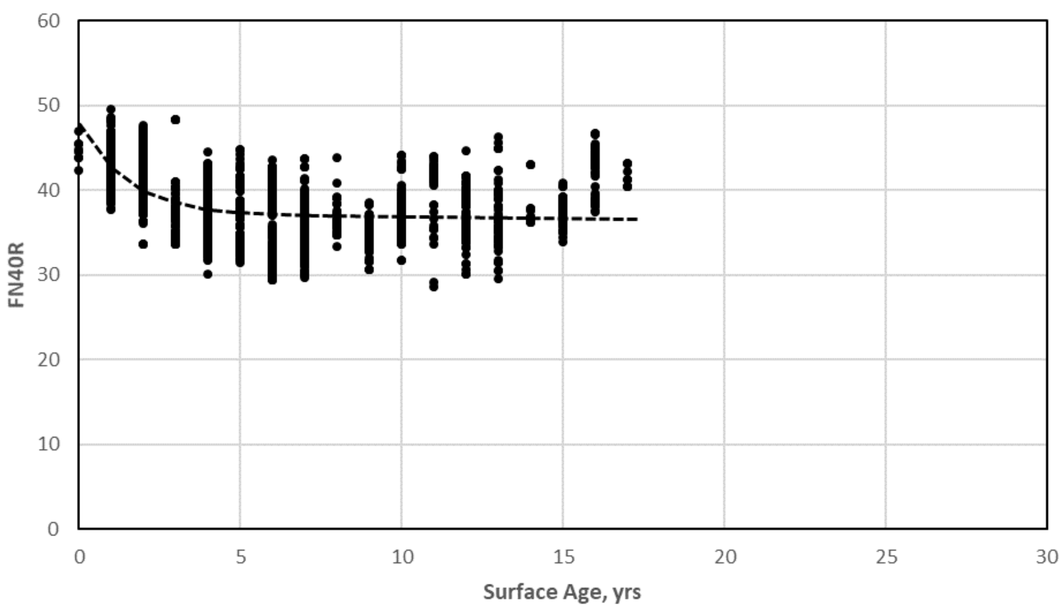


Figure 94. Graph. Friction versus age for divided primary, non-event segments, low traffic (AADT < 15,000) and PFC surfaces.

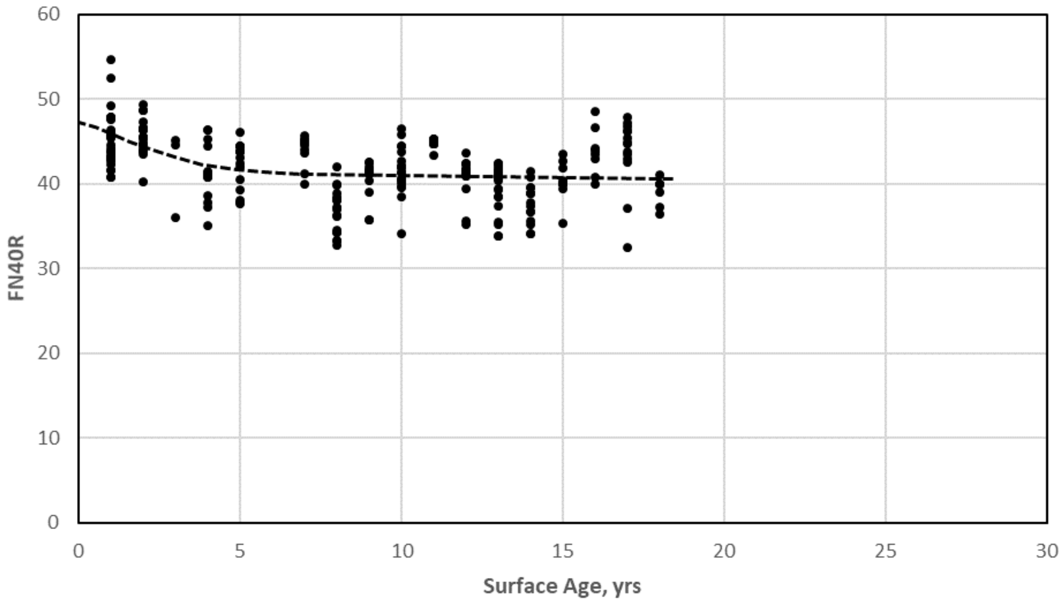


Figure 95. Graph. Friction versus age for undivided primary, event segments, low traffic (AADT < 15,000) and DGAC surfaces.

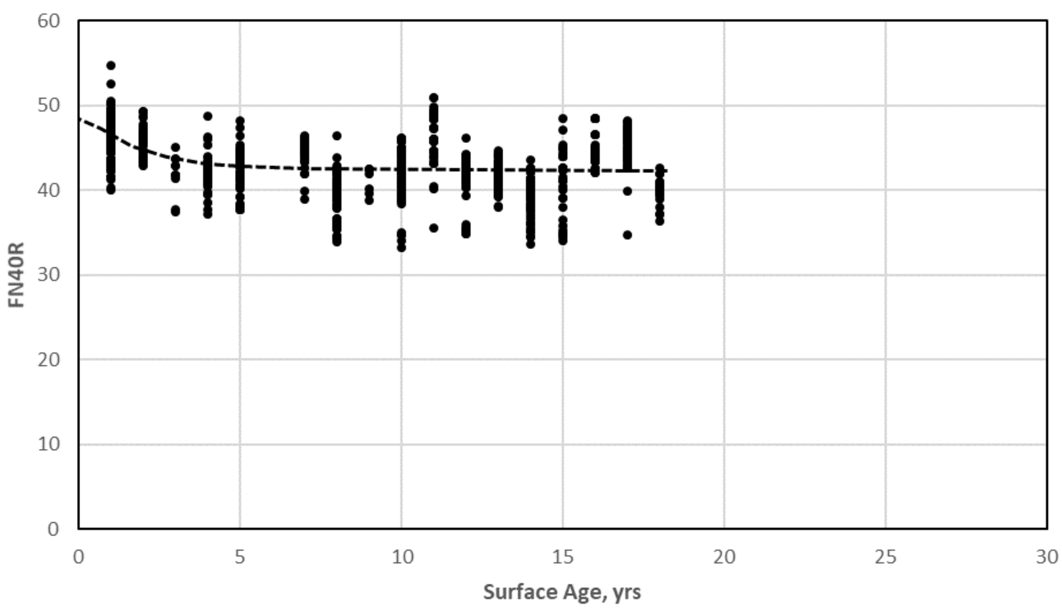


Figure 96. Graph. Friction versus age for undivided primary, non-event segments, low traffic (AADT < 15,000) and DGAC surfaces.

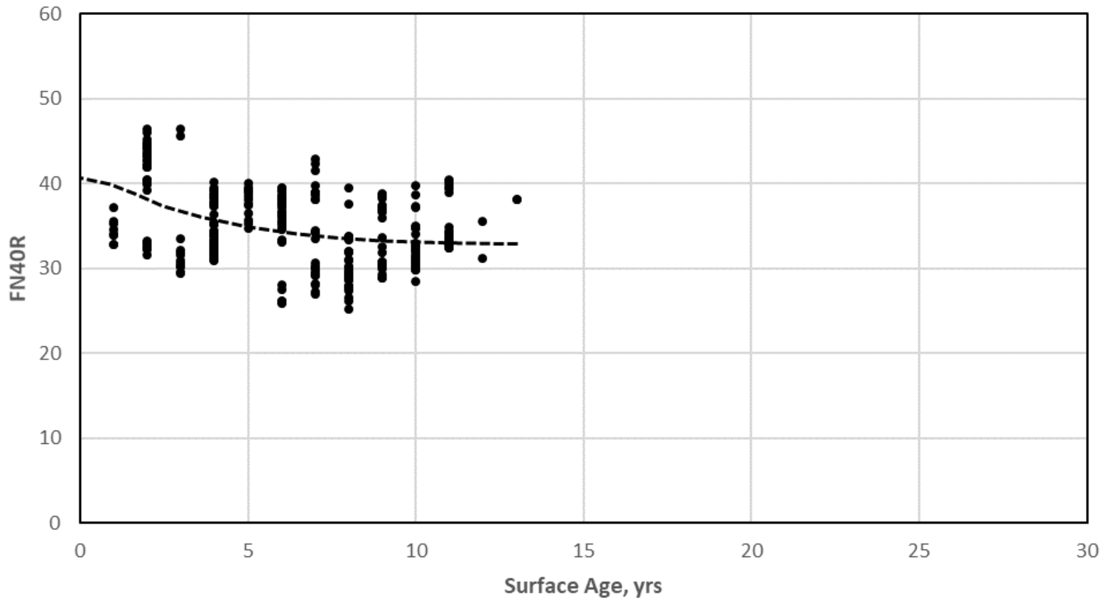


Figure 97. Graph. Friction versus age for interstate, event segments, low traffic (AADT < 15,000) and PFC surfaces.

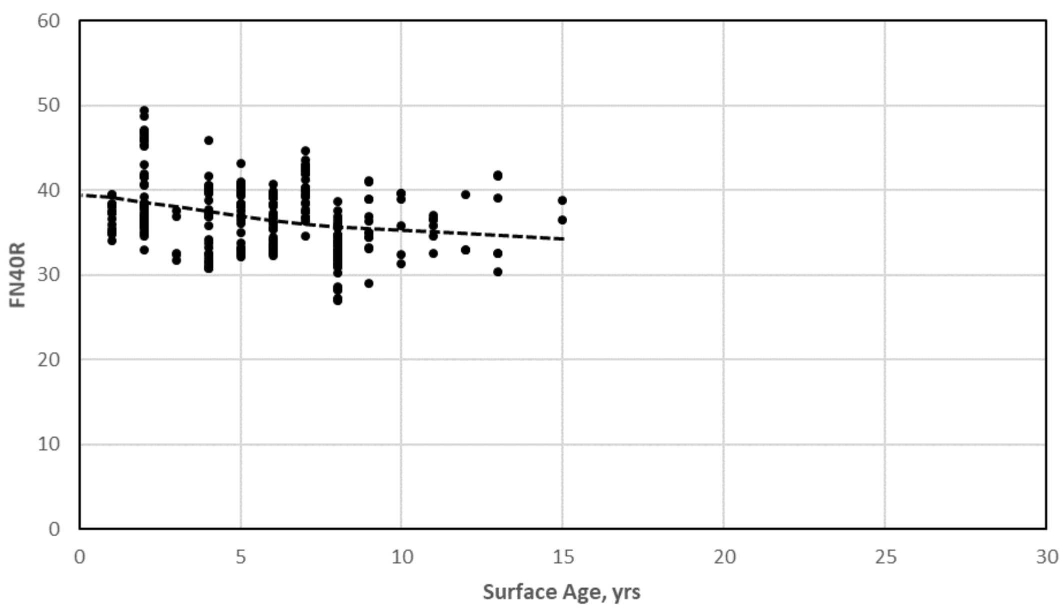


Figure 98. Graph. Friction versus age for interstate, event segments, high traffic (AADT > 15,000) and PFC surfaces.

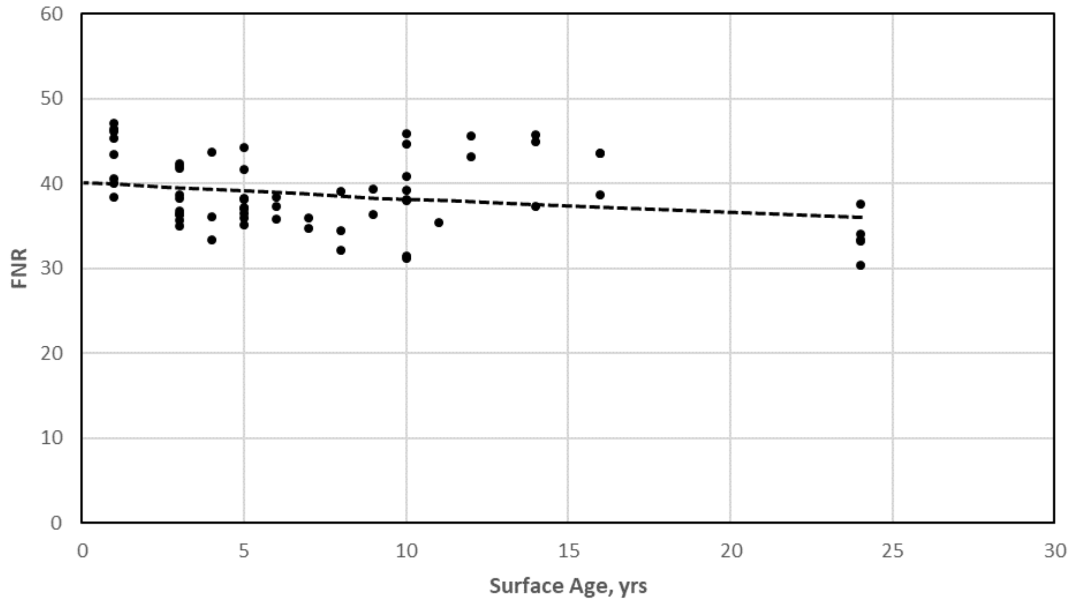


Figure 99. Graph. Friction versus age for interstate, event segments, low traffic (AADT < 15,000) and PCC surfaces.

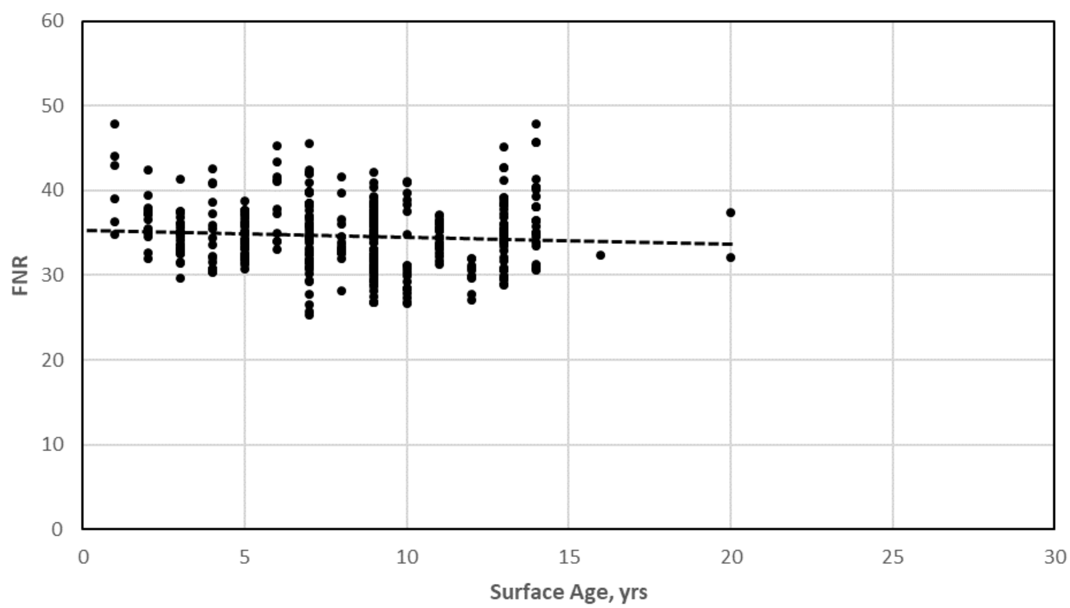


Figure 100. Graph. Friction versus age for interstate, event segments, high traffic (AADT > 15,000) and PCC surfaces.

