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Pavement Friction Management Program Demonstration

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Abstract:

A pavement friction management program (PFMP) should involve both equipment to collect friction and other relevant data as well as processes to analyze friction and crash data to determine possible friction enhancement treatments on sections that warrant it. This project built on previous experience with PFMPs to (1) propose an enhanced methodology for systematically screening a highway network and identifying sections that may warrant a detailed safety investigation and (2) demonstrate that methodology on the Corridors of Statewide Significance (CoSS) in Virginia.

This project evaluated 7,000 miles of highway in Virginia. The demonstration collected friction, macrotexture, and geometric data; processed and filtered the data; and conducted a systemic analysis of the network. The analysis investigated the relationship between crashes and friction and other roadway properties, and developed Safety Performance Functions (SPFs) to quantify this relationship. The SPFs were then used in empirical Bayes analyses to estimate crash counts before and after friction enhancement treatment and identify sections with friction deficiencies that may benefit from them.

The network-level screening identified 1,709 0.1-mile sections of roadway that can benefit from a friction enhancement treatment and thus may require a detailed safety investigation. The application of the selected friction enhancement treatment to the sections could result in a reduction of up 12,949 crashes (approximately 20% of crashes observed over 3 years) in the network analyzed. The friction enhancement treatments would cost about $42 million but could generate potential economic savings over $1.75 billion.

The network-level assessment of the CoSS demonstrated the benefits and practicality of adopting a proactive, systemic pavement friction management approach to screen for sections that may benefit from friction enhancement treatment and warrant a detailed section investigation. The results of the demonstration suggest that the statewide adoption of the methodology can help reduce a significant number of crashes and associated fatalities and injuries.

The project surveyed a significant portion of the CoSS, screened the network, and identified many sections in which friction enhancement treatment could result in high potential return on investment. Each district can utilize the data collected in the project to target their detailed safety analyses and design safety improvement projects with collaboration from the Traffic Engineering, Maintenance, and Materials Divisions.

FINAL REPORT

PAVEMENT FRICTION MANAGEMENT PROGRAM DEMONSTRATION

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Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

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VTRC 22-R14

DISCLAIMER

ABSTRACT

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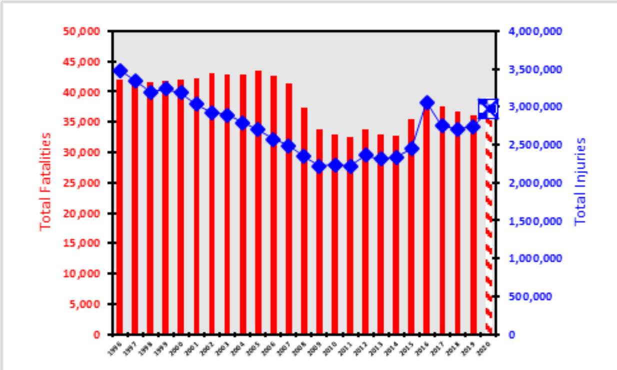
INTRODUCTION

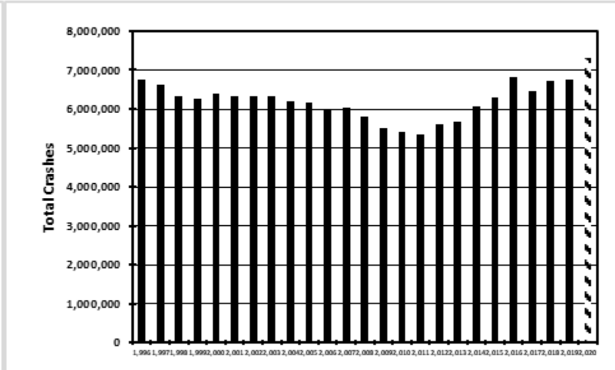
Background

FHWA Technical Advisory T 5040.38—*Pavement Friction Management* (FHWA, 2010) provides technical information and guidelines for implementing a pavement friction management program (PFMP) that 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 reflects the new approach to more substantive safety analysis using a systemic approach rather than concentrating on crash concentration spots (FHWA, 1980).

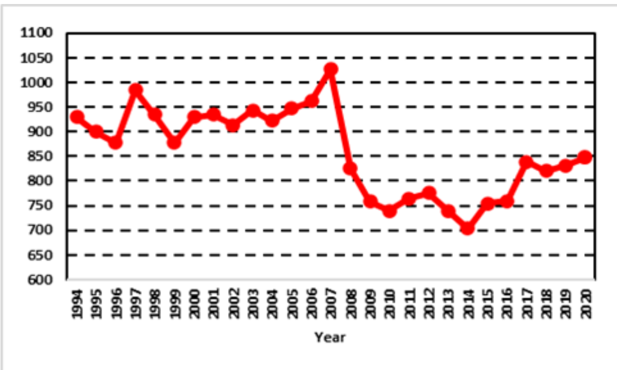
A study made in 2010 by the National Highway Traffic Safety Administration (NHTSA) found that about 6 million yearly crashes in the United States cost more than $747 billion (Blincoe et al., 2015). Figure 1a and Figure 1b summarize the total crashes and resulting fatalities in the United States between 1996 and 2020 (NSC, 2020; NHTSA, 2020). Notice that there has been a sustained increase in both since 2011 to unprecedented numbers of total crashes in 2020 (more than 7 million). Additionally, the numbers of fatalities and injuries are equal to those before 2008 and 2002, respectively. In Virginia, the decreasing trend reversed after 2014 and has been flat until the decisively unusual increase in 2020, as can be seen in Figure 1c and Figure 1d (Virginia DMV, 2021).



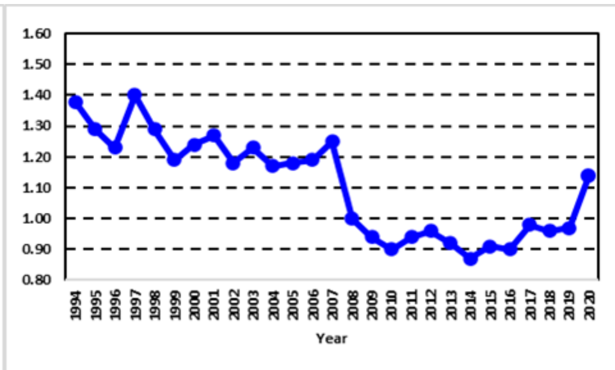
(a) US total fatalities/injuries (2020 est.)



(b) US total crashes (2020 est.)



(c) Virginia total fatalities



(d) Virginia fatality rate per 100 MVMT

Figure 1. Number of (a) Fatalities and Injuries, (b) Crashes in the United States, 1996–2020 (NSC and NHTSA, 2020), (c) Fatalities in Virginia, and (d) Fatality Rate in Virginia, 1994-2020 (VA DMV, 2021)

Proactive friction management is one way to reduce the number of crashes and associated fatalities. Virginia Transportation Research Council (VTRC) Report 16-R8 examined the use of continuous friction measurement equipment (CFME) as a network management tool to help predict crashes using pavement friction (de León et al., 2016). This project developed a friction inventory for VDOT's Salem District using a Grip Tester, a low-cost CFME. The CFME data were coupled with radius of curvature (when available) and crash records to develop Safety Performance Function (SPF) models to predict crash counts.

The enhanced crash count predictive functions were combined with crash cost estimates to produce network-level economic trade-off analyses that could help manage pavement friction. The results predicted significant potential crash reductions with potential comprehensive (total societal) economic savings of $100 million or more. These results suggested that the returns on investment would easily justify proactive state-level friction management using CFME. The findings also indicated the need for further enhancement of crash count predictions by considering the effects of other pavement-related characteristics, such as macrotexture, grade, and cross-slope (superelevation).

These results were consistent with previous studies that suggested that average annual daily traffic (AADT), shoulder width and speed limit, "as well as roadway geometry (curvature and cross-slope) and pavement condition (skid resistance and roughness) are significantly related to roadway departure (RD) crashes" (Appiah and Zhao, 2020). Another recent report developed a systemic safety improvement plan for RD crashes on two-lane rural roads in Virginia (Cho et al., 2020). These reports suggest that using pavement friction data could improve safety improvement plans in Virginia.

Implementing Pavement Friction Management Programs

Published in 2008, the AASHTO *Guide for Pavement Friction* (GPF) contains guidelines and recommendations for managing and designing for friction on highway pavements (AASHTO, 2008). 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), and
- Suggests 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 current GPF recommends that highway agencies develop a comprehensive PFMP consisting of five key components: (a) network definition, (b) network-level data collection, (c) network-level data analysis, (d) detailed section investigation, and (e) 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.

Critical aspects of a PFMP include (a) the equipment used to collect friction data, (b) 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 (c) the cost-effectiveness comparison of different possible friction enhancement treatments on sections that warrant it.

Although the GPF does not emphasize the use of CFME, these systems have several advantages: (a) CFMEs provide high spatial coverage, thus reducing the chances of missing localized areas with friction deficiencies; and (b) modern CFMEs also provide other data needed for a proactive network-level PFMP, especially when using safety analyses methods, for screening to identify locations with potential for safety improvement. The AASHTOware Safety software allows for the creation of risk models using SPFs with empirical Bayes (SPF-EB) methods (AASHTO, 2021). More details on this topic and other theoretical considerations can be obtained from the FHWA report (de Leon et al., 2019). Figure 2 presents a flowchart that an agency can use to develop a comprehensive PFMP.