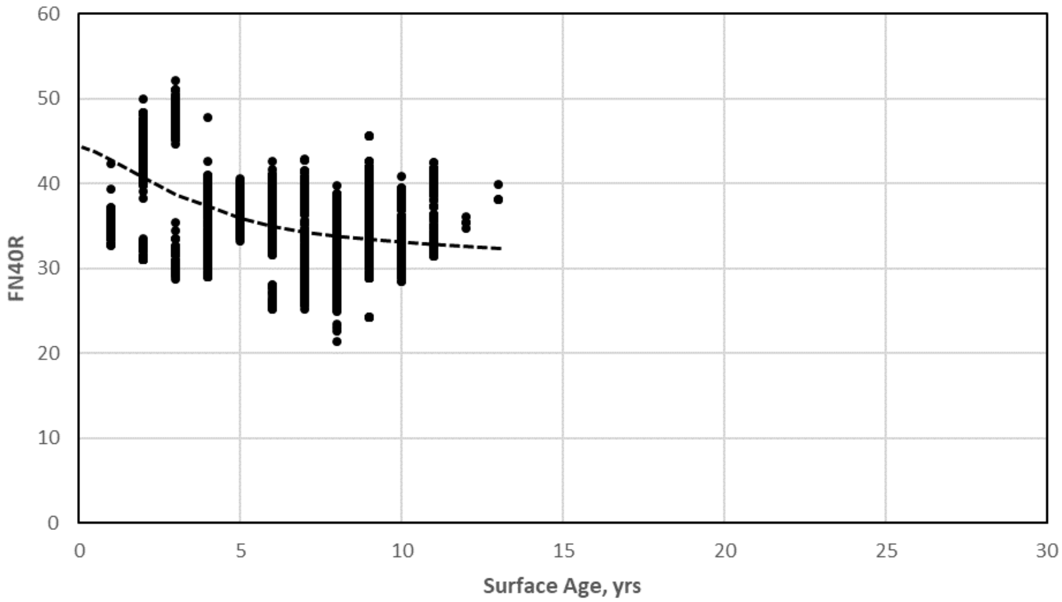


Figure 101. Graph. Friction versus age for interstate, non-event segments, low traffic (AADT < 15,000) and PFC surfaces.

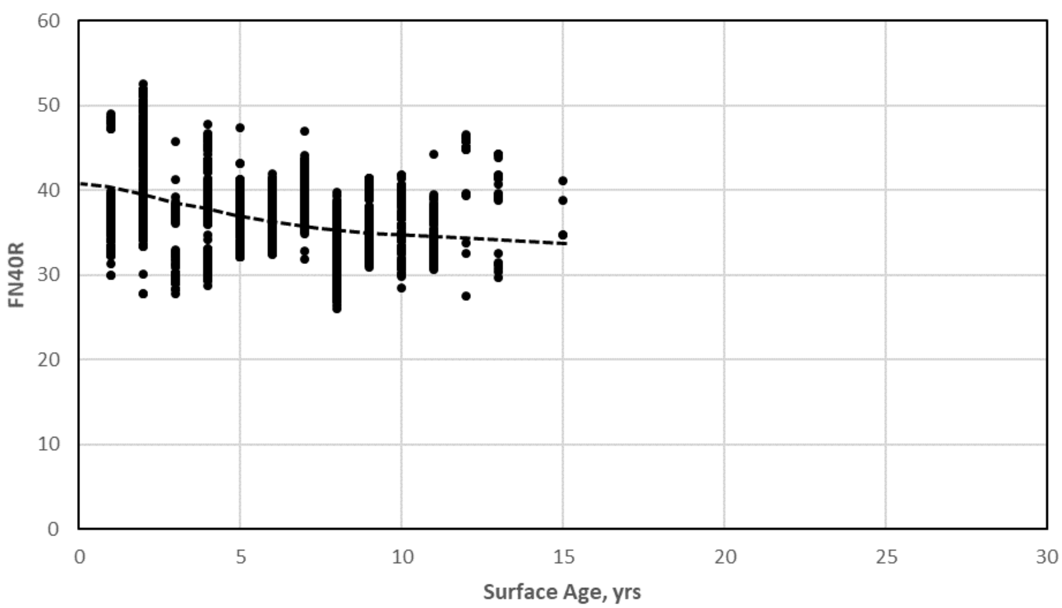


Figure 102. Graph. Friction versus age for interstate, non-event segments, high traffic (AADT > 15,000) and PFC surfaces.

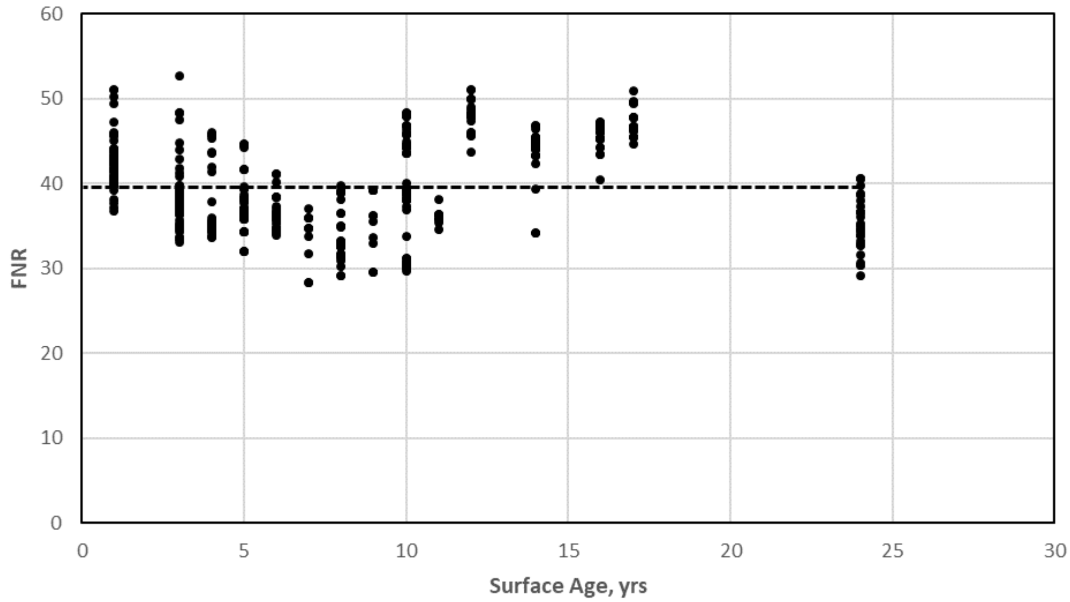


Figure 103. Graph. Friction versus age for interstate, non-event segments, low traffic (AADT < 15,000) and PCC surfaces.

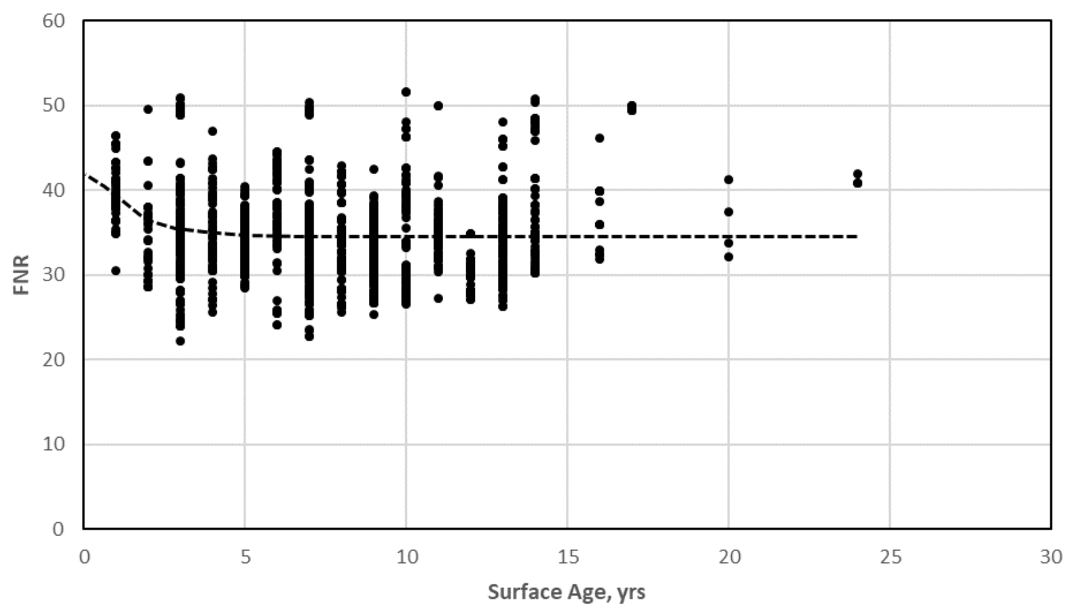
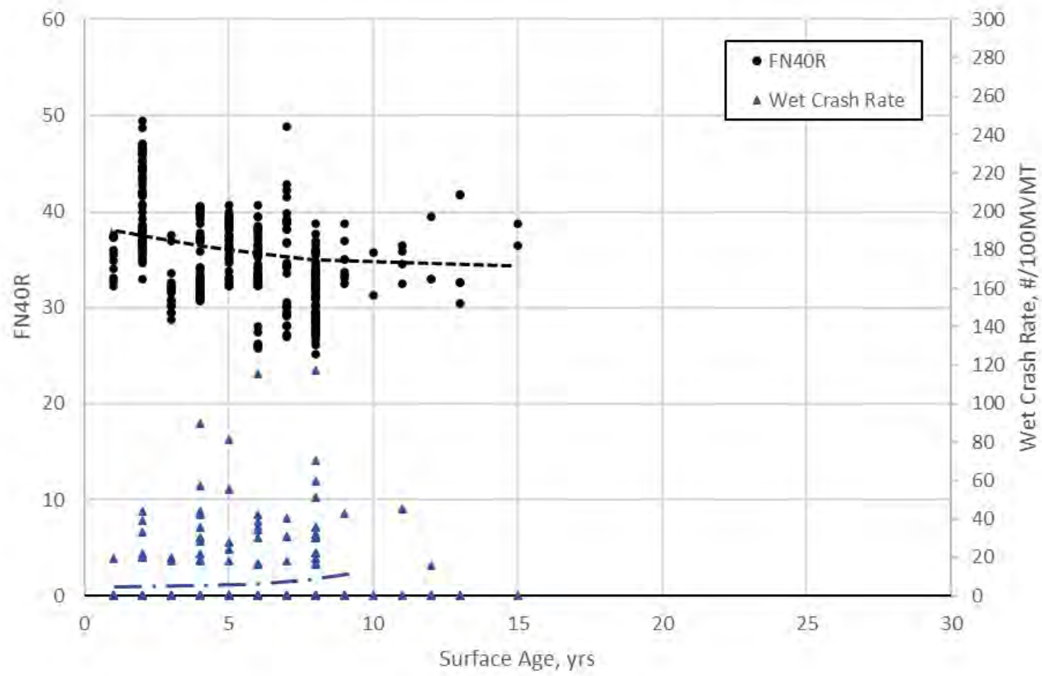


Figure 104. Graph. Friction versus age for interstate, non-event segments, high traffic (AADT > 15,000) and PCC surfaces.

GPF METHOD 2



Note: Wet crash rate = wet crash count/100 million vehicles miles traveled (MVMT).

Figure 105. Graph. Friction and wet crash rate versus age for interstate, event segments, all traffic levels and PFC surfaces.

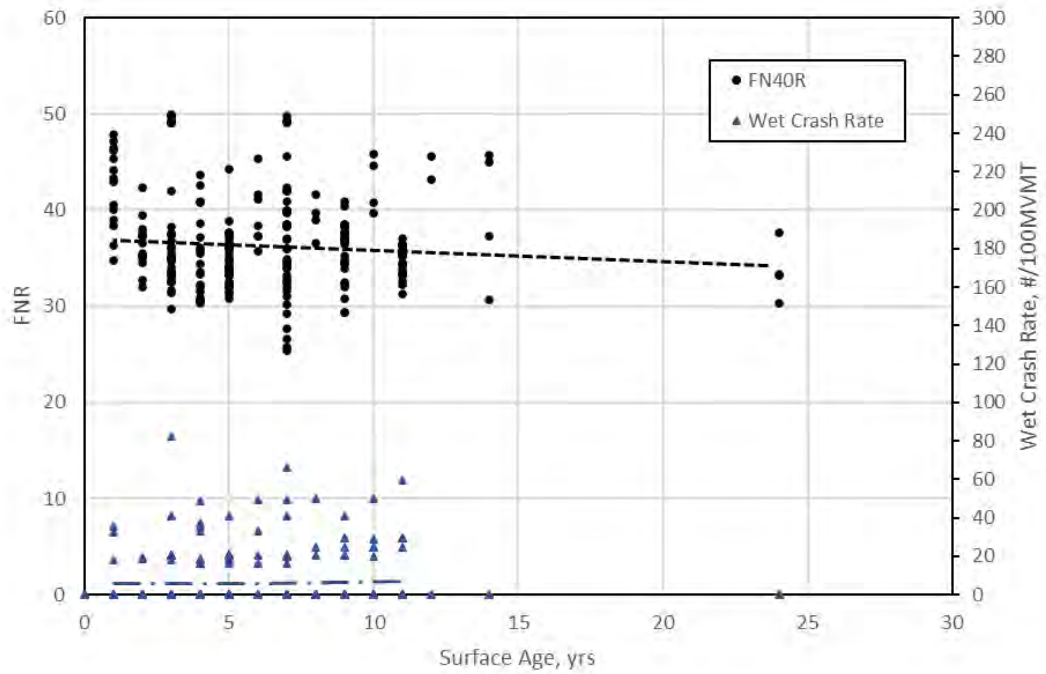


Figure 106. Graph. Friction and wet crash rate versus age for interstate, event segments, all traffic levels and PCC surfaces.

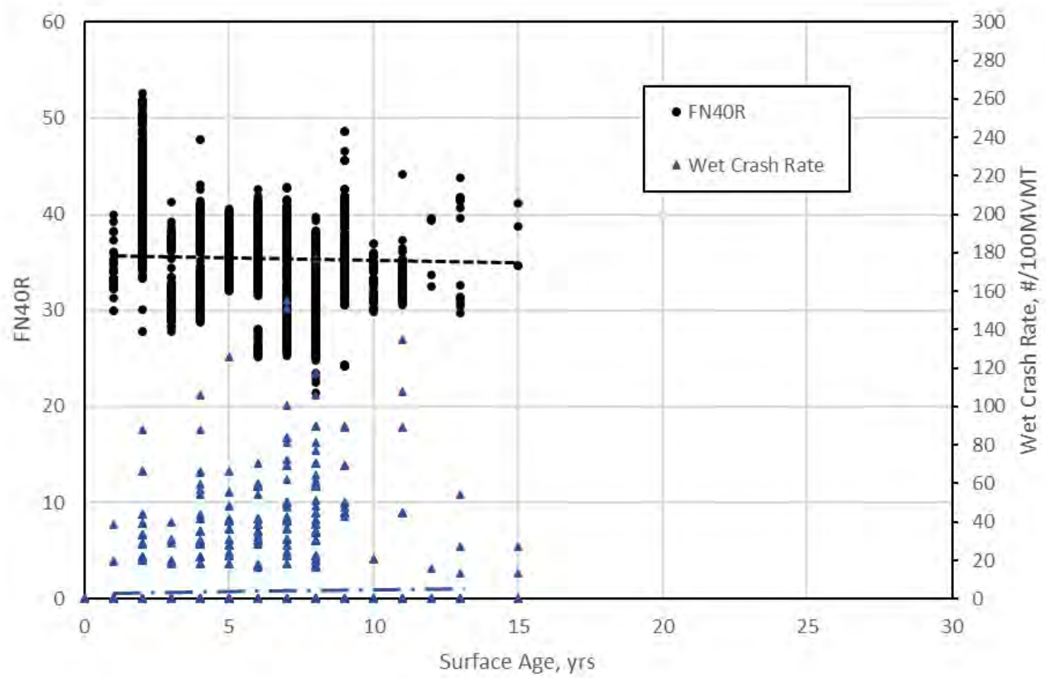


Figure 107. Graph. Friction and wet crash rate versus age for interstate, non-event segments, all traffic levels and PFC surfaces.