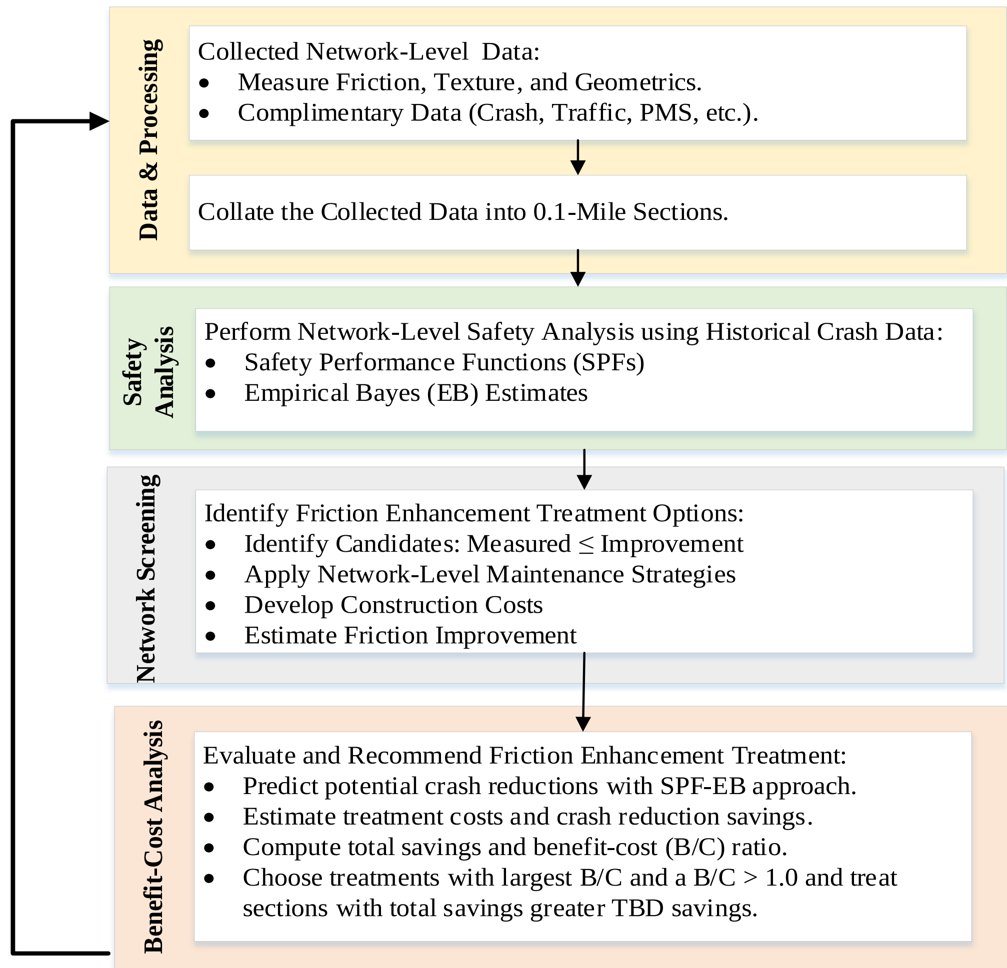


Figure 2. Proposed Pavement Friction Management Program Flowchart (FHWA, 2019)

Modern PFMPs require that adequate levels of friction be maintained on all roadway sections based on the friction demand needed for the different types of roadway sections so that vehicles do not lose control. If this approach is used, different friction investigatory levels can be set based on road types (interstate, primaries, etc.) or the geometry of the roadway section (intersection, curve, grade, etc.). When friction thresholds are not met, a detailed section investigation can be performed to verify if an increase in the friction level is warranted to reduce the crash risk (e.g., of roadway departure fatal and serious injury crashes).

A 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 coordination of safety and pavement management planning and implementation to supplement and complement the traditional crash concentration-spot section analysis. It helps agencies broaden their traffic safety efforts and consider risk as well as crash history when identifying where to make safety improvements following the Safe System approach and principles. The Safe System approach looks to improve road safety through shared responsibility and redundancy to reduce crashes or outcomes since people make mistakes and are vulnerable to kinetic energy changes (Finkel et al, 2020).

Friction Demand

Friction demand is the level of friction (micro- and macrotexture) needed to safely perform braking, steering, and acceleration maneuvers. The goal is for the pavement surface friction supply to always meet or exceed friction demand. 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. The number of friction demand categories should be kept reasonably small so that enough pavement friction sections are available to perform a statistical regression analysis.

Larson et al. (2008) reviewed studies that investigated the relationship between pavement friction based on locked-wheel friction testing data and highway skid crashes. The report found varied levels of success largely determined by the unique set of roadway circumstances and unique data collection and analysis practices of individual highway agencies. However, many studies have shown that, in general, crash risk is higher for sections with lower friction (de León et al., 2019; Bray, 2003; Kuttesch, 2004; Viner et al., 2005; Reddy et al., 2008).

Since most devices used to measure highway friction in the United States do not 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 overall crashes where the impact of reducing crashes can have significant influence (Viner et al., 2005). PFMs are already in place and friction demand categories have been established in many countries. For example, Table 1 shows the standard currently used in the United Kingdom (with text edits to adapt them to U.S. terminology and customary units).

Table 1. Recommended Friction Demand Categories in the United Kingdom (Highways England, 2020)

Site category and definition		Investigatory Level for Friction at 30mph (50 km/h)							
		0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
A	Motorway								
B	Non-event divided roadways								
C	Non-event two lane divided roadways								
Q	Approaches to and across minor and major intersections (and roundabouts)								
K	Approaches to pedestrian crossings and other high-risk areas								
R	Roundabouts								
G1	Slope 5-10% longer than 160 ft								
G2	Slope >10% longer than 160 ft								
S1	Curves with radius < 1600 ft – divided roadways								
S2	Curves with radius < 1600 ft – two lane roadways								

Note: 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.

The friction demand categorical levels coupled with macrotexture (mean profile depth [MPD], ASTM E1845) levels will lead to important pavement design decisions for the roadway classification, vehicle traffic volumes, surface mix type, and speeds. In North Carolina, a 2017 study recommended minimum macrotexture values of MPD of 0.80 mm on pavements with speeds between 50 and 70 mph and MPD of 1.0 mm for speeds higher than 70 mph (de Leon Izeppi et al., 2017).

In the United Kingdom, *The Specifications for Highway Works for Bituminous Materials (Series 900)*, Clause 921, establishes initial surface macrotexture for bituminous surface courses and specifies that it shall be measured using the volumetric sand patch method (British Standards EN 13036-1). Table 2 provides the initial macrotexture requirements for various road and surfacing types in the UK.

Table 2. Initial Texture Depth Requirements for Trunk Roads Including Motorways (Highways England, 2019)

Road type	Surfacing type	Average/1,000 m	Average/10 measures
High speed roads >50 mph	Thin surface overlay Aggregate size < 14mm	MPD 1.4 mm	MPD 1.0 mm
	Surface treatments	MPD 1.6 mm	MPD 1.25 mm
Lower speed roads <40 mph	Thin surface overlay Aggregate size <14 mm	MPD 1.4 mm	MPD 0.9 mm
	Surface treatments	MPD 1.25 mm	MPD 1.0 mm
Roundabout, high speed >50 mph	All surfaces	MPD 1.25 mm	MPD 1.0 mm
Roundabout, low speed <40 mph	All surfaces	MPD 1.0 mm	MPD 0.9 mm

Note: The values in the following table have been converted to MPD using the equation in ASTM E1845, where MPD = (ETD -0.2)/0.80. ETD is the estimated texture depth equivalent to the measurement obtained from the sand patch method.

Safety Needs for Virginia's Corridors of Statewide Significance

The Fixing America's Surface Transportation Act (FAST Act) directed the Federal Highway Administration (FHWA) to establish a National Highway Freight Network (NHFN) to improve the performance of highway portions of the U.S. freight transportation system and to prepare and submit a report that describes the conditions and performance of the NHFN. The NHFN includes the following subsystems of roadways: Primary Highway (37,436 miles of Interstate and 4,082 miles of non-Interstate), Other Interstate portions (9,843 miles), Critical Freight Corridors (4,412 miles), and Critical Urban Freight Corridors (2,213 miles) (FHWA, 2020).

The General Assembly of Virginia and the Office of Intermodal Planning and Investment (OIPI) directs the Commonwealth Transportation Board (CTB) to identify the needs of the Commonwealth's transportation system through VTrans, also known as the Statewide Transportation Plan, which is a long-range multimodal transportation plan that utilizes the NHFN concept to define what is known as the Corridors of Statewide Significance (CoSS) (Commonwealth's Office of Intermodal Planning and Investment, 2017[a]). To be considered as a CoSS, a corridor must meet four criteria: be multimodal; connect regions, states, and major activity centers; accommodate high volume; and offer a unique statewide function. As part of the VTrans effort, the CTB identified 11 CoSS in 2009 and one additional CoSS in 2011. The CoSS includes five interstate highways, six U.S. highways, and one Virginia state highway.

The VTrans Multimodal Transportation Plan (VMTP) directs the CTB to perform a data-driven analysis called the Needs Assessment that identifies the transportation needs of each CoSS based on four performance metrics: redundancy and mode choice, congestion and bottlenecks, reliability, and safety (Commonwealth's Office of Intermodal Planning and Investment, 2017[b]). To define mid-term safety needs for project planning, the safety performance of the roadway network, including the CoSS subset, is evaluated using the crash analysis methodology described in the *Highway Safety Manual* (HSM) with data provided by the Virginia Department of Transportation (VDOT) Traffic Engineering Division (AASHTO, 2010). The

HSM methods model crash outcomes with traffic volumes and data on roadway and roadside characteristics.

Current applications of the analysis methodology have not considered important characteristics of the pavement surface that can impact the crash risk and therefore the safety performance of the corridors. Further, there has been little to correlate and coordinate pavement performance management and planning to safety performance planning and related crash outcomes and severity.

A pavement friction management program (PFMP) is one of the tools available for conducting a systemic, data-based screening of the VDOT network to identify areas where pavement friction deficiencies may be contributing to crashes and may need a safety intervention. The pilot study from Salem District (de León et al., 2016) found significant potential returns on investment to justify statewide pavement friction management (PFM) that incorporates continuous friction measurement equipment (CFME) enhanced with other roadway pavement-related characteristics, such as macrotexture, grade, and cross-slope (superelevation).

PURPOSE AND SCOPE

The objective of this research is to continue the development and implementation of a systemic, data-driven PFMP for VDOT. The study explores the use of other important pavement characteristics, proposes improvements to the methodology used in the Salem pilot, and expands the application to CoSS.

To accomplish the objective, the research team: (a) proposed step-by-step guidance for VDOT staff on how to collect, compile, and analyze friction, macrotexture, and geometric data to develop and implement a PFMP; (b) conducted CFME measurements (friction, macrotexture, and geometry) on the CoSS in Virginia; (c) collected comprehensive crash, classification, pavement type, and other data from VDOT; and (d) illustrated the use of the screening methodology as applied to one of the districts.

METHODS

Network Definition

Figure 3 features a geographic information system-based map of Virginia showing the measured network in black and the analyzed network in red. The measured network (black) has 7,000.2 miles of interstate and primary roadway. Of the measured network, 5,796.6 miles (82.8%) were considered for analysis (i.e., the surveyed network). After further processing (explained later), 3,830.4 miles (54.7%) of the measured network were analyzed (red).

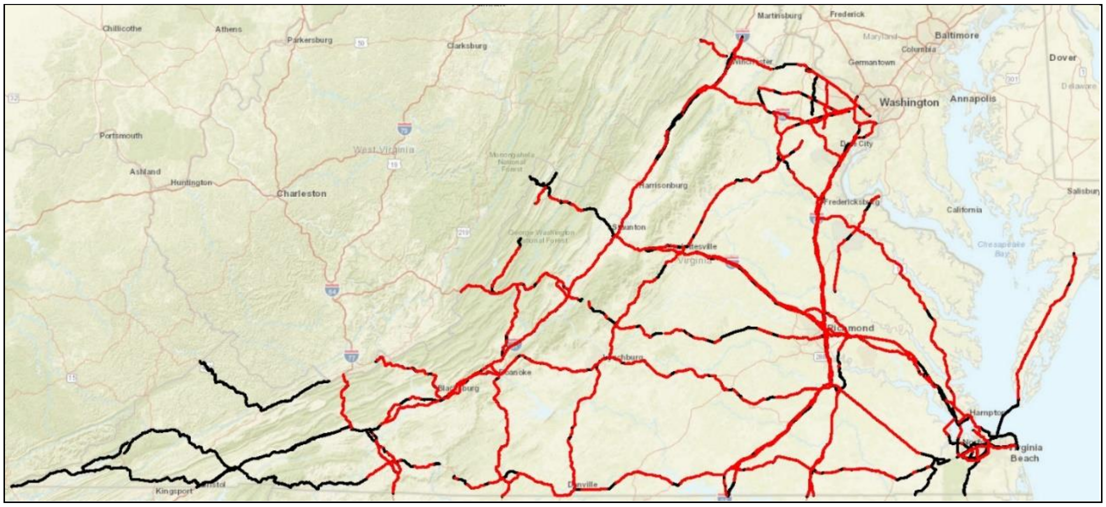


Figure 3. Measured (Black) and Analyzed (Red) Network

The total measured, surveyed, and analyzed mileage are separated by district in Table 3. In terms of analyzed mileage, the majority (23%) is in District 4.

Table 3. Total Miles Measured, Surveyed, and Analyzed by VDOT District

District		Test Date	Measured	Surveyed	Analyzed
1	Bristol	2019	892.2	62.3	47.0
2	Salem	2019	841.0	794.4	590.4
3	Lynchburg	2019	544.1	522.9	355.3
4	Richmond	2019	1,249.5	1,224.0	881.6
5	Hampton Roads	2019	1,245.7	1,172.7	626.6
6	Fredericksburg	2020	473.7	470.8	342.9
7	Culpeper	2020	470.7	413.8	254.9
8	Staunton	2020	737.2	664.4	449.0
9	Northern Virginia	2018	546.0	471.3	282.7
Total		**-**	**7,000.2**	**5,796.6**	**3,830.4**

The size of the measured network was determined to be large enough to construct SPF models. The differences between the lengths of the measured, surveyed, and analyzed networks in Table 3 were influenced by GPS dropouts during measurement, construction observed during testing, and maintenance activities (resulting in significant surface changes) that occurred during the 3-year study period chosen for the crash and traffic data.

Data Collection

Pavement Surface Characteristics

The CFME device used in this project was the FHWA's SCRIM, which measures friction, macrotexture, grade (%), cross-slope (%), and horizontal curvature (1/m). This CFME measure of friction is called a Sideway-force Friction Number (SFN), or SFN40, since it is standardized at 40 mph. The CFME also measures the macrotexture (MPD), which is the average value of the mean of two 50-millimeter sub-segment depths of a 100-millimeter segment. Both measurements are averaged in 10-meter intervals for network-level processing. The averages, standard deviations, and histograms of all measurements are provided for District 4 in Results and for the remaining districts in the appendices.

Highway Data

Once the measured network was well-defined, the following information was collected from the district and VDOT statewide databases:

- Pavement surface mix (surface types and mixes, aggregate types and surface texturing used, and surface mix completion year)
- Highway location referencing information (mile-points [MPs] and GPS coordinates) using the iVision video logging system (District 4 data are from VirginiaRoads.org).
- Roadway type (Interstate/Primary and Divided/Undivided)
- Traffic volume (AADT)
- Controlled intersection and ramp access locations (GPS coordinates)

Crash Data

Three-year crash data, including crash location (GPS coordinates), surface condition (wet/dry), and weather condition (clear, rain, etc.), were downloaded from VirginiaRoads.org. The inputs used to classify and describe the crashes include (a) the location (route, direction, and MP) of each crash, (b) the reported surface condition (wet/dry), (c) weather condition when the surface condition is unknown, and (d) crash severity. The crash severity is the worst type of injury resulting from a crash, which is reported using the KABCO scale defined in the HSM as shown below (AASHTO, 2010).

- K – Fatality Injury
- A – Incapacitating Serious Injury
- B – Non-Incapacitating Evident Injury
- C – Possible Injury
- O– No Injury; Property Damage Only (PDO)

The 3-year crash period includes the year most recent to testing that has a complete crash record at the time of processing and the two consecutive years prior. To evaluate all the sections correctly, the crash data should only be used when there have been no major changes in pavement characteristics.

Data Processing

Table 4 lists the data that were collected for this project from two sources: VDOT and the CFME.

Table 4. Data Collected from the VDOT Database and with the Available CFME

VDOT	CFME
Location of MPs	Distance (m)
Crash Counts	Friction (SFN)
AADT	Macrotexture (MPD, in mm)
Divided or Undivided Roadway	Horizontal Curvature (1/m)
Locations of Intersections and Ramp Access Points	Cross-slope (%)
Pavement Surface Mix Classification	Grade (%)
Location and Date of Pavement Surface Changes	GPS Coordinates of Measurements
Number of Travel Lanes	

Note: AADT = average annual daily traffic; SNF = Sideway-force Friction Number; MPD = mean profile depth; GPS = Global Positioning System.

Filtering Measured Network

The measured network has approximately 7,000 miles. The 10-meter CFME data were filtered before being matched and paired with the VDOT data to create the surveyed network. Ten-meter sections were removed for invalid friction, macrotexture dropouts, or no GPS connectivity.

Data Matching and Pairing

The following process was used to create the database for the surveyed network. The data collected with the CFME were processed and paired with the data provided by VDOT to synchronized them according to the following steps:

1. The friction (SFN) measurements were determined by smoothing the friction profile using a moving three-point average and picking the minimum value in each 0.1-mile section. The rest of the data collected by the CFME were averaged over the 0.1-mile section.
2. GPS coordinates of the 10-meter measurements from the CFME were paired with the GPS coordinates of the VDOT MPs.
3. Both CFME and VDOT MPs and any remaining unpaired VDOT data were summarized into 0.1-mile roadway sections following the steps described in Table 5.

Filtering Surveyed Network

The surveyed network is about 5,800 miles. The surveyed network was filtered further to create the analyzed network. This process removed 10-meter measurements that could not be paired with an MP (i.e., outside the VDOT maintained network) or 0.1-mile sections that received a pavement surface change between the start of the 3-year period to the date the pavement characteristics were measured with the CFME.

Table 5. Steps for Summarizing Data into 0.1-Mile Roadway Sections

Data	Step for Processing
Crash Counts (3 Years)	1. Sum each crash injury severity level (KABCO scale) 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. Compute the natural log.
Divided Roadway *(Indicator Term)*	0 – No; 1 – Yes
Pavement Surface Mix (*Categorical Variable*)	DGAC (Reference), THMACO, SMA, MICRO, PCCP
Number of Travel Lanes	Reported value (database) or CFME survey video recording
Route Type *(Indicator Term)*	0 – Primary; 1 – Interstate
Controlled Intersections & Access to Ramps	0 – No; 1 – Yes
Macrotexture (MPD, in mm)	Compute the average MPD.
SFN40	1. Run a 3-point (30-m) moving average filter. 2. Take the minimum value.
Horizontal Curvature (1/m) & Cross-Slope (%)	1. Take the absolute values. 2. Compute the average from the absolute values.
Grade (%)	Compute the average.