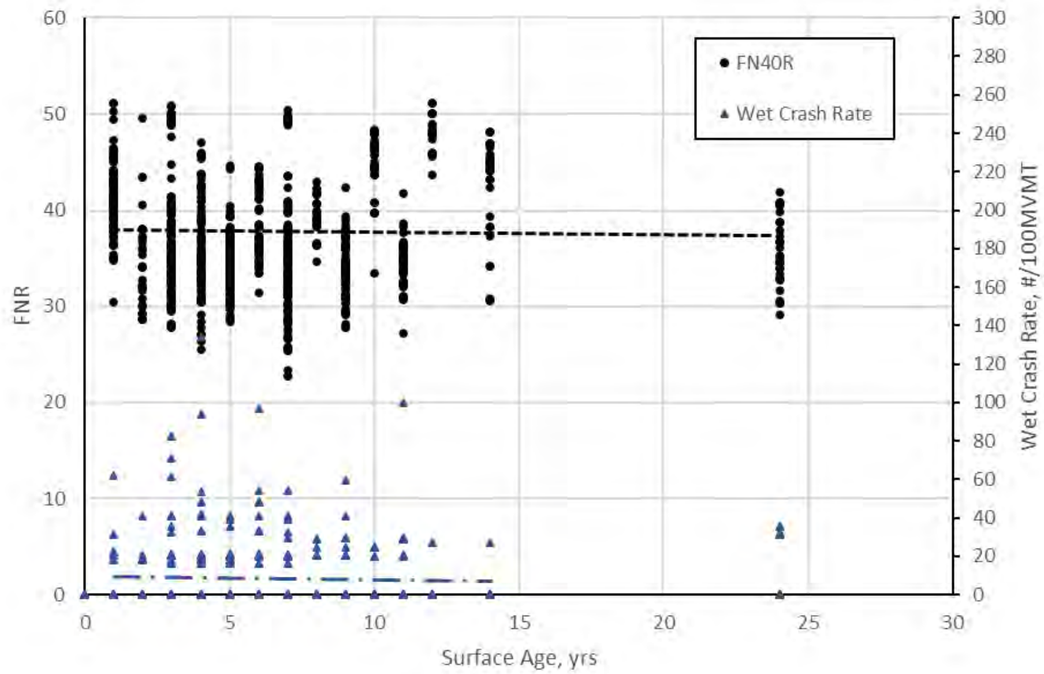


Figure 108. Graph. Friction and wet crash rate versus age for interstate, non-event segments, all traffic levels and PCC surfaces.

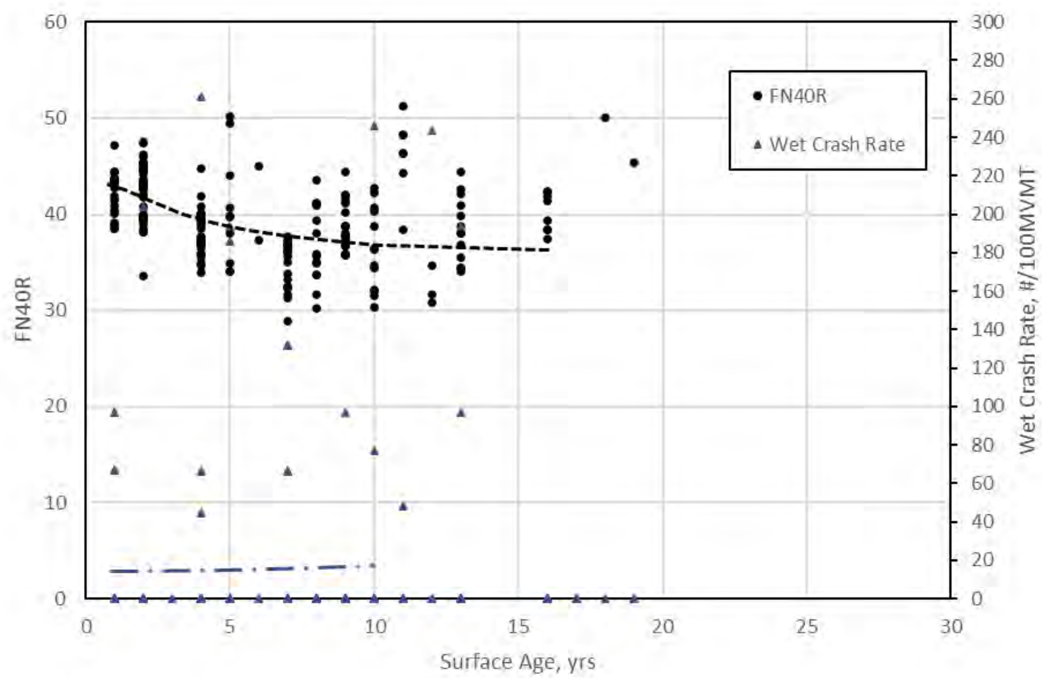


Figure 109. Graph. Friction and wet crash rate versus age for divided primary, event segments, all traffic levels and DGAC surfaces.

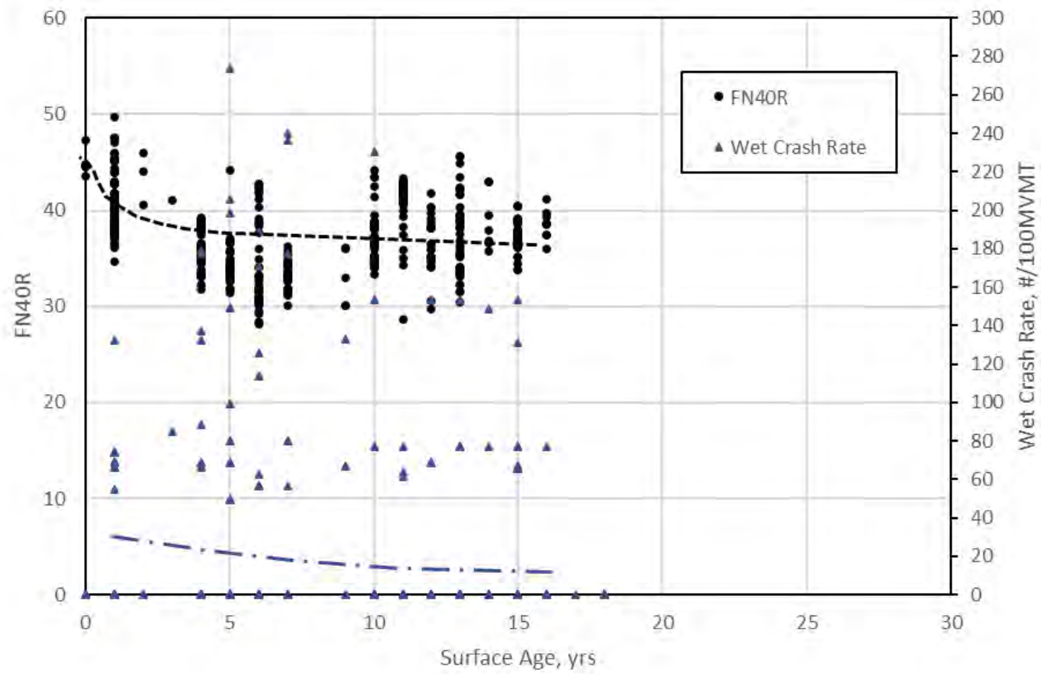


Figure 110. Graph. Friction and wet crash rate versus age for divided primary, event segments, all traffic levels and PFC surfaces.

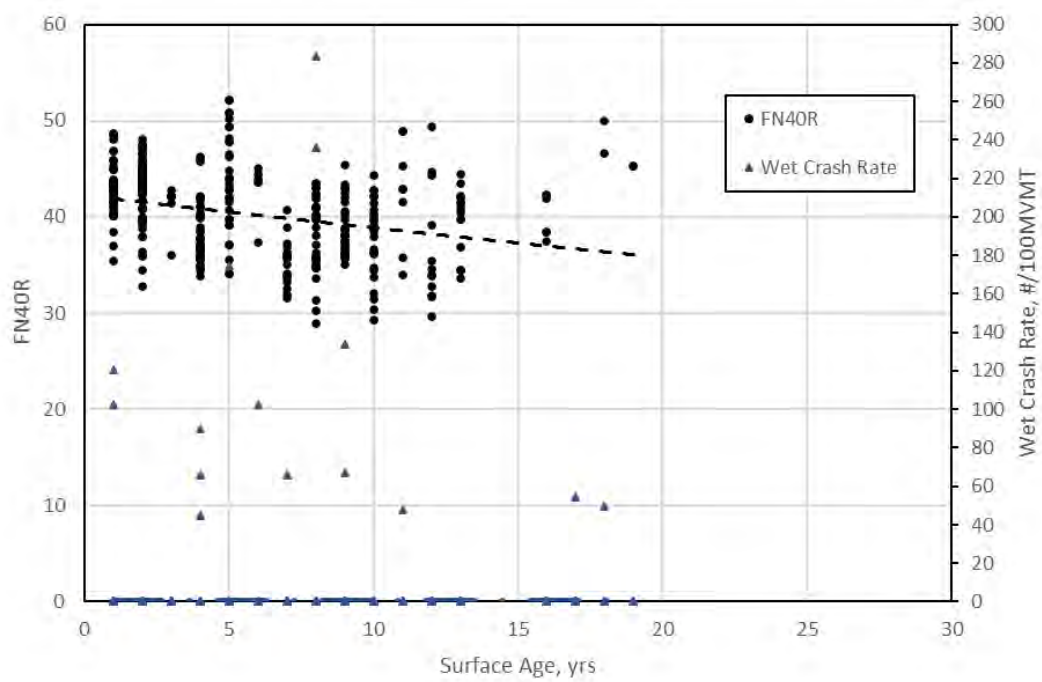


Figure 111. Graph. Friction and wet crash rate versus age for divided primary, non-event segments, all traffic levels and DGAC surfaces.

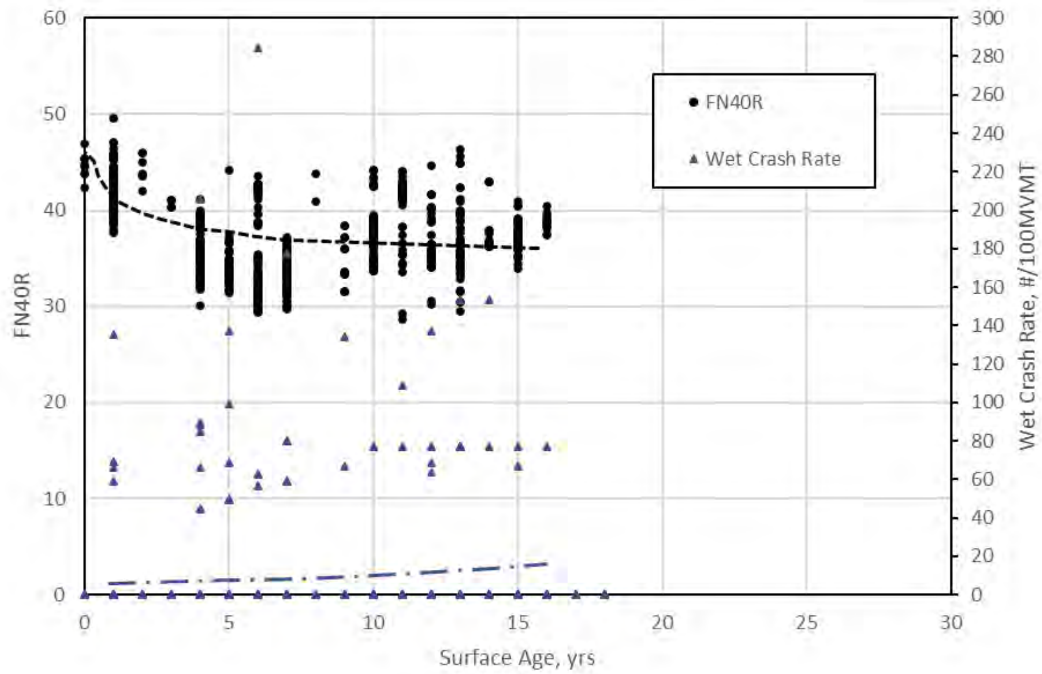


Figure 112. Graph. Friction and wet crash rate versus age for divided primary, non-event segments, all traffic levels and PFC surfaces.

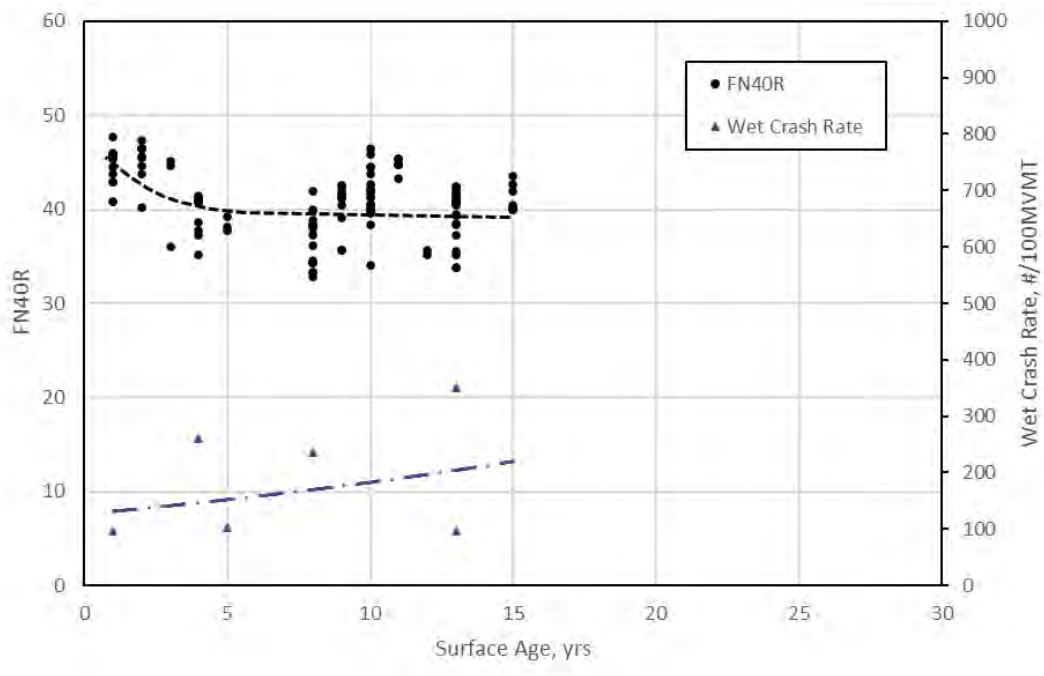


Figure 113. Graph. Friction and wet crash rate versus age for undivided primary, event segments, all traffic levels and DGAC surfaces.