DGAC = dense-graded asphalt concrete, THMACO = thin hot-mix asphalt overlay, SMA = stone matrix asphalt, MICRO = microsurfacing, PCCP = Portland cement concrete pavement.

Safety Analysis

A crash is defined in the HSM as a combination of events on a roadway that results in the collision of one or more motorized 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 probability (risk) for a crash. In general, most events combine to form a low level of risk, and for that 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). Of these factors, only roadway elements, condition, and applied technology can be administered by highway agencies through design, construction, and maintenance practices and policies for safety and pavement management. The interaction of the remaining three categories of factors is usually less controlled and results in random variation in the annual number of traffic crashes. The safety analysis in this report follows the methodology recommended by de Leon et al. (2016) and refined subsequently in de Leon et al. (2019).

Safety Performance Functions and Empirical Bayes Methodology

Crash counts are essential for evaluating highway safety, and they are reported as non-negative integers (*y*). The 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 and traffic characteristics. The NB model uses a Poisson-gamma distribution parameterized with the inverse link function shown in Equation 1a. The variance is parameterized as shown in Equation 1b (Lord and Mannering, 2010; Srinivasan and Bauer, 2013; Hauer et al., 2002).

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

$$V[y_i] = \lambda_i + \alpha \times \lambda_i^2 \quad \text{Eq. 1b}$$

where $E[y_i] = \lambda_i$ = Expected number of crashes for section *i*.
$V[y_i]$ = Variance of the expected 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*.
α = SPF overdispersion parameter.

Srinivasan and Bauer (2013) recommend the use of the NB model to generate SPFs in highway safety management practice as a network-level screening process to identify sections that have elevated crashes and to assess the potential benefits of friction enhancement (or other infrastructure) treatment. The SPFs predict the expected number of crashes per year on a road section as a function of AADT and other additional roadway characteristics specified by an agency (Hauer et al., 2002).

The SPFs (one per district) developed in this study are used to predict the expected number of crashes over a 3-year period. Each model was developed using statistical software that selected predictors based on a forward-backward stepwise approach. All the predictors considered in the study are listed in Table 6, which includes 11 independent variables and 9 interaction terms. The interaction terms are created to determine the combined impact of SFN40 and the other variables on crash risk.

Table 6. SPF Model Predictors

Independent Variables	Interaction Terms
1. ln(AADT)	1. SFN40 × Route Type
2. Friction (SFN40)	2. SFN40 × MPD
3. Texture (MPD, in mm)	3. SFN40 × Grade (%)
4. Grade (%)	4. SFN40 × Cross-slope (%)
5. Cross-slope (%)	5. SFN40 × Curvature (1/m)
6. Horizontal curvature (1/m)	6. SFN40 × Intersections/Ramp Access
7. Divided Roadway	7. SFN40 × Divided Roadway
8. Controlled Intersections & Ramp Access	8. SFN40 × Pavement Surface Mix
9. Route Type	9. SFN40 × Number of Travel Lanes
10. Pavement Surface Mix	
11. Number of Travel Lanes	

The EB method is used to produce a more reliable estimate of the "expected" number of crashes and corrects for the occurrence of regression-to-the-mean (RTM) (Srinivasan and Bauer 2013; Hauer et. al., 2002). RTM describes a situation in which crashes are artificially high (or low) without any improvement or change in the road and can happen randomly in any one year. The EB method combines the observed crash count (*y*) and the SPF prediction into a weighted average using the function in Equation 2a. The weighted term (W) in Equation 2b varies depending on the size of the overdispersion parameter (α). A large overdispersion could 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 overdispersion is small, then W will be larger and the resulting EB estimate will be closer to the SPF (Srinivasan and Bauer, 2013).

$$\mathrm{EB}_i = \mathrm{W}_i \times \lambda_i + (1 - \mathrm{W}_i) \times \mathrm{y}_i \qquad \text{Eq. 2a}$$

$$\mathrm{W}_i = \frac{1}{1+\lambda_i \times \alpha} \qquad \text{Eq. 2b}$$

where W_i = Weight term for road section *i*.
λ_i = Predicted number of crashes per year for road section *i*.
α = Overdispersion parameter for the SPF.
EB_i = EB estimate for road section *i*.
y_i = Observed crash count for road section *i*.

Selection and Prioritization of Short- and Long-term Restoration Treatments

Cost-benefit analysis can be used to identify sections with a high expected number of crashes that could potentially benefit from friction enhancement or other pavement treatments. Roadway sections identified in this analysis should be followed with a detailed crash, pavement, and roadway characteristic site investigation to determine feasible treatments. This section provides the details to understand the cost-benefit analysis that was performed for the analyzed network. Although the method focuses on improving friction, the procedure should consider and could also apply to surface macrotexture. Note that the methodology is illustrated for District 4

(Richmond); the friction enhancement treatments, parameters, and results for the other districts can be found in the appendices.

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 estimate the potential effectiveness of various friction enhancement treatments (i.e., expected crash count reduction). The economic analysis will evaluate the costs and benefits of implementing friction enhancement treatments in any section.

Step 1: Compute the expected crashes for each 0.1-mile section (untreated).

The estimated expected number of crashes for each 0.1-mile section prior to friction enhancement treatment is computed using the SPF predicted values with the EB method using Equation 2. This would be the number of crashes that can be expected to occur over the next 3 years if no friction enhancement treatment is applied to the section. Therefore, the modeling assumption is that the pavement friction is the same as the measured value.

Step 2: Compute the number of treated (estimated) crashes for each 0.1-mile section.

For each pavement surface mix in the analyzed network, an expected friction value was determined considering a replacement of the current pavement surface. The research team used friction values expected for a new pavement treatment as the mean values of friction for each pavement type plus one standard deviation, as can be seen in Table 7. However, not all the treatments are used in each district.

The lack of sensitivity of the CFME tire to the macrotexture of the pavements measured is reflected by the lower values of friction obtained on SMA pavements. These lower values are caused by the higher porosity found in these pavement types, which causes loss of contact area between the pavement and the tire. Other pavements where this occurs include any porous asphalt pavement or grooved concrete pavements. This has been cited in studies by other researchers measuring friction with locked-wheel skid testers equipped with ribbed tires (Wambold et al., 1986).

Table 7. Estimated Average Friction Values (SFN40) for New Friction Enhancment Treatments in District 4

Current Surface	Surveyed SFN40 Mean	Surveyed SFN40 Standard Deviation (SD)	SFN40 Enhancement (Mean + 1.0 SD)
DGAC	52.8	7.0	60
SMA	47.3	6.1	55
MICRO	55.5	7.0	65
PCCP	52.2	8.7	60 (w/CDG)
HFST	—	—	80

Notes: DGAC is dense-graded asphalt concrete. SMA is stone-matrix asphalt. MICRO is microsurfacing. PCCP CDG is Portland cement concrete pavement with a conventional diamond grind finish. The average friction values assigned are based on all PCCP sections on the surveyed network. Not all PCCP values included in the computation had CDG at the time when measured. HFST is high-friction surface treatment. The average friction value for an HFST treatment is based on measurements in several states.

Using the friction values for each pavement type, the potential (estimated) number of crashes is computed using calibrated SPF and EB values directly related to the new friction value (SFN40) obtained for the treatment applied in that section. For this study, it was also agreed that the analysis would consider the outcome using an HFST treatment. The calibrated EB is calculated using Equation 3.

$$\mathrm{EB}_{\mathrm{Treated},i} = \frac{\mathrm{SPF}_{\mathrm{Treated},i}}{\mathrm{SPF}_{\mathrm{Untreated},i}} \times \mathrm{EB}_{\mathrm{Untreated},i} \qquad \text{Eq. 3}$$

Step 3: Calculate the potential crash reduction.

The benefit of the treatment is quantified by the reduction in the number of crashes. The potential crash reduction is calculated as the difference (reduction) between the existing EB (untreated) and the achievable crashes of the new EB (treated) expected crashes. This difference will then be multiplied by the average cost per crash to acquire the benefit of the crash reduction.

Step 4: 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 US Department of Transportation (USDOT) quantifies the economic benefit of reducing "the expected number of fatalities by one" using a measurement called the Value of a Statistical Life (VSL) (USDOT, 2021). Furthermore, the USDOT uses an Abbreviated Injury Scale (AIS), shown in Table 8, 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, 2010). The AIS rates the losses resulting from different types of injury crashes by severity using a scale called quality-adjusted life years (USDOT, 2021).

Table 8. 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

Most states, including Virginia, still use the KABCO five-level scale, which is why a 2018 publication by FHWA, "Crash Costs for Highway Safety Analysis," was used to compute the comprehensive costs of fatalities, injuries, and PDO crashes as shown in Table 9 (Harmon et al., 2018).

Table 9. Comprehensive Crash Costs for the District 4 Analyzed Network

Crash Severity	Crash Count (2016–2018)	FHWA Cost/Crash	Comprehensive Costs
Fatality (K)	96	$11,295,402	$1,084,358,592
Injury A	779	$654,967	$510,219,293
Injury B	3,856	$198,492	$765,385,152
Injury C	553	$125,562	$69,435,786
PDO (O)	12,324	$11,906	$146,729,544
Total	17,608	—	$2,576,128,367

For this study, the average, comprehensive crash cost for each district was computed in two steps. First, multiply the 3-year crash count and the FHWA cost per crash to obtain the comprehensive crash costs of each crash severity level for the analyzed network. Second, obtain the average, comprehensive crash cost for the network by dividing the total comprehensive crash costs by the total crash count ($2,576,128,367 ÷ 17,608 = $146,304). Note that this value changes for every district.

Step 5: Estimate treatment costs.

The treatment costs per lane per 0.1 miles shown in Table 10 were provided by VDOT maintenance personnel in District 4. The treatments and costs may vary slightly by district.

Table 10. Average Cost for Friction Enhancement Treatments by Pavement Surface Mix in District 4

Treatment Options	Cost/Lane/Mile	Cost/Lane/0.1 Miles
DGAC	$65,875	$6,588
SMA	$85,250	$8,525
MICRO	$18,700	$1,870
PCCP w/CDG	$42,240	$4,224
HFST	$190,000	$19,000

Step 6: Calculate benefit-cost ratio (BCR).

The final step in the economic analysis uses the benefit-cost ratio (BCR) to choose sections that yield the best return on investment. The BCR is calculated as the monetary benefit of the friction enhancement treatment (B) equal to the value of the crash reduction multiplied by the average cost per crash divided by the cost of applying a friction enhancement treatment (C). If BCR > 1.0, there is an economic benefit to applying the treatment from the reduction in the number of crashes in the 3-year analysis period. The benefits and the costs are conservative benefits and did not use life cycle cost criteria to divide by the life of a treatment. It is recognized that this is a pending task for the implementation of the PFMP in the next phase.

Prioritizing Sections for Friction Enhancement Treatment

In each district, a treatment option is identified as a possible solution to enhance the friction of a section if (a) the current SFN40 is lower than the estimated improvement in Table 7, (b) the BCR for the treatment option is greater than 1.0, and (c) the surface mix for the section meets the criteria provided in the treatment implementation strategy provided by the district. Each district may have a different strategy. Table 11 shows an example, which is the strategy provided by District 4. It should also be noted that an HFST can be a possible solution for every surface, regardless of age, if the current SFN40 is less than 80.

Table 11. Treatment Option Implementation Strategy for District 4

Interstate			
Strategy	**Current Surface Mix**	**Mix Age**	**Treatment Option**
1	All Asphalt	—	SMA
2	PCCP	—	PCCP w/CDG
Primary			
Strategy	**Current Surface Mix**	**Mix Age**	**Treatment Option**
1	DGAC or SMA	< 6 Years	MICRO
2	DGAC or MICRO	≥ 6 Years	DGAC
3	SMA	≥ 6 Years	SMA
4	PCCP	≥ 6 Years	PCCP w/CDG

Note: Pavement age in 2018.

A further step is necessary to decide which treatments to choose from the list of those that have a BCR > 1.0. Agencies can decide what minimum total savings are required for them to perform a treatment. Total savings, or (B minus C), would be computed and compared to the value established by the agency as the minimum. If (B minus C) is greater than that value, it should be considered a possible treatment. For this report, the minimum value of savings was set as those sections with treatments with savings greater than $500,000. A final priority table should be made with all possible treatments ordered by BCR, and then listed by the highest to the minimum acceptable savings value.

RESULTS AND DISCUSSION

The application of the methodology is demonstrated in this section using District 4 as a case study. The results for the other eight districts are provided in the appendices. In District 4, 1,249.5 miles of pavements were measured. After initially processing the measurements, i.e., pairing MPs and grouping the data into 0.1-mile sections, 1,244 miles remained as the surveyed dataset. Table 12 separates the surveyed miles and lane-miles by route type and pavement surface mix classification. The table shows that 57% of the surveyed network consists of primary routes and 49% of the network has DGAC.

Table 12. Miles and Lane-miles by Pavement Surface Mix for District 4 Surveyed Network

	Miles Surveyed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	87.2	25.9	379.8	1.4	26.6	520.9
Primary	506.7	0.0	35.2	135.5	25.7	703.1
Total	593.9	25.9	415.0	136.9	52.3	1,224.0
	Lane-Miles Surveyed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	195.9	61.3	968.6	2.8	67.3	1,295.9
Primary	1,267.6	0.0	109.2	305.7	52.9	1,735.4
Total	1,463.5	61.3	1,077.8	308.5	120.2	3,031.3

Next, 28% of the sections from the surveyed dataset were removed due to pavement surface changes that occurred between 2016 and 2018. Table 13 lists the total miles, lane-miles, and average AADT for the analyzed network separated by route type and pavement surface mix classification.

Table 13. Miles, Lane-miles, and Average AADT by Pavement Surface Mix for District 4 Analyzed Network

	Miles Analyzed by Pavement Surface Mix				
Road Type	*DGAC*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	52.3	289.3	1.4	16.1	359.1
Primary	392.7	34.8	69.5	25.5	522.5
Total	445.0	324.1	70.9	41.6	881.6
	Lane-Miles Analyzed by Pavement Surface Mix				
Road Type	*DGAC*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	126.1	740.4	2.8	42.3	911.6
Primary	1,002.9	108	163.5	53.4	1,327.8
Total	1,129.0	848.4	166.3	95.7	2,239.4
	Average AADT by Pavement Surface Mix				
Road Type	*DGAC*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	56,614	54,197	24,000	16,772	52,754
Primary	11,496	11,468	11,662	9,769	11,432

The analyzed dataset includes 881.6 miles of roadway with no remaining THMACO. Most of interstate routes have SMA (81%) and the primary routes have DGAC (75%), respectively. The majority (59%) of the analyzed miles and lane-miles are on primary routes. Average traffic volume on interstate routes are about 3.6 times larger than on the primary routes.

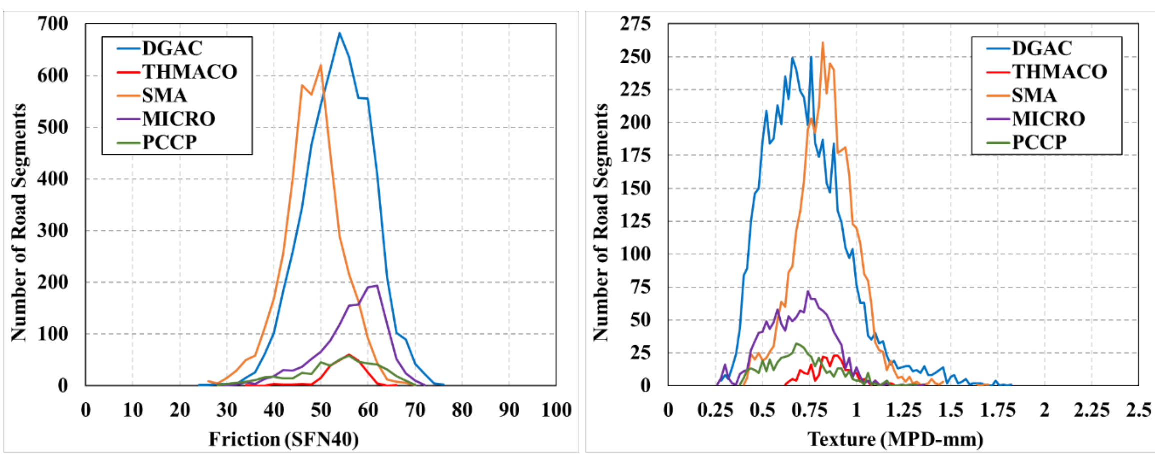
Pavement Friction and Texture

Table 14 shows the mean and standard deviation (SD) of the friction (SFN40) and texture (MPD) measurements for the surveyed and analyzed data. As expected, the average values of SFN40 and MPD are higher and lower, respectively, for the surveyed network that includes all recent 3-year maintenance work. This shows that, on average, newer surfaces are not as polished (SFN40) and not as cracked (MPD).

Table 14. Mean and Standard Deviation for SFN40 and MPD for District 4 Surveyed and Analyzed Data

Surface Mix	Surveyed Network				Analyzed Network			
	Friction (SFN40)		Texture (MPD, in mm)		Friction (SFN40)		Texture (MPD, in mm)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DGAC	52.8	7.0	0.72	0.22	51.9	6.7	0.77	0.22
THMACO	53.9	4.0	0.86	0.11	-	-	-	-
SMA	47.3	6.1	0.83	0.15	46.9	6.2	0.83	0.16
MICRO	55.5	7.0	0.68	0.17	56.4	6.2	0.73	0.16
PCCP	52.2	8.7	0.70	0.17	51.6	8.7	0.68	0.18

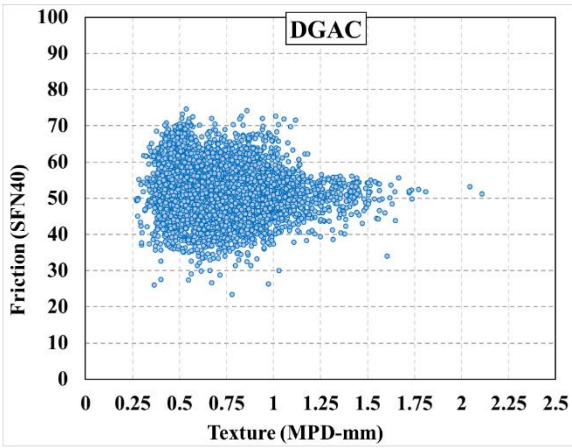
Figure 4 illustrates the variations in the SFN40 and MPD measurements for the different surface mixes on the surveyed network.