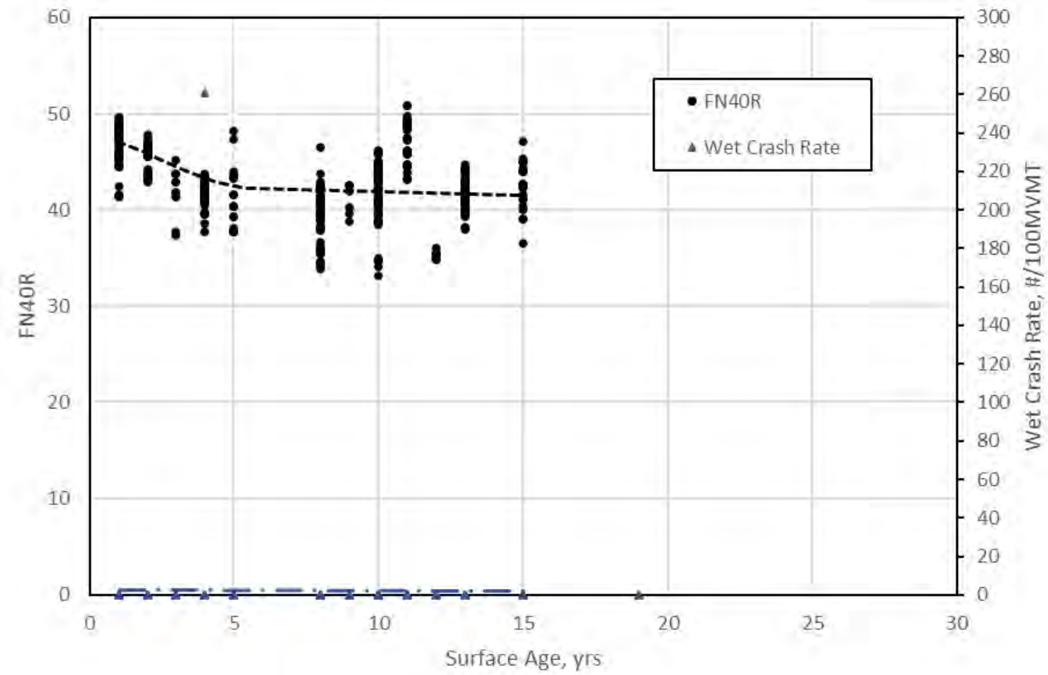


Figure 114. Graph. Friction and wet crash rate versus age for undivided primary, non-event segments, all traffic levels and DGAC surfaces.

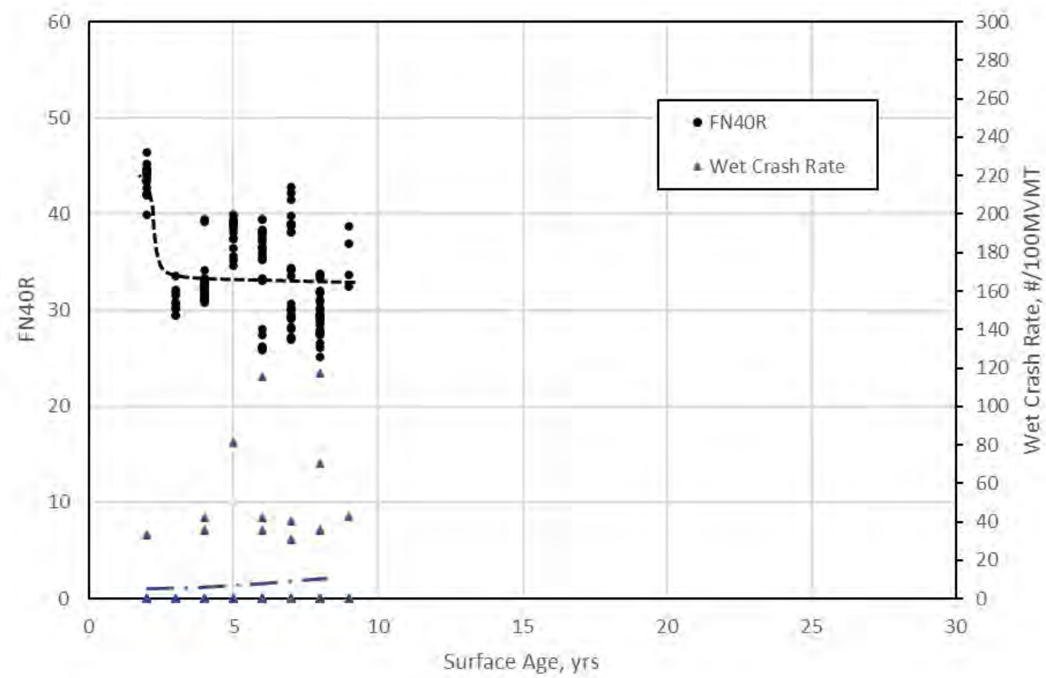


Figure 115. Graph. Friction and wet crash rate versus age for interstate, event segments, low traffic (AADT < 15,000) and PFC surfaces.

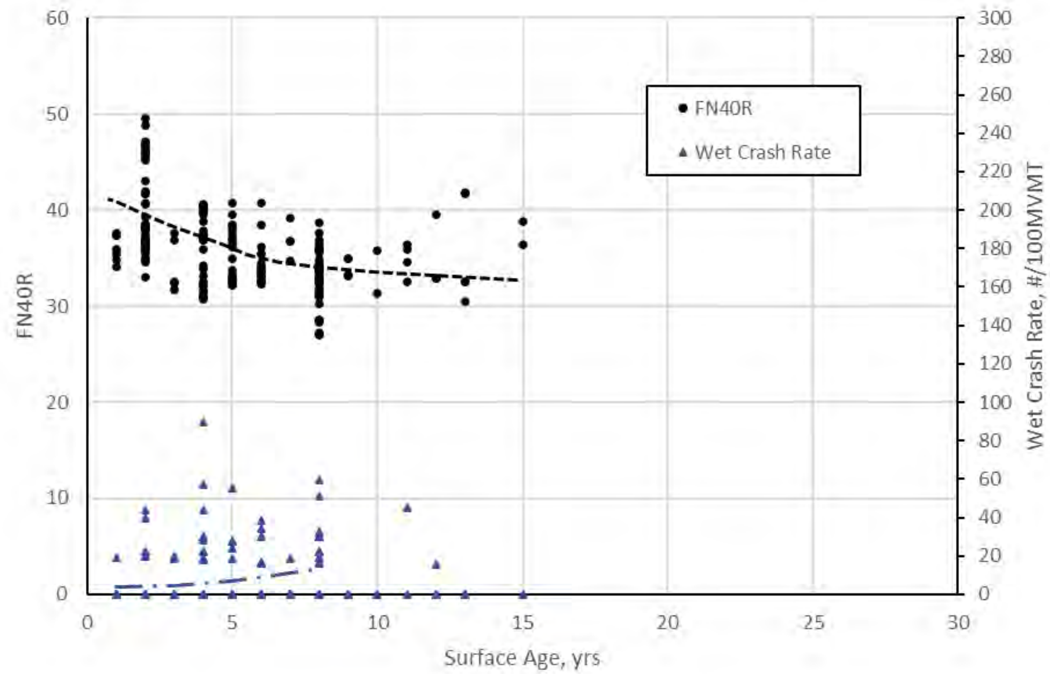


Figure 116. Graph. Friction and wet crash rate versus age for interstate, event segments, high traffic (AADT > 15,000) and PFC surfaces.

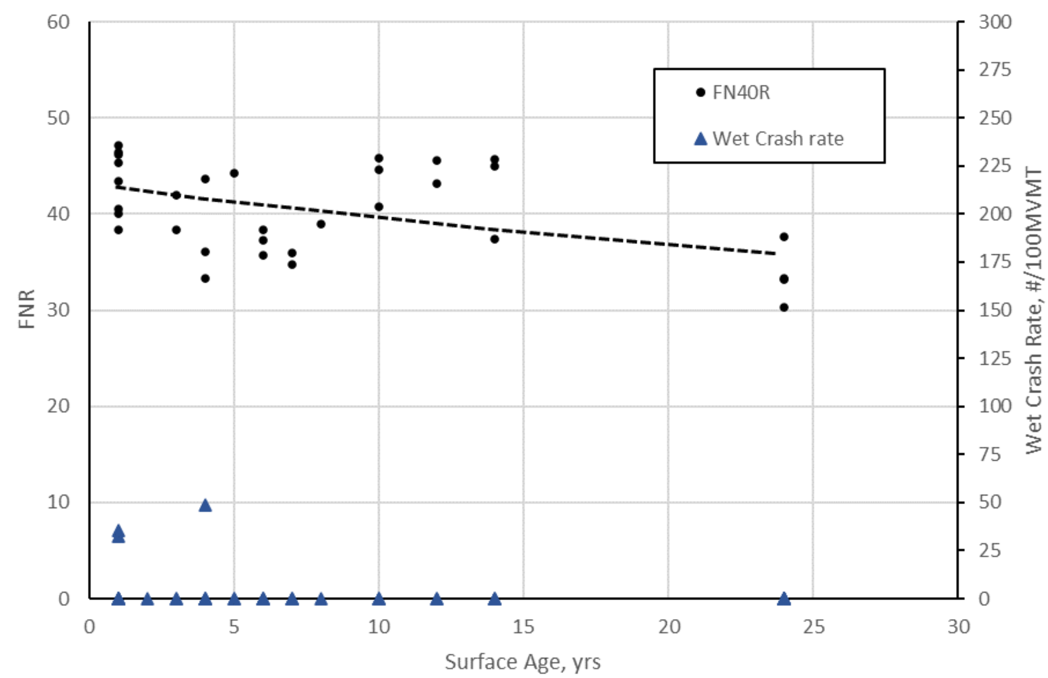


Figure 117. Graph. Friction and wet crash rate versus age for interstate, event segments, low traffic (AADT < 15,000) and PCC surfaces.

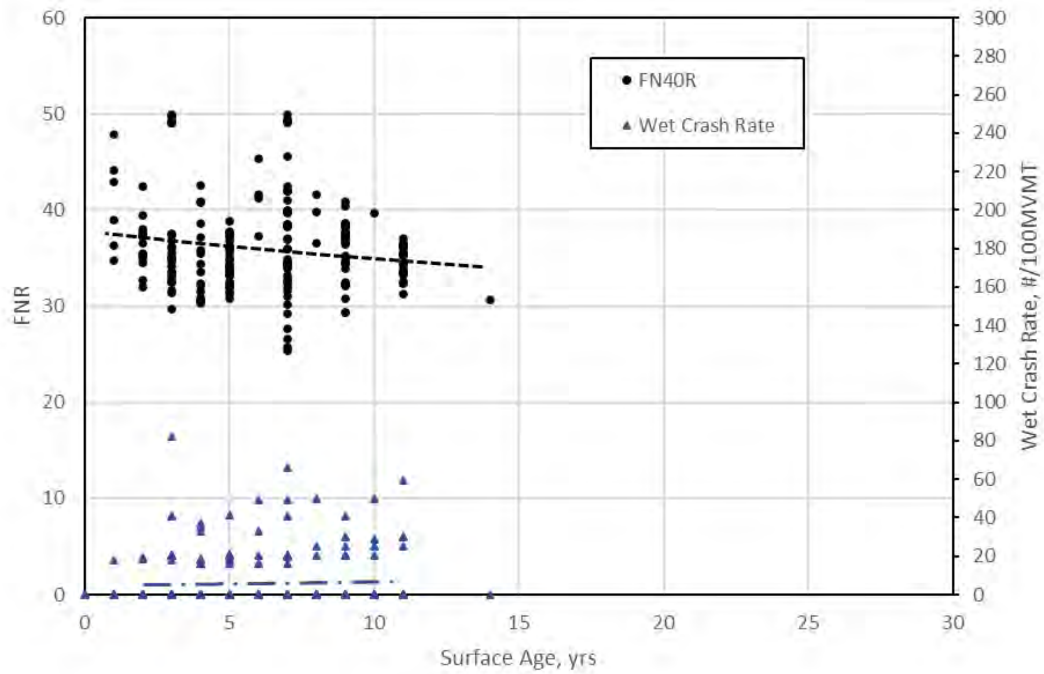


Figure 118. Graph. Friction and wet crash rate versus age for interstate, event segments, high traffic (AADT > 15,000) and PCC surfaces.

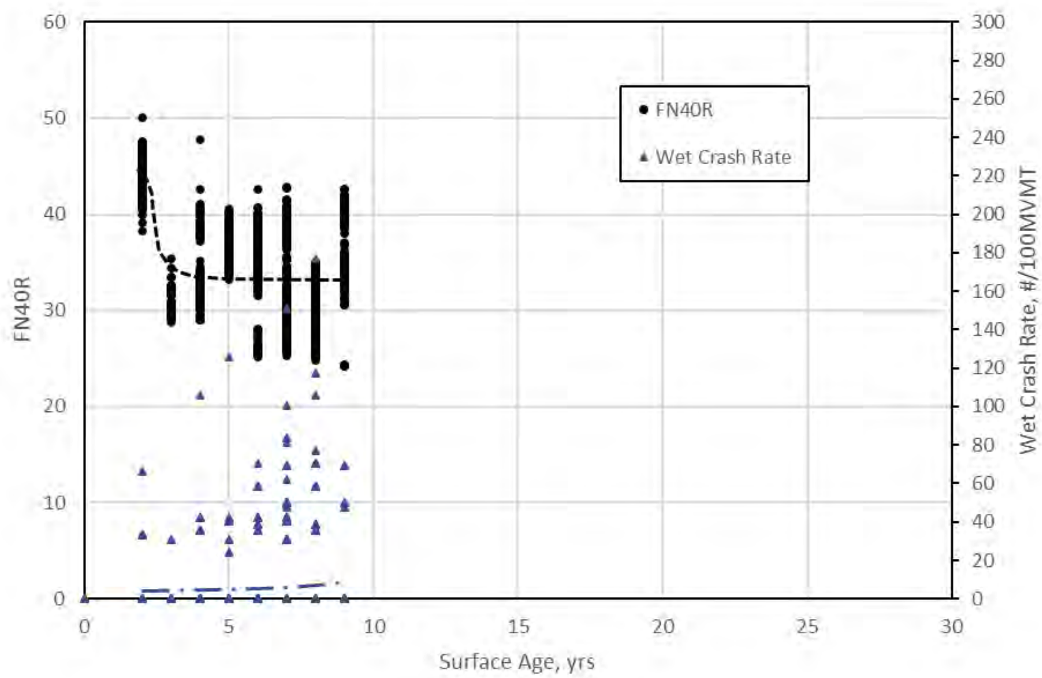


Figure 119. Graph. Friction and wet crash rate versus age for interstate, non-event segments, low traffic (AADT < 15,000) and PFC surfaces.

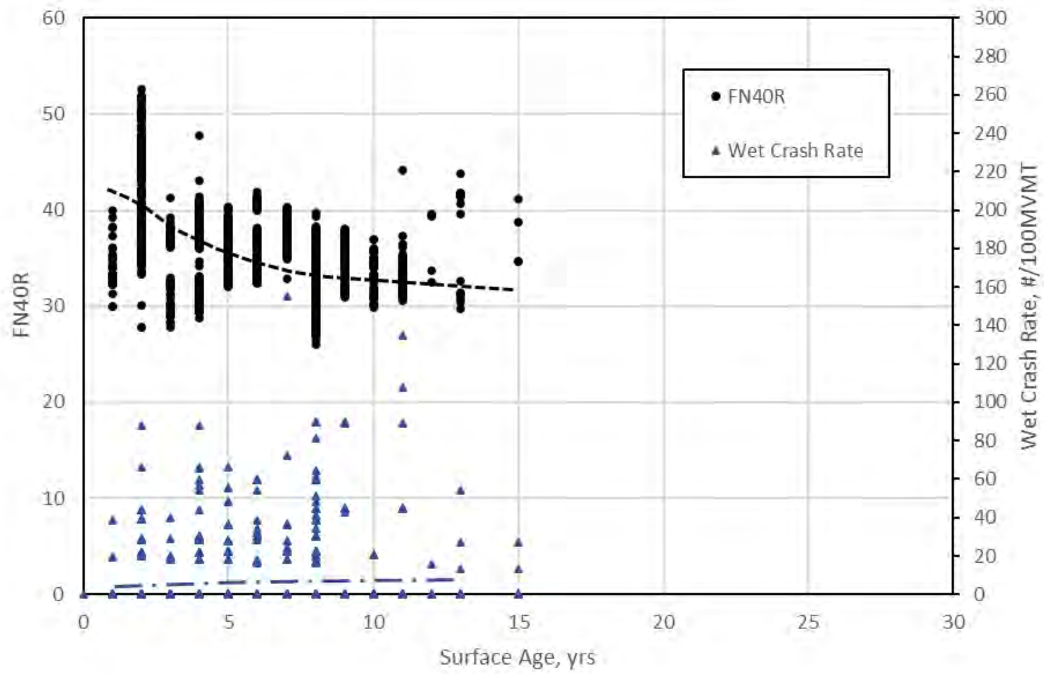


Figure 120. Graph. Friction and wet crash rate versus age for interstate, non-event segments, high traffic (AADT > 15,000) and PFC surfaces.

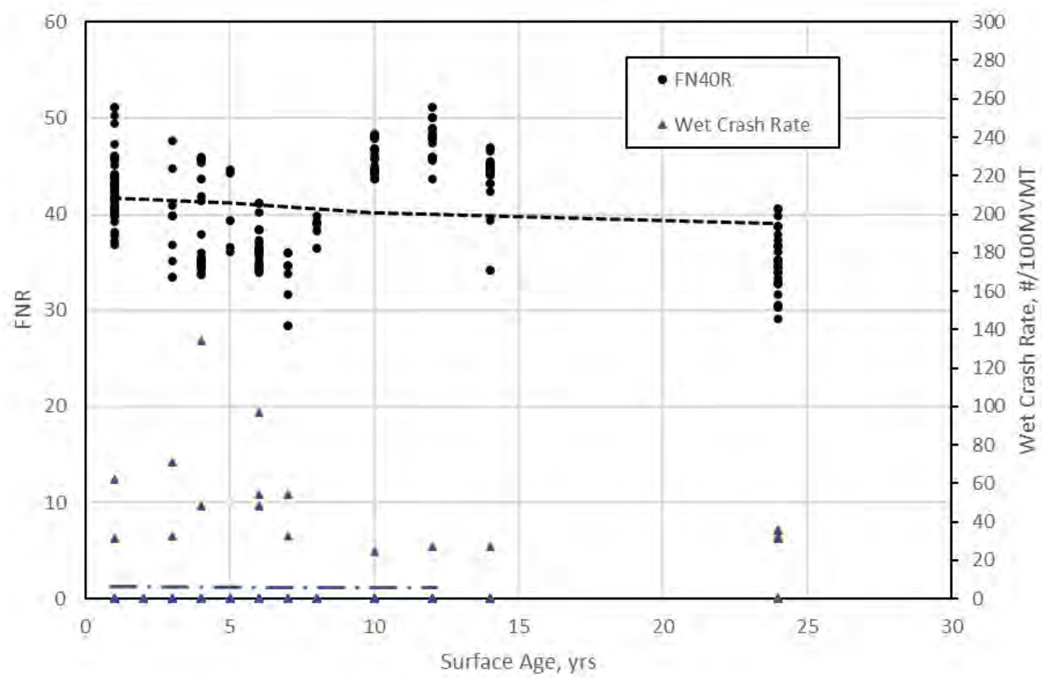


Figure 121. Graph. Friction and wet crash rate versus age for interstate, non-event segments, low traffic (AADT < 15,000) and PCC surfaces.

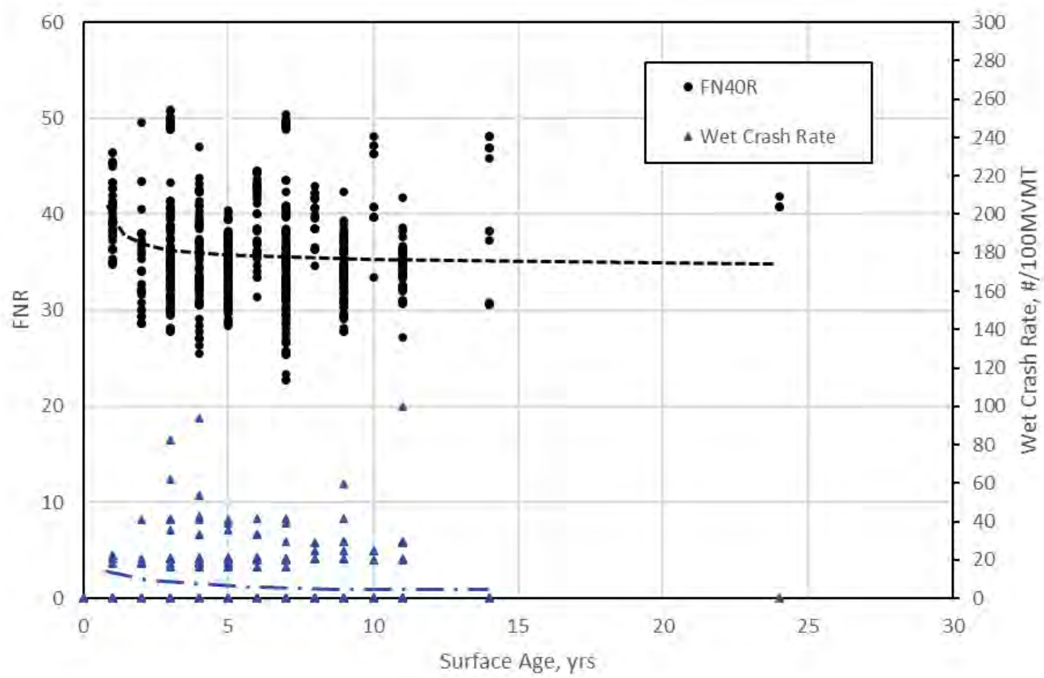


Figure 122. Graph. Friction and wet crash rate versus age for interstate, non-event segments, high traffic (AADT > 15,000) and PCC surfaces.

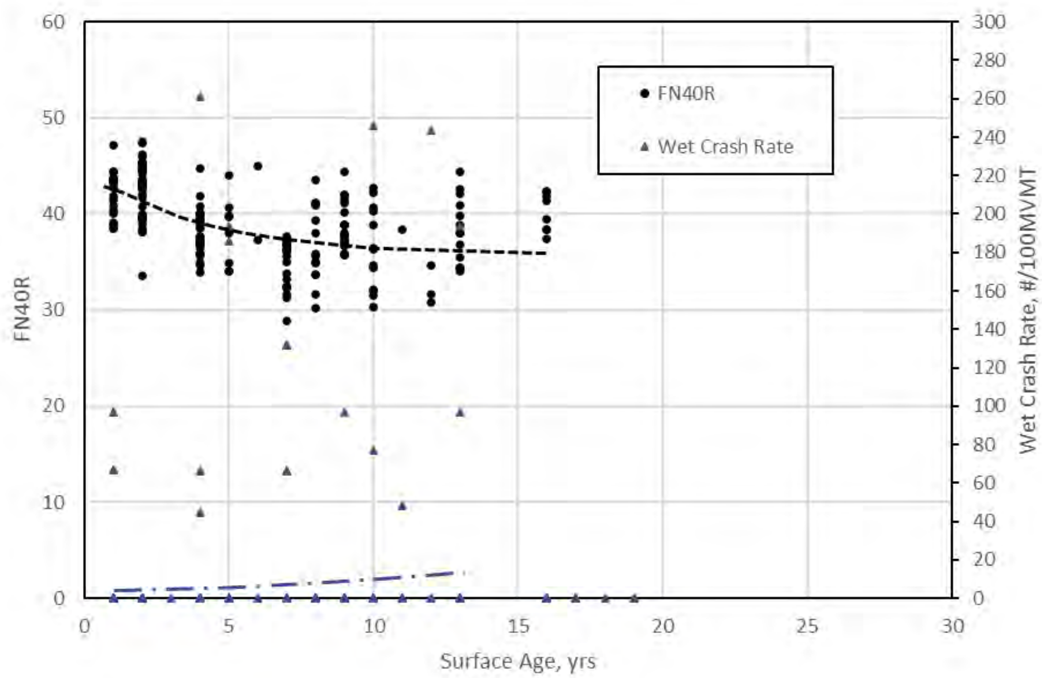


Figure 123. Graph. Friction and wet crash rate versus age for divided primary, event segments, low traffic (AADT < 15,000) and DGAC surfaces.

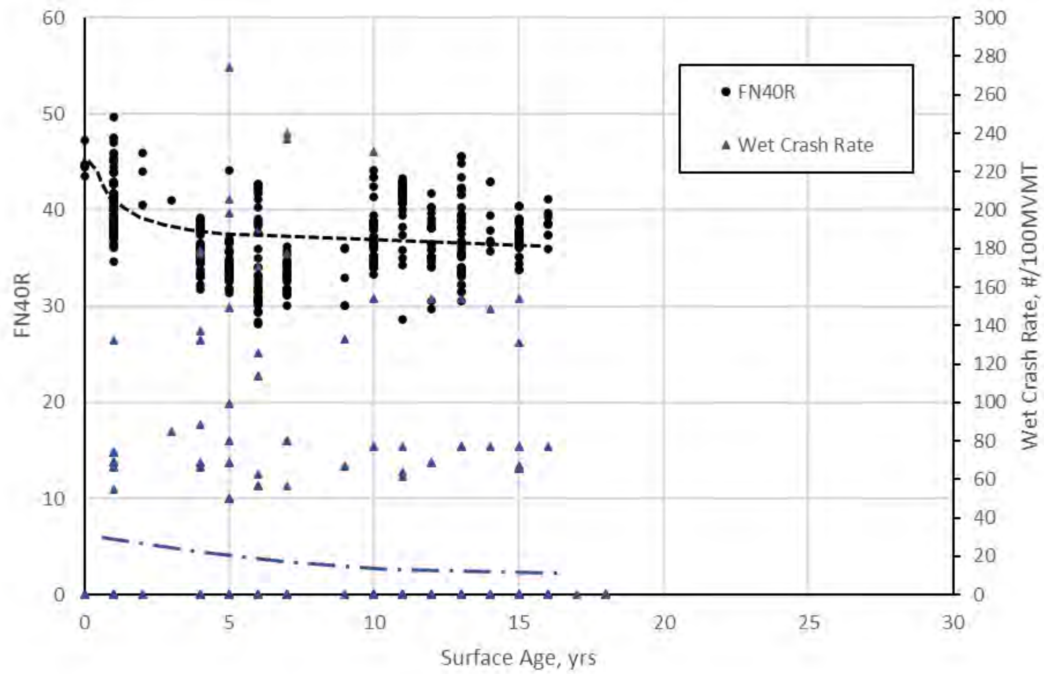


Figure 124. Graph. Friction and wet crash rate versus age for divided primary, event segments, low traffic (AADT < 15,000) and PFC surfaces.

GPF METHOD 3

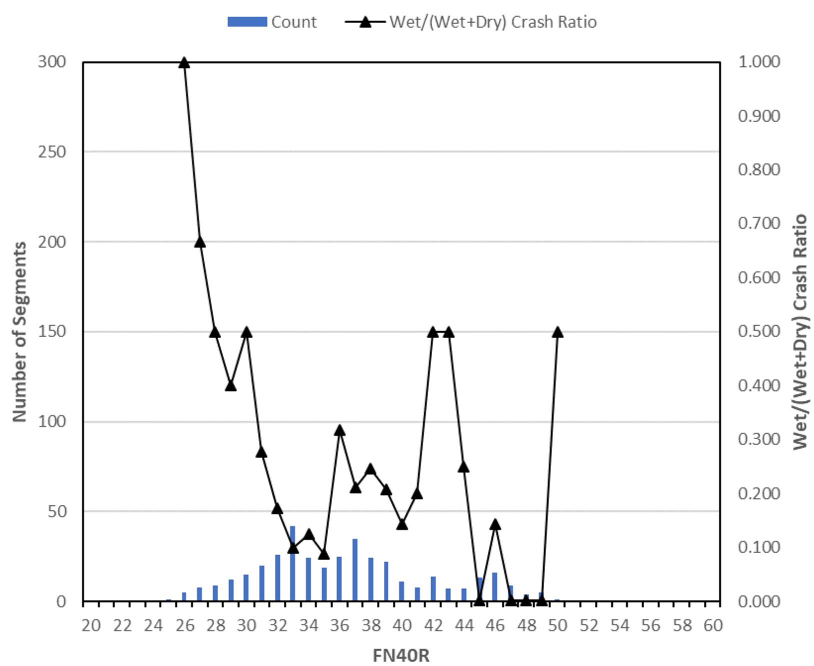


Figure 125. Graph. Friction number distribution and wet/(wet+dry) crash ratio for interstate, event segments, all traffic levels and PFC surfaces.

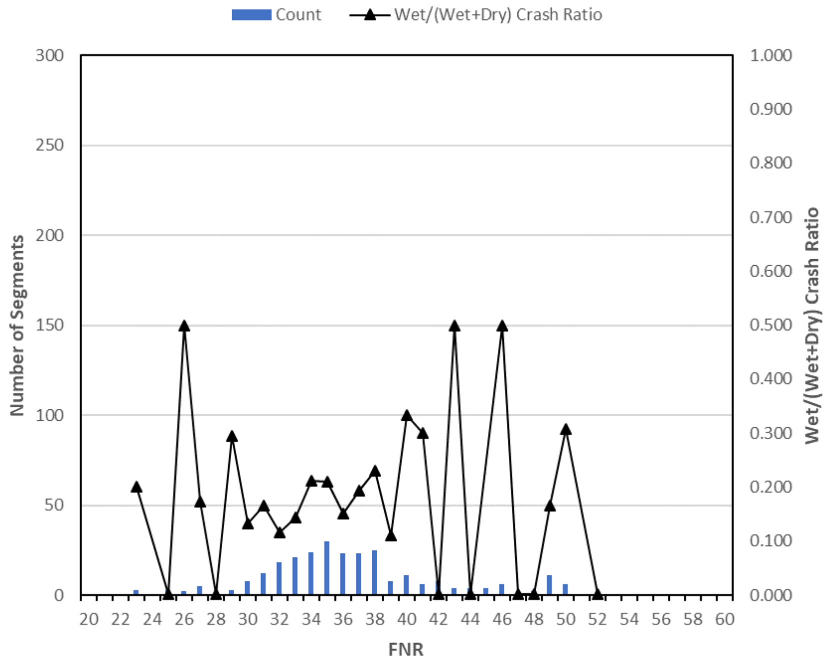


Figure 126. Graph. Friction number distribution and wet/(wet+dry) crash ratio for interstate, event segments, all traffic levels and PCC surfaces.