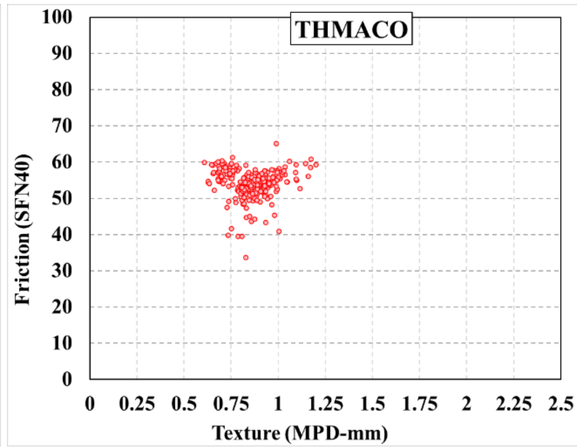
(a) SFN40 (b) MPD

Figure 4. Friction (SFN40) and Texture (MPD) for District 4 Surveyed Data

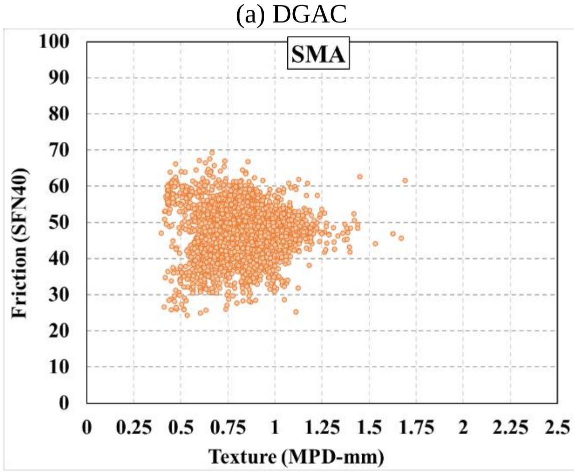
Figure 5a–e plot SFN40 versus MPD for the different surface mixes of the surveyed network.



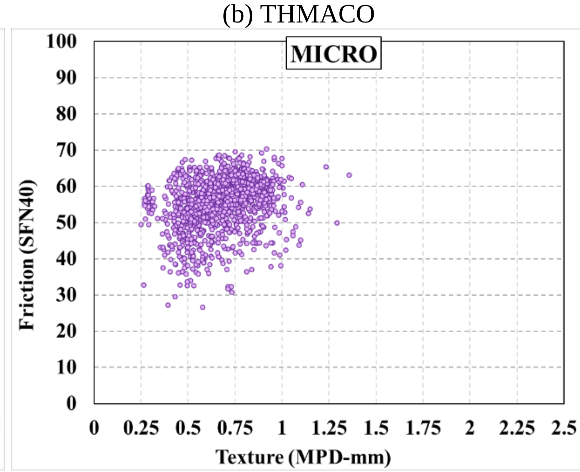
(a) DGAC



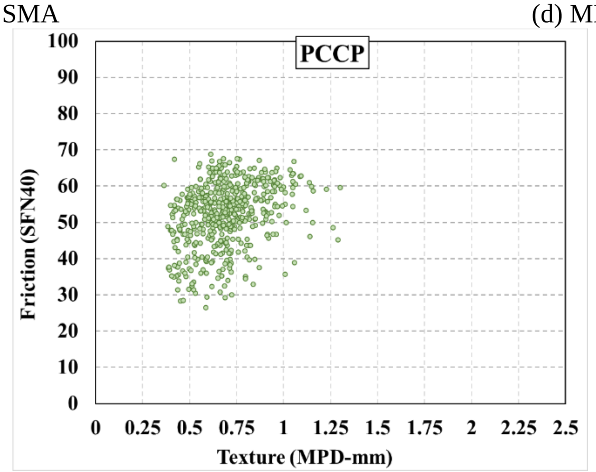
(b) THMACO



(c) SMA



(d) MICRO



(e) PCCP

Figure 5. SFN40 vs. MPD Plots by Pavement Surface Mix (District 4 Surveyed Data)

Crash Data Selection and Assessment

The overall goal for VDOT 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 safety performance associated with a section of road. Crash prediction models, like SPFs, determine the average 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 (reported crashes). For greater precision, more observations are necessary.

Table 15 shows the total and average number of wet and dry crashes per 0.1-mile section that were reported between 2016 and 2018 and separated by pavement surface mix for the analyzed interstate and primary road networks. The crash potential increases when road sections with fewer lanes serve the same traffic volume as those with more lanes, especially when nearing capacity.

Table 15. Total and Average Crash Count per Lane per 0.1 Miles by Pavement Surface Mix for District 4 Analyzed Network

	Total Crash Count by Pavement Surface Mix				
Road Type	*DGAC*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	1,634	7,669	6	126	9,435
Primary	6,918	289	764	202	8,173
Total	8,552	7,958	770	328	17,608
	Average Crash Count by Pavement Surface Mix				
Road Type	*DGAC*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	13.0	10.4	2.1	3.0	10.3
Primary	6.9	2.7	4.7	3.8	6.2

The charts in Figure 6a–d illustrate the relationships from the data in Table 13 and Table 15. Figure 6a shows that the interstates have more crashes than the primary network despite having fewer lane-miles due to the higher traffic volumes, as can be seen in Figure 6c. This is a good example of how traffic volume is a key factor in crashes, as crash risk generally increases with higher AADT (Srinivasan and Bauer, 2013).

Figure 6b shows that the majority (81%) of the interstate lane-miles are SMA and the majority (76%) of the primary network is DGAC. Finally, Figure 6d shows the number of sections that experienced at least one crash during the 3-year study period. However, the effect of surface mix on crashes cannot be directly inferred by this information alone since crashes are the result of many other factors.

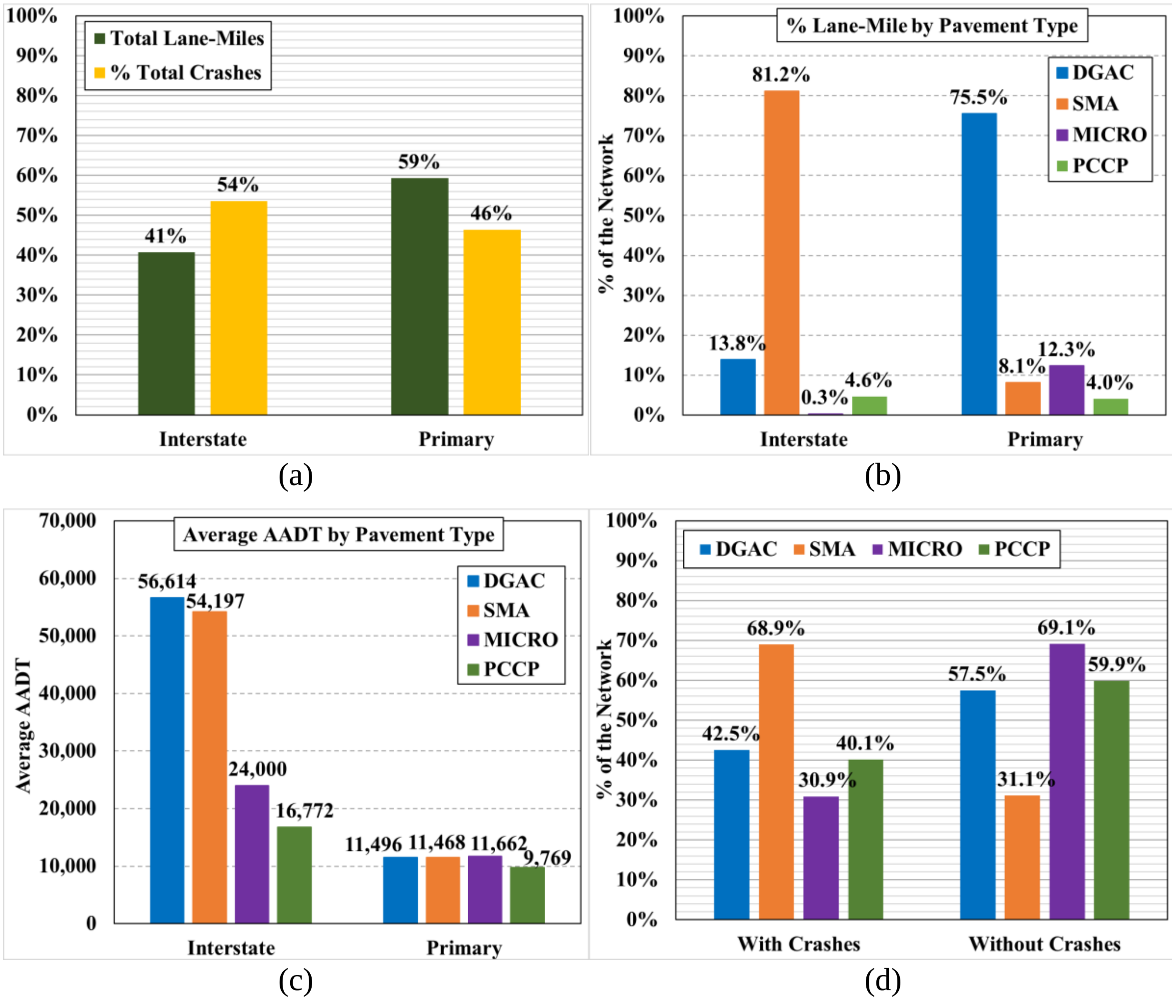


Figure 6. Crashes, Lane-miles, and Traffic by Pavement Surface Mix (District 4 Analyzed Network)

Table 16 lists the observed number of crashes for the analyzed network in District 4, separated by the reported surface condition and crash severity. In District 4, the wet surface crashes (as reported by police) made up approximately 19% of all the crashes occurring on the analyzed network. Therefore, to acquire an appropriate number of observations (i.e., crash counts) for the regression analysis, the total (wet and dry) number of crashes (combining all crash severities) at each road section was used. Furthermore, and critical to the analysis, research has shown that the risk for both wet and dry crashes increase as pavement friction decreases (Najafi et al., 2017; Wu et al., 2014; Pratt et al., 2014). Additionally, the data obtained in every district show that both wet and dry crashes increase when SFN40 decreases. Finally, for the wet and dry surfaces combined, there were 17,608 crashes, of which fatal and serious injury crashes are about 5% (approximately equal to the statewide proportion).