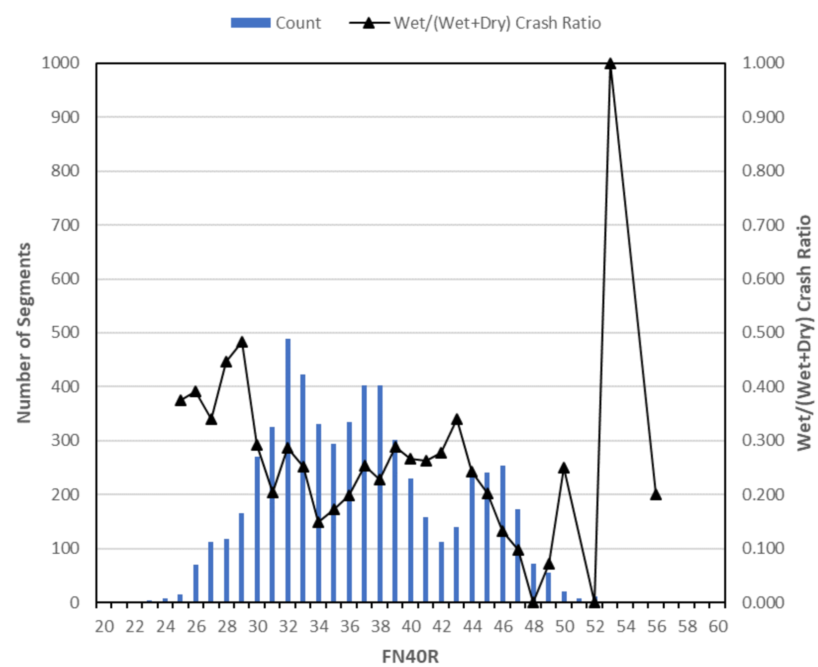


Figure 127. Graph. Friction number distribution and wet/(wet+dry) crash ratio for interstate, non-event segments, all traffic levels and PFC surfaces.

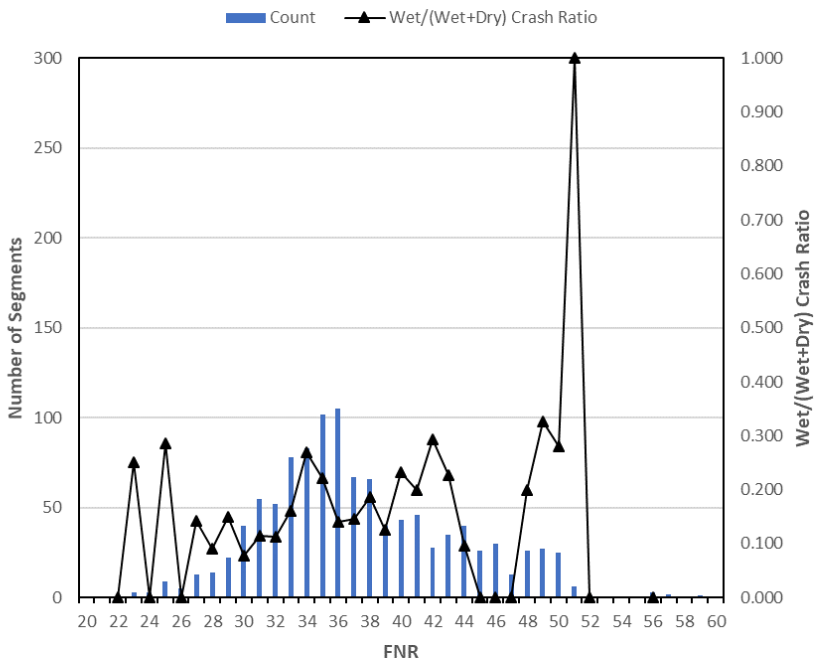


Figure 128. Graph. Friction number distribution and wet/(wet+dry) crash ratio for interstate, non-event segments, all traffic levels and PCC surfaces.

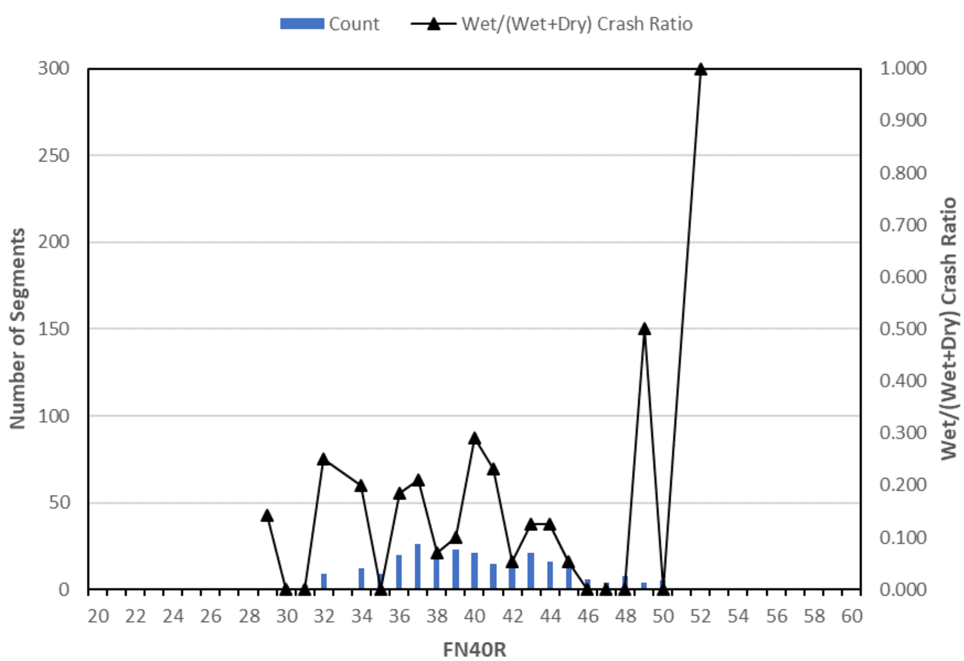


Figure 129. Graph. Friction number distribution and wet/(wet+dry) crash ratio for divided primary, event segments, all traffic levels and DGAC surfaces.

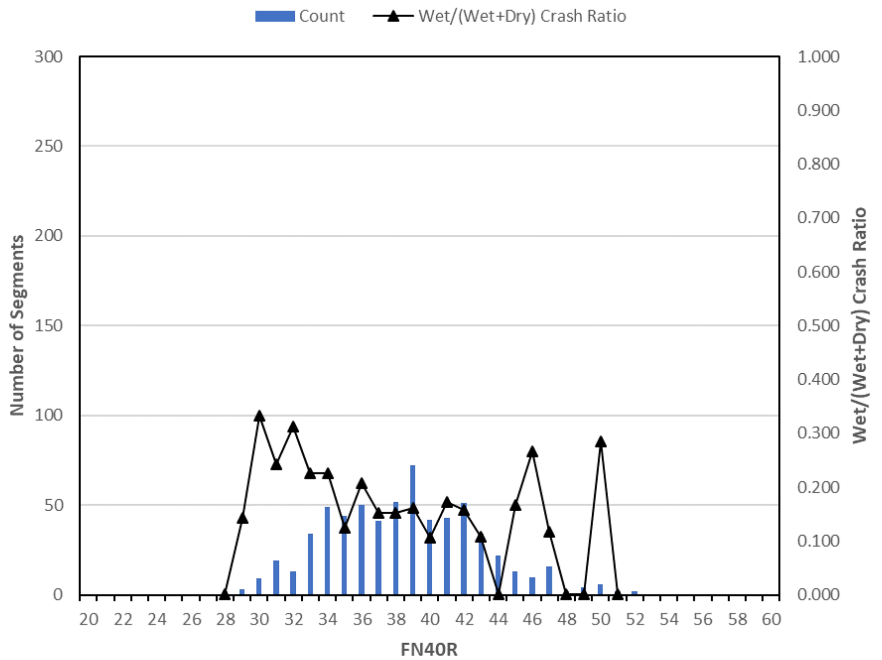


Figure 130. Graph. Friction number distribution and wet/(wet+dry) crash ratio for divided primary, event segments, all traffic levels and PFC surfaces.

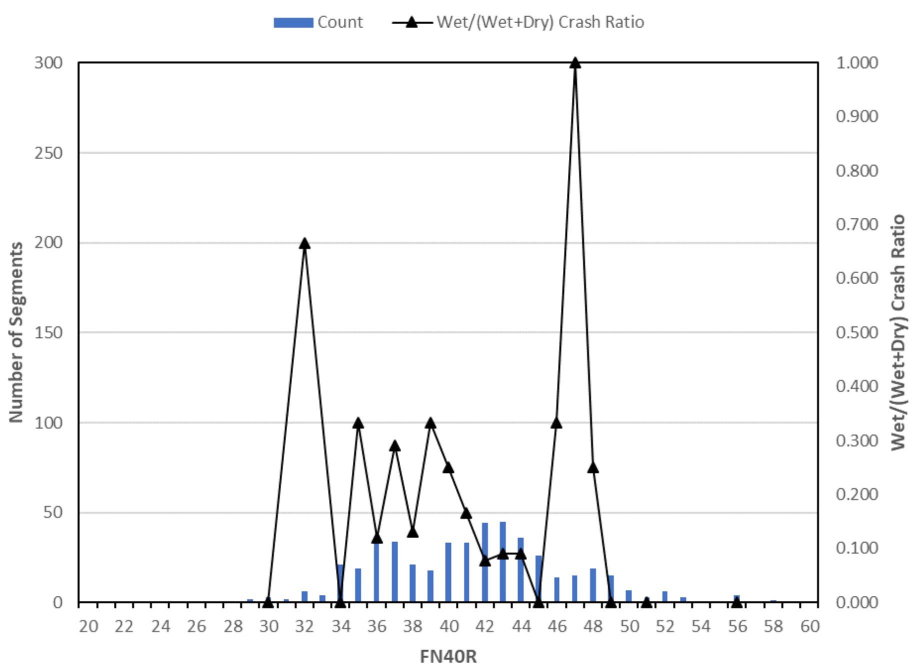


Figure 131. Graph. Friction number distribution and wet/(wet+dry) crash ratio for divided primary, non-event segments, all traffic levels and DGAC surfaces.

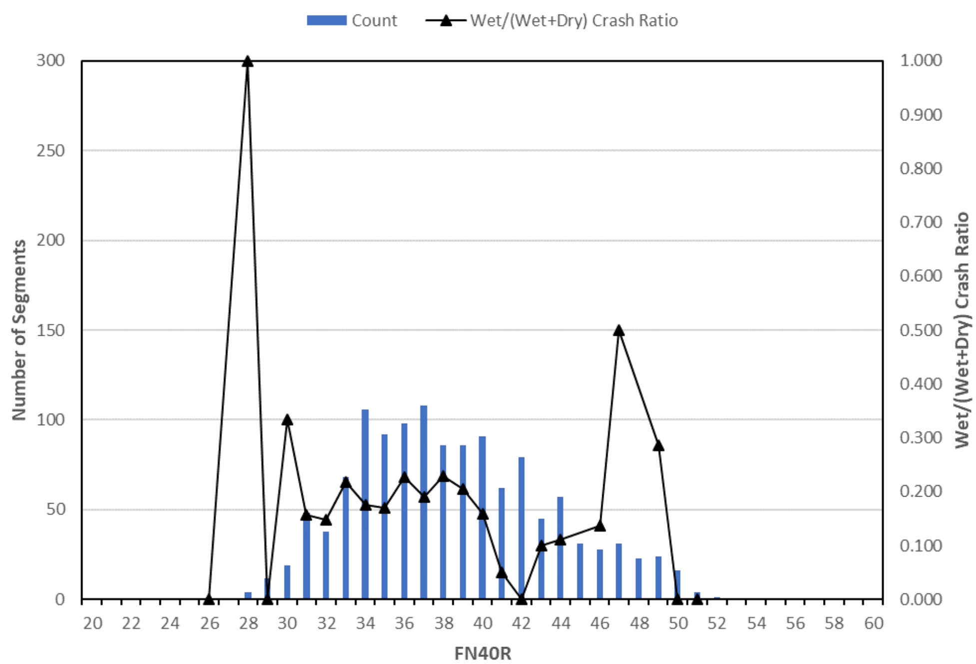


Figure 132. Graph. Friction number distribution and wet/(wet+dry) crash ratio for divided primary, non-event segments, all traffic levels and PFC surfaces.

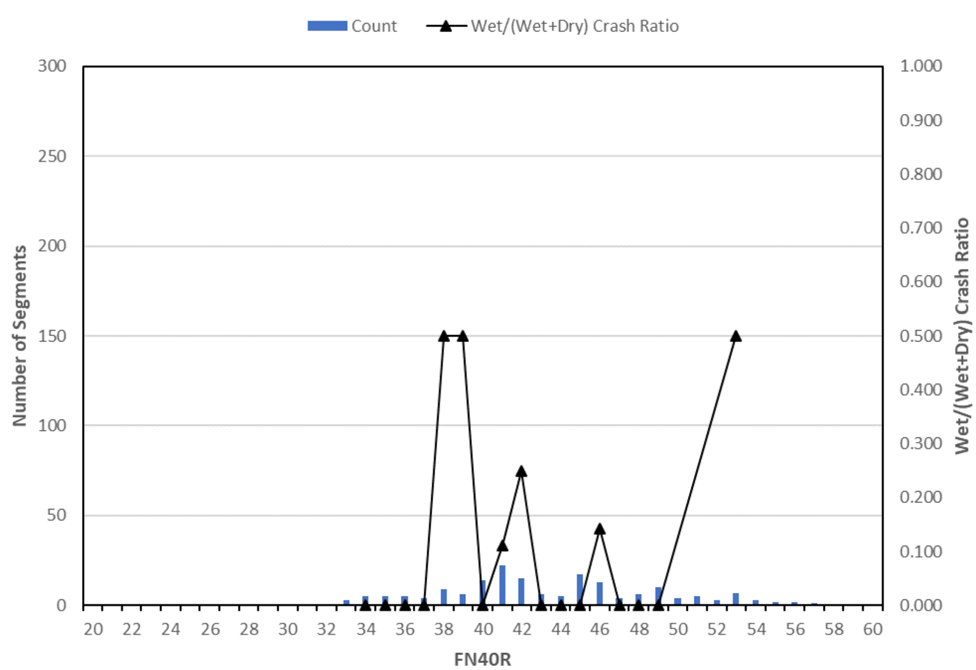


Figure 133. Graph. Friction number distribution and wet/(wet+dry) crash ratio for undivided primary, event segments, all traffic levels and DGAC surfaces.

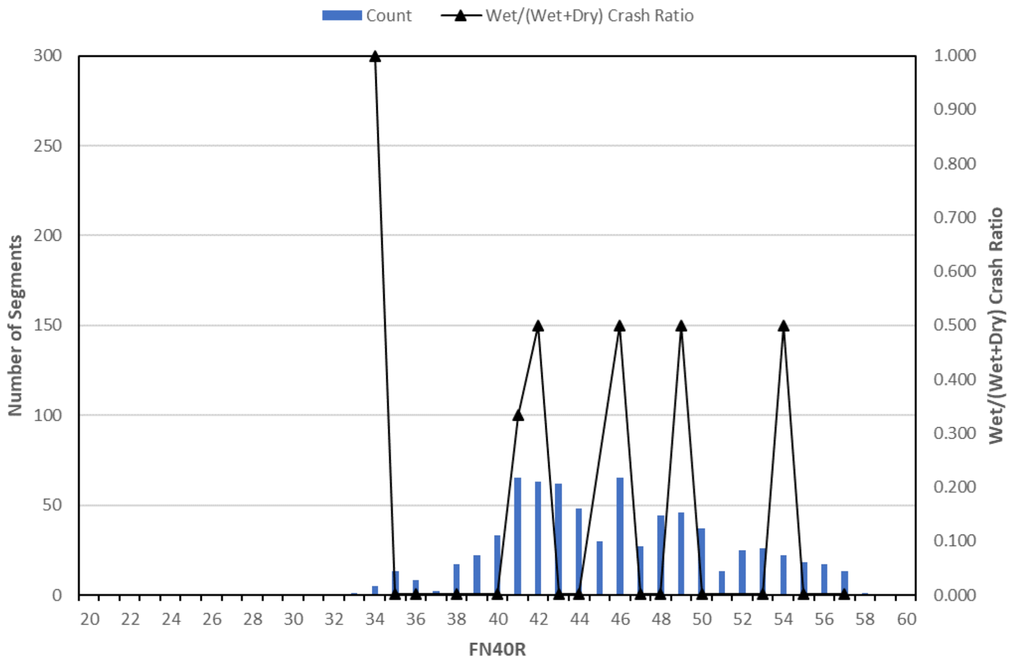


Figure 134. Graph. Friction number distribution and wet/(wet+dry) crash ratio for undivided primary, non-event segments, all traffic levels and DGAC surfaces.

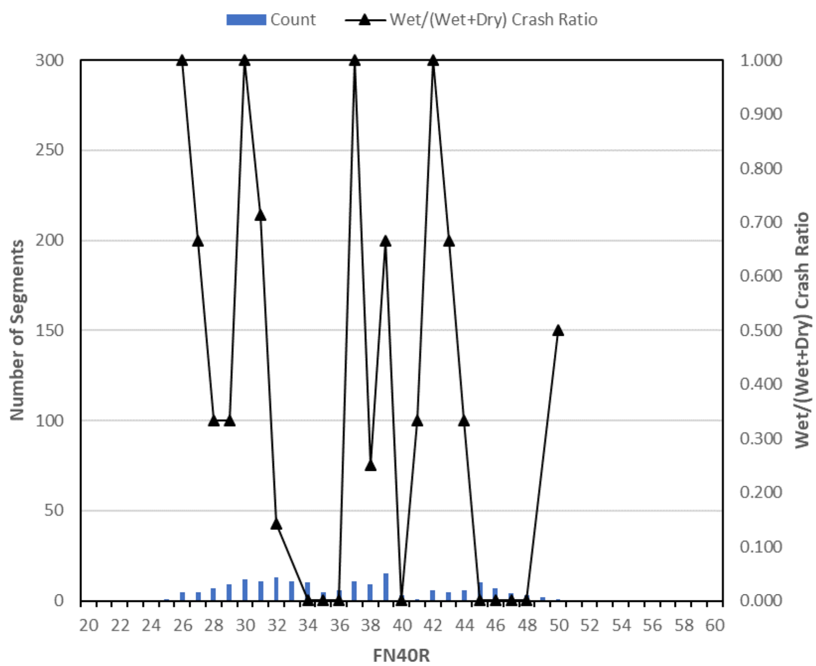


Figure 135. Graph. Friction number distribution and wet/(wet+dry) crash ratio for interstate, event segments, low traffic (AADT < 15,000) and PFC surfaces.

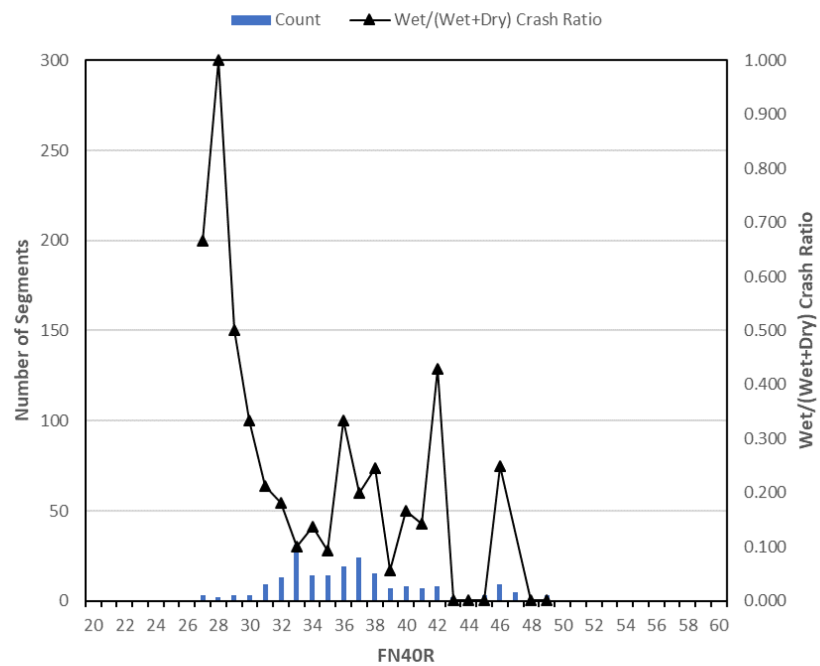


Figure 136. Graph. Friction number distribution and wet/(wet+dry) crash ratio for interstate, event segments, high traffic (AADT > 15,000) and PFC surfaces.

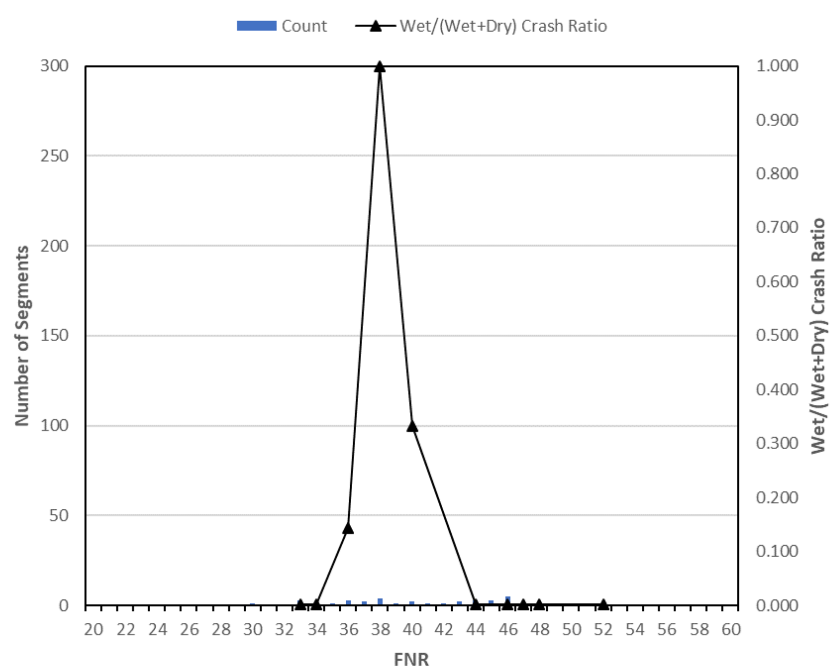


Figure 137. Graph. Friction number distribution and wet/(wet+dry) crash ratio for interstate, event segments, low traffic (AADT < 15,000) and PCC surfaces.

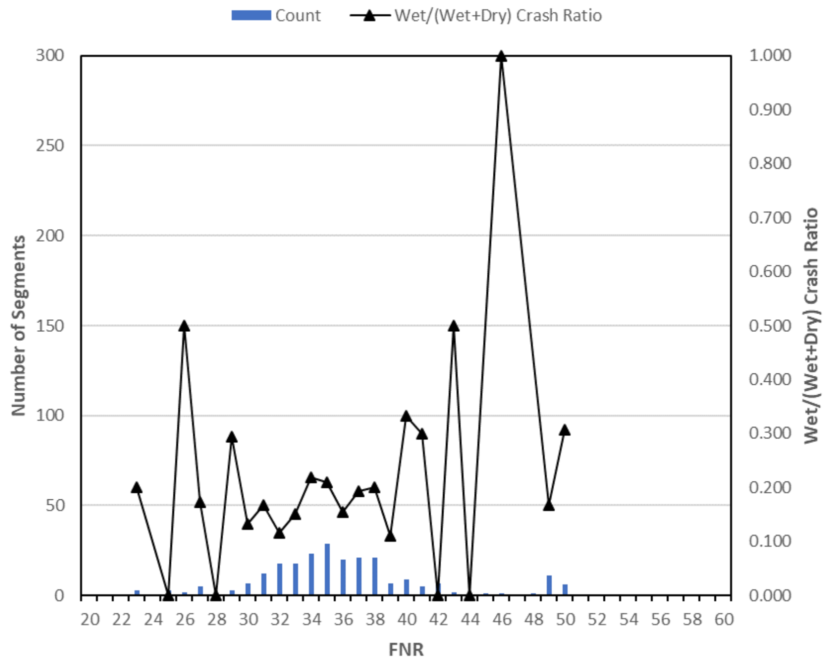


Figure 138. Graph. Friction number distribution and wet/(wet+dry) crash ratio for interstate, event segments, high traffic (AADT > 15,000) and PCC surfaces.

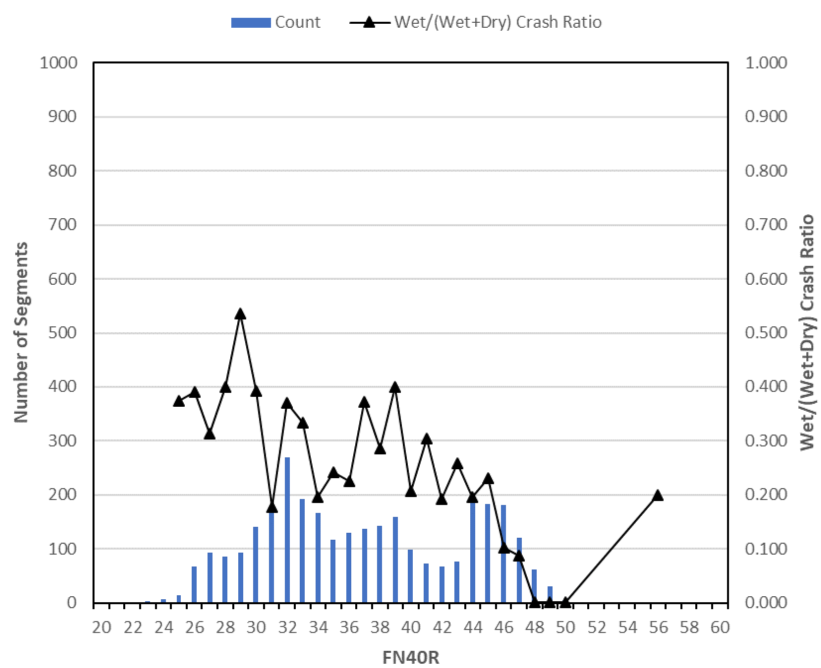


Figure 139. Graph. Friction number distribution and wet/(wet+dry) crash ratio for interstate, non-event segments, low traffic (AADT < 15,000) and PFC surfaces.

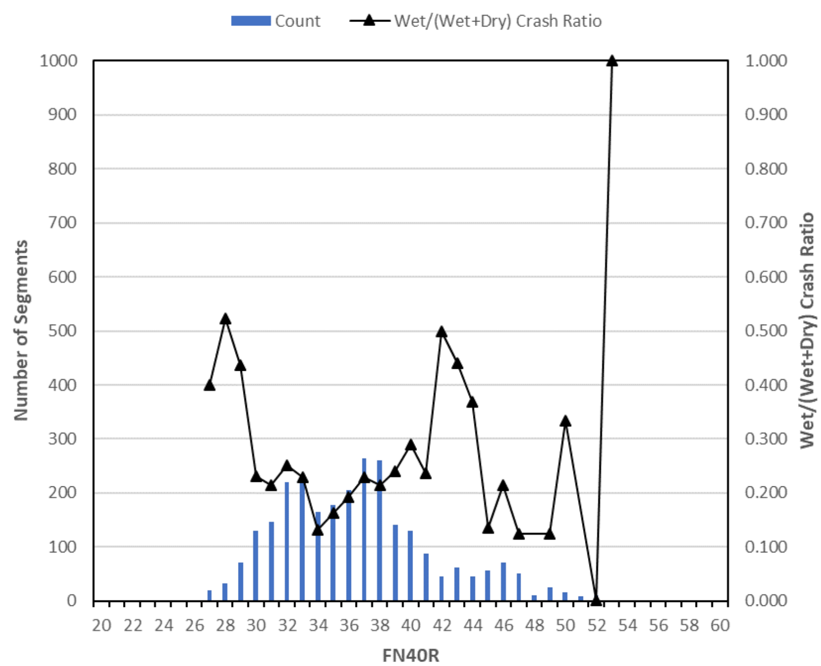


Figure 140. Graph. Friction number distribution and wet/(wet+dry) crash ratio for interstate, non-event segments, high traffic (AADT > 15,000) and PFC surfaces.

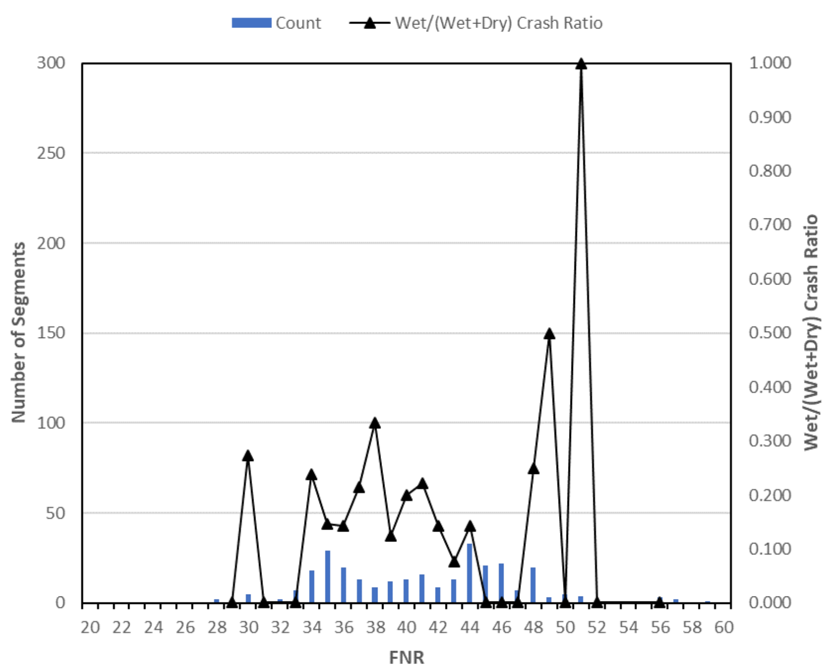


Figure 141. Graph. Friction number distribution and wet/(wet+dry) crash ratio for interstate, non-event segments, low traffic (AADT < 15,000) and PCC surfaces.