Table 16. Crash Counts Separated by Surface Condition and Severity for District 4 Analyzed Network

Crash Severity	Wet Crashes		Dry Crashes		Wet and Dry Crashes	
	Observed	%Wet	Observed	%Dry	Observed	%Wet+Dry
Fatality (K)	10	0.30%	86	0.60%	96	0.55%
Serious Injury (A)	115	3.45%	664	4.65%	779	4.42%
Other Injury (B & C)	791	23.73%	3,618	25.35%	4,409	25.04%
PDO (O)	2,417	72.52%	9,907	69.40%	12,324	69.99%
(K) + (A)	125	3.75%	750	5.25%	875	4.97%
Total	3,333	—	14,275	—	17,608	—

Cost-Benefit Analysis

The SPF model for the data analyzed in District 4 is given in Table 17. The overdispersion and log-likelihood value for the SPF model developed are 1.057 and −13,609, respectively. As explained before, District 4 maintenance personnel provided this list of possible pavement friction enhancement treatment options and a strategy for implementation. These were described in Table 7, Table 10, and Table 11.

Table 17. Final SPF Coefficients for District 4 with CFME Data

Model Variables	*β*	*p*-value	Model Variables	*β*	*p*-value
Intercept	-0.005	1.00	Interaction Term(s):		
ln(AADT)	0.266	0.00	SFN40 × Route Type	0.039	0.00
Friction (SFN40)	-0.094	0.00	SFN40 × Texture	-0.042	0.00
Texture (MPD, in mm)	1.482	0.02	SFN40 × Grade (%)	—	—
Divided	-0.114	0.79	SFN40 × Cross-slope (%)	-0.005	0.01
Intersections & Ramp Access Points	1.474	0.00	SFN40 × Curvature (1/m)	26.741	0.00
Route Type	-1.407	0.00	SFN40 × Intersections/Ramp Access	-0.011	0.04
Pavement Surface Mix			SFN40 × Divided Roadway	0.025	0.00
SMA	-0.982	0.00	SFN40 × Number of Travel Lanes	0.010	0.01
MICRO	1.821	0.00	SFN40 × Pavement Surface Mix		
PCCP	-1.538	0.00	*SFN40 × SMA*	0.015	0.03
Grade (%)	—	—	*SFN40 × MICRO*	-0.037	0.00
Cross-slope (%)	0.295	0.00	*SFN40 × PCCP*	0.019	0.06
Curvature (1/m)	-991.525	0.00			
Number of Travel Lanes	0.057	0.77			

Note: Indicator variable reference values; for route type is primary; and pavement surface mix is DGAC.

Table 18 presents a summary of the number of sections that could benefit from friction enhancement treatment that have a potential savings greater than $500,000 and BCR > 1.0 separated by the type of treatment. A total of 604 sections met these criteria, which is about 6.9% of all analyzed sections. The majority (70%) of the friction enhancement treatments suggested are on DGAC pavements and the majority (40%) of the treatments are DGAC. The second largest groups of pavement treatments (26% and 27%) are MICRO and HFST. Together, these three categories cover 93% of the proposed sections.

Table 18. Number of Recommended 0.1-Mile Friction Enhancement Treatment Sections with BCR > 1 and Savings > $500,000 in District 4

Savings per Section >	Number of 0.1-Mile Friction Enhancement Treatment Sections					
	DGAC	SMA	MICRO	PCCP w/CDG	HFST	Total
$5.0 M	4	0	2	0	0	6
$4.0 M	0	0	3	0	2	5
$3.0 M	6	0	9	0	3	18
$2.0 M	20	2	18	0	11	51
$1.0 M	85	8	47	1	37	178
$0.5 M	128	29	76	4	109	346
Total	243	39	155	5	162	604

The total predicted reduction in the number of crashes and the corresponding savings in each of these sections are estimated in Table 19. This information has been ordered by savings, like Table 18, in which the lowest savings category is between $0.5 and $1.0 million. There are 346 sections recommended for treatment within this range, which could reduce as many as 1,709 crashes. In total, the table shows that for this study, 604 sections with a projected savings greater than $500,000 could be recommended for treatment, which could potentially reduce upwards of 5,156 crashes. This is approximately 29% of the crashes predicted for the current network using the SPF-EB method. This is a very high projection that can be obtained by treating a very small percentage of sections, which shows that District 4 does not have a lot of sections with friction problems in their highways.

Table 19. Potential Crash Reductions and Total Cost Savings Benefits for the Recommended 0.1-Mile Friction Enhancement Treatment Sections in District 4

Savings per Section >	0.1-Mile Sections	Predicted Crash Reductions	Total Treatment Cost	Total Savings
$5.0 M	6	269	$83,683	$39,281,997
$4.0 M	5	156	$111,830	$22,740,794
$3.0 M	18	433	$315,585	$63,065,758
$2.0 M	51	840	$1,056,223	$121,890,996
$1.0 M	178	1,748	$3,994,058	$251,775,545
$0.5 M	346	1,709	$9,579,325	$240,394,533
Total	604	5,156	$15,140,703	$739,149,623

Note: The crash reductions are the total predicted over a 3-year period following a proposed friction enhancement treatment.

The cost of treating all 604 sections is $15 million, but treatment could potentially result in estimated economic savings from the reduction in crashes greater than $700 million. This represents an overall average BCR of 50 to 1. If the reductions of fatal crashes and serious injuries in the 604 sections are proportional to the total crashes (as shown in Table 16), this would result in a potential reduction of 28 fatalities and 228 serious injuries in the analyzed network over 3 years.

Figure 7 shows that the rate of change in cumulative total benefits and predicted crash reduction decreases as the cumulative total treatment cost increases. Projects with higher BCR will reduce more crashes for every dollar spent than projects with lower BCR. For example, an investment of $0.5 million to treat the 79 sections with the highest BCR could result in potential savings of $200 million. Investing an additional $0.5 million (bringing the cost to $1 million) would treat an additional 71 sections and could increase the potential savings by approximately $90 million, which brings the total savings close to $300 million.

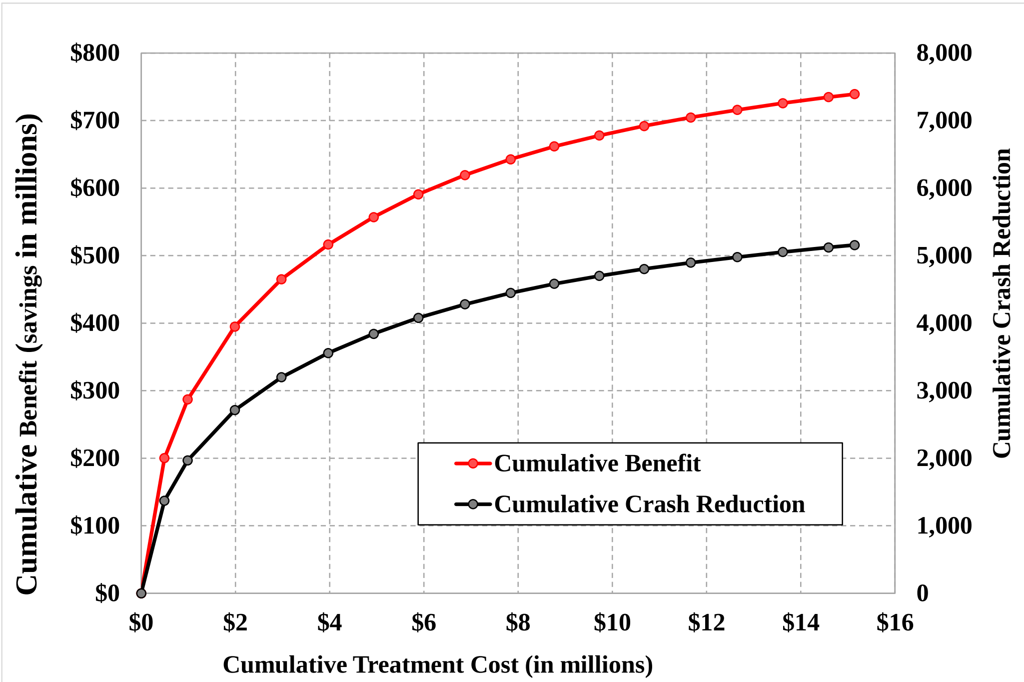


Figure 7. Cumulative Benefits and Crash Reductions vs. Cumulative Costs (District 4)

Figure 8 shows a map of the 0.1-mile sections recommended for friction enhancement treatment that the Maintenance and Traffic Engineering Divisions can review together. The predicted potential crash reductions for these sections are color coded as illustrated in the figure legend.

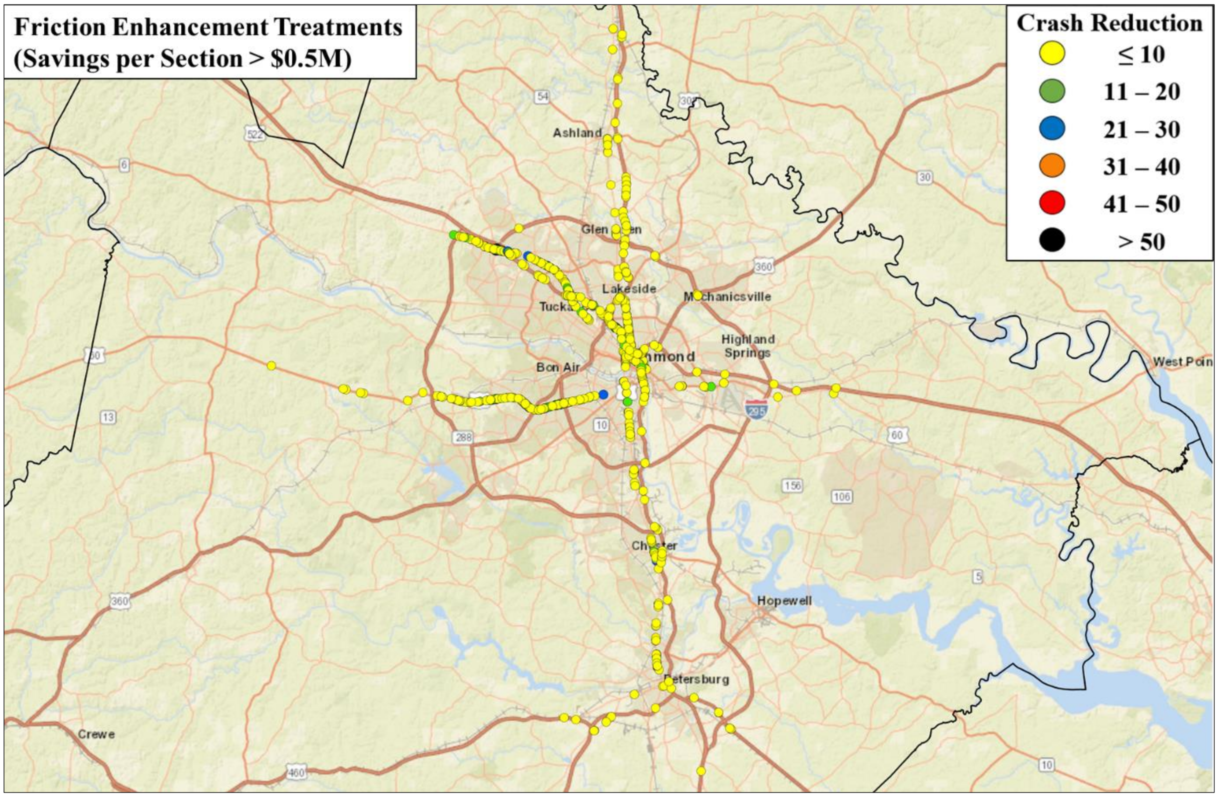


Figure 8. Friction Enhancement Treatments in District 4 (Savings > $0.5 million)

Table 20 presents a short list of the top-15 locations with the highest potential savings in District 4 and can be used as a case study to illustrate the results. This list is a summary of the first 15 of all 604 possible treatments found with the SPF-EB analysis. It is arranged in descending order of BCR, which represents the order of priority that the economic analysis suggests in obtaining the maximum value of return for each $1 of investment. The total cost savings do not necessarily follow the same order, as some sections further down the list may have higher savings but not higher BCR. Closer, project-level detailed section investigation should be performed by District 4 to examine the final order of construction based on the Department's policies and regulations.

Table 20. Recommended Friction Enhancement Treatment 0.1-mile Sections with the Top 15 BCR in District 4

No	Route ID	Rte. Type	Mix Type	Age	AADT	Lanes	Divided	MP	SFN40	MPD	Treatment	CR	Savings	BCR	Facility
1	US250W	Primary	DGAC	4	77,000	3	1	31.2	48.7	0.77	MICRO	60	$8,704,462	1,552.6	I/R
2	US60E	Primary	DGAC	3	57,000	3	1	33.4	41.8	0.77	MICRO	36	$5,298,968	945.6	I/R
3	US250W	Primary	DGAC	4	77,000	3	1	31.6	53.3	0.82	MICRO	34	$4,911,817	876.5	I/R
4	US60E	Primary	DGAC	3	57,000	3	1	33.1	41.6	0.83	MICRO	32	$4,724,024	843.1	I/R
5	US250E	Primary	DGAC	3	77,000	3	1	31.6	44.8	0.66	MICRO	28	$4,038,785	720.9	I/R
6	US250E	Primary	DGAC	4	77,000	3	1	31.4	42.3	0.30	MICRO	27	$3,942,006	703.7	I/R
7	US250E	Primary	DGAC	4	77,000	3	1	31.3	49.4	0.27	MICRO	25	$3,621,213	646.5	I/R
8	US250W	Primary	DGAC	4	77,000	3	1	31.1	48.7	0.80	MICRO	25	$3,592,213	641.3	DPN
9	US60E	Primary	DGAC	3	63,000	3	1	30.9	37.9	0.70	MICRO	24	$3,523,238	629.0	I/R
10	US60W	Primary	DGAC	5	34,000	2	1	26.4	30.0	0.66	MICRO	16	$2,313,468	619.6	I/R
11	US250W	Primary	DGAC	4	77,000	3	1	31.0	49.8	0.76	MICRO	23	$3,428,916	612.2	I/R
12	US250W	Primary	DGAC	4	77,000	3	1	31.4	46.6	0.75	MICRO	23	$3,362,103	600.3	I/R
13	US250W	Primary	DGAC	3	11,000	3	1	34.8	40.2	0.71	MICRO	22	$3,254,834	581.2	I/R
14	US60W	Primary	DGAC	5	34,000	2	1	26.0	37.0	0.63	MICRO	15	$2,158,196	578.1	I/R
15	US60E	Primary	DGAC	5	43,000	2	1	26.9	35.3	0.52	MICRO	14	$2,116,015	566.8	I/R

Notes:

1. Route ID: I = Interstate, US = US Route, SR = State Route
2. Pavement Surface Mix and Treatment: DGAC = dense-graded AC, SMA = stone matrix AC; MICRO = microsurfacing, PCCP = Portland cement concrete pavement.
3. Age: Pavement age since 2018.
4. AADT = annual average daily traffic.
5. Lanes: Number of lanes per direction of travel.
6. MP = Starting Mile-Point. All the sections are 0.1-miles long.
7. SFN40 = friction parameter, Sideway-force Friction Number converted to standard speed of 40 mph.
8. MPD = mean profile depth, in mm.
9. BCR = benefit-cost ratio.
10. Facility type: I/R = intersection/ramp access, Curve = any section with a radius < 2,000 feet, I/R Curve = intersections/ramp access and curve; DPN = divided primary nonevent, UPN = undivided primary nonevent, IN = interstate nonevent.

The map in Figure 9 shows the predicted potential crash reduction of the top 15 sections. The treatments at these locations would reduce as many as 404 crashes, which is approximately 6% of the crashes predicted with the SPF-EB method. The total cost for these suggested treatments is $78,540, but the projected potential total savings for reducing the 404 crashes are around $59 million.

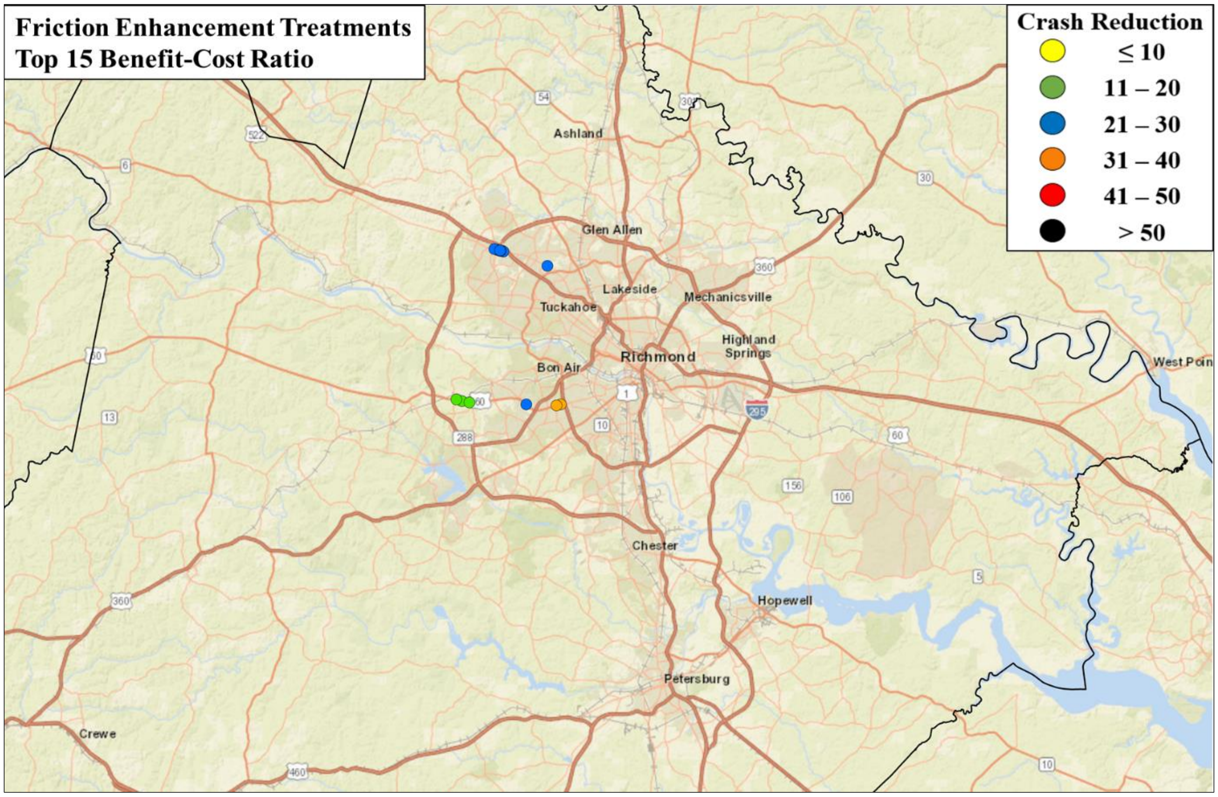