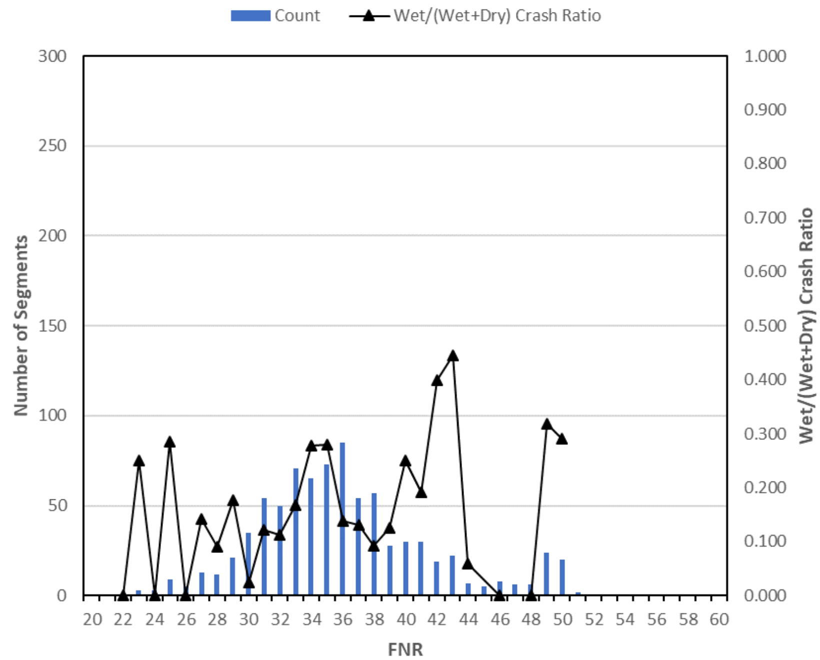


Figure 142. Graph. Friction number distribution and wet/(wet+dry) crash ratio for interstate, non-event segments, high traffic (AADT > 15,000) and PCC surfaces.

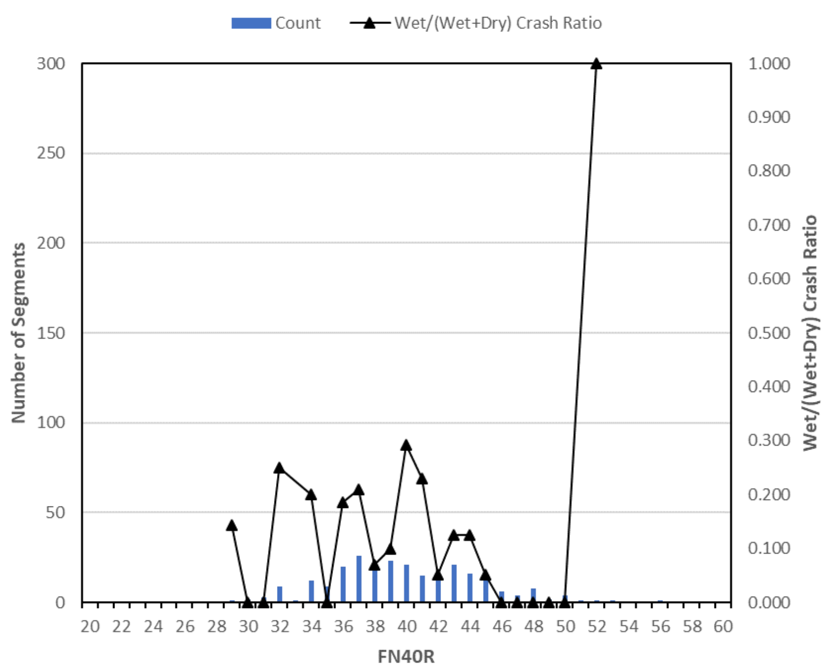


Figure 143. Graph. Friction number distribution and wet/(wet+dry) crash ratio for divided primary, event segments, low traffic (AADT < 15,000) and DGAC surfaces.

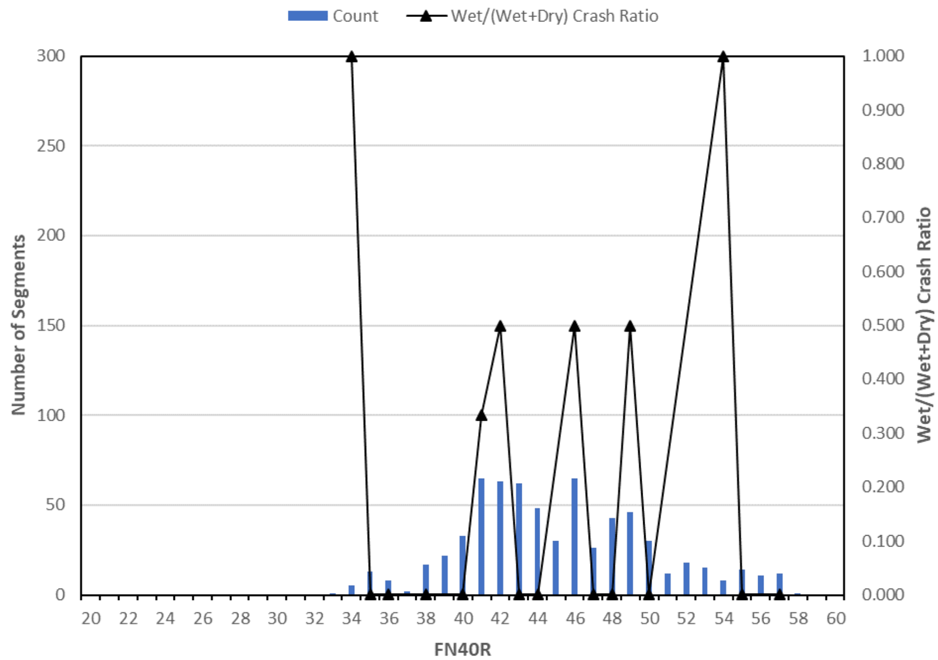


Figure 144. Graph. Friction number distribution and wet/(wet+dry) crash ratio for undivided primary, non-event segments, low traffic (AADT < 15,000) and DGAC surfaces.

REFERENCES

American Association of State Highway and Transportation Officials. (2008). *Guide for Pavement Friction*, Publication Code GPVF-1, Washington, DC.

American Association of State Highway and Transportation Officials. (2010). *Highway Safety Manual*, First Edition, Volumes 1-3, *Highway Safety Manual with Supplement 201*, Washington, DC.

American Association of State Highway and Transportation Officials. (2011). *A Policy on Geometric Design of Highways and Streets*, Washington, DC.

Akaike, H. (1978). "A Bayesian Analysis of the Minimum AIC Procedure." In E. Parzen, K. Tanabe, & G. Kitagawa (Eds.), *Selected Papers of Hirotugu Akaike*, pp. 275-280, Springer, New York. doi:10.1007/978-1-4612-1694-0

Blincoe, L. J., Miller, T. R., Zaloshnja, E., and Lawrence, B. A. (2015, May). *The Economic and Societal Impact of Motor Vehicle Crashes, 2010* (Revised), Report No. DOT HS 812 013, National Highway Traffic Safety Administration, Washington, DC.

Boyd, S. (2017) "Constrained Least Squares." Available online: https://stanford.edu/class/ee103/lectures/constrained-least-squares_slides.pdf, retrieved January 30, 2018.

Bray, J. S. (2003). "Skid Accident Reduction Program (SKARP): Targeted Crash Reductions." Presented at Institute of Transportation Engineers Technical Conference and Exhibit, Fort Lauderdale, FL.

de León Izeppi, E., Flintsch, G., and McCarthy, R. (2017). *Evaluation of Methods for Pavement Surface Friction Testing on Non-Tangent, Roadways and Segments*, Report No. FHWA/NC/2017-02, North Carolina Department of Transportation, Raleigh, NC.

de León Izeppi, E., Katicha, S., Flintsch, G., McCarthy, R., and McGhee, K. (2019). *Locked-wheel and Sideway-force Continuous Friction Measurement (CFME) Comparison and Evaluation Report*, Report Project No. FHWA-RC-19-001, Federal Highway Administration Pavement Friction Management (PFM) Support Program, Washington, DC.

Federal Highway Administration. (2005). *Surface Texture for Asphalt and Concrete Pavements*, Technical Advisory T 5040.36, Washington, DC.

Federal Highway Administration. (2010). *Pavement Friction Management*, Technical Advisory T 5040.38, Washington, DC.

Glennon, J. C. (1996). *Roadway Defects and Tort Liability*, Lawyers & Judges Publishing Company, Inc., Tucson, AZ.

Golembiewski, G. A., and Chandler, B. (2011). *Roadway Safety Information Analysis: A Manual for Local Rural Road Owners*, Federal Highway Administration, Washington, DC.

Hall, J. W., Smith, K. L., Titus-Glover, L, Wambold, J. C., Yager, T. J., and Rado, Z. (2009). *Guide for Pavement Friction*, Web-Only Document 108, National Cooperative Highway Research Program (NCHRP), Washington, DC. Available online: http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w108.pdf, retrieved July 26, 2016.

Harmon, T., Bahar, G., and Gross, F. (2018). *Crash Costs for Highway Safety Analysis*, Report No. FHWA-SA-17-071, Federal Highway Administration Office of Safety, Washington, DC.

Henry, J. J. (2000). *Evaluation of Pavement Friction Characteristics*, Transportation Research Board, Washington, DC. Available online: https://trid.trb.org/view.aspx?id=675639, retrieved August 5, 2016.

Herbel, S., Laing, L., and McGovern, C. (2010). *Highway Safety Improvement (HSIP) Manual*, FHWA-SA-09-029, Federal Highway Administration, Office of Safety, Washington, DC.

Highways England. (2020). *Design Manual for Roads and Bridges*, Volume 7, Section 3, *CS 228, Revision 1, Pavement, Inspection and assessment. Skidding Resistance* (formerly HD 28/15 – Withdrawn). Crown, United Kingdom.

Kummer, H. W., and Meyer, W. E. (1967). *NCHRP Report 37 Tentative Skid-Resistance Requirements for Main Rural Highways*, Transportation Research Board (TRB), Washington, DC.

Kuttesch, J. S. (2004). *Quantifying the Relationship between Skid Resistance and Wet Weather Accidents for Virginia Data*, Master of Science (MS) Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Larson, R. M., Hoerner, T. E., Smith, K. D., and Wolters, A. S. (2008). *Relationship Between Skid Resistance Numbers Measured with Ribbed and Smooth Tire and Wet Accident Locations*, Report No. FHWA/OH-2008/11, Ohio Department of Transportation, Columbus, OH.

Lord, D., and Mannering, F. (2010). "The Statistical Analysis of Crash-Frequency Data: A Review and Assessment of Methodological Alternatives." *Transportation Research Part A: Policy and Practice*, *44*, pp. 291-305. doi:10.1016/j.tra.2010.02.001.

Najafi, S., Flintsch, G. W., and Medina, A. (2017). "Linking Roadway Crashes and Tire–Pavement Friction: A Case Study," Technical Note, *International Journal of Pavement Engineering*, *18*(2), pp. 119-127. doi:10.1080/10298436.2015.1039005.

National Center for Statistics and Analysis. (2018, October). *2017 Fatal Motor Vehicle Crashes: Overview*, Traffic Safety Facts Research Note, Report No. DOT HS 812 603, National Highway Traffic Safety Administration, Washington, DC.

National Highway Traffic Safety Administration. (2019). *Traffic Safety Facts 2017 A Compilation of Motor Vehicle Crash Data*, DOT HS 812 806, Washington, DC.

New Zealand Transport Agency. (2013). S*kid Resistance Investigation and Treatment Selection, T10 Specification*. Available online: https://www.nzta.govt.nz/resources/skid-resistance-investigation-treatment-selection.

Owen, M. (2014). "An Overview of NZ History with Skid Resistance on the Highway Network." Presented at the 4th International Safer Roads Conference, Cheltenham, UK.

Pratt, M., Geedipally, S., Pike, A., Carlson, P., Celoza, A., and Lord, D. (2014). *Evaluating the Need for Surface Treatments to Reduce Crash Frequency on Horizontal Curves*, Report No. FHWA/TX-14/0-6714-1, Austin, Texas.

Reddy, V., Datta, T., Savolainen, P., and Pinapaka, S. (2008). *Evaluation of Innovative Safety Treatments: A Study of the Effectiveness of Tyregrip High Friction Surface Treatment*, Florida Department of Transportation, Tallahassee, FL.

Rogers, M. P., and Gargett, T. (1991). "A Skidding Resistance Standard for the National Road Network." *Highways and Transportation, 38*, No. 4, pp. 10-16.

Smith, K. L., Larson, R. L., Flintsch, G., and de León Izeppi, E. (2011). *Development and Demonstration of Pavement Friction Management Programs: Theoretical Relationships of Vehicle-Tire-Pavement Interactions and Skid Crashes*, Federal Highway Administration, Washington, DC.

Srinivasan, R., and Bauer, K. (2013). *Safety Performance Function Development Guide: Developing Jurisdiction-Specific SPFs*, FHWA-SA-14-005, Highway Safety Research Center and the Federal Highway Administration, Washington, DC.

Stevenson, A., Premathilaka, A., and Donbavand, J. (2011). "Asset Management & SCRIM: A Targeted Approach to the Management of Skidding Resistance." Presented at the 3rd International Safer Roads Conference, Gold Coast, Australia.

Treat, J. R., Tumbas, N. S., McDonald, S. T., Dhinar, D., Hume, R. D., Mayer, R. E., Stansifer, R. L., and Castellan, N. J. (1979). *Tri-level Study of the Causes of Traffic Crashes: Final Report—Executive Summary*, Report No. DOT-HS-034-3-535-79-TAC(S), Institute for Research in Public Safety, Bloomington, IN.

U.S. Department of Transportation and the National Highway Traffic Safety Administration. (2015). *Traffic Safety Facts: Summary of Motor Vehicle Crashes (Early Edition)*, Washington, DC. Available online: https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812376, retrieved April 6, 2017.

U.S. Department of Transportation. (2015, June 17). *Guidance on Treatment of the Economic Value of a Statistical Life (VSL) in U.S. Department of Transportation Analysis - 2015 Adjustment*, Washington, DC. Available online:

https://www.transportation.gov/regulations/economic-values-used-in-analysis, retrieved December 9, 2016.

Viner, H. E., Sinhal, R., and Parry, A. R. (2005). "Linking Road Traffic Accidents with Skid Resistance – Recent UK Developments." Presented at International Conference for Surface Friction for Roads and Runways, Christchurch, New Zealand.

Von Quintus, H., and Mergenmeier, A. (2015). *Case Study: Kentucky Transportation Cabinet's High Friction Surface Treatment and Field Installation Program*, Report No. FHWA-SA-15-038, Federal Highway Administration, Washington, DC.

Wu, Y., Parker, F., and Kandhal, K. (2014). *Aggregate Toughness/Abrasion Resistance and Durability/Soundness Tests Related to Asphalt Concrete Performance in Pavements*, NCAT Report 98-04, National Center for Asphalt Technology (NCAT), Auburn, Alabama.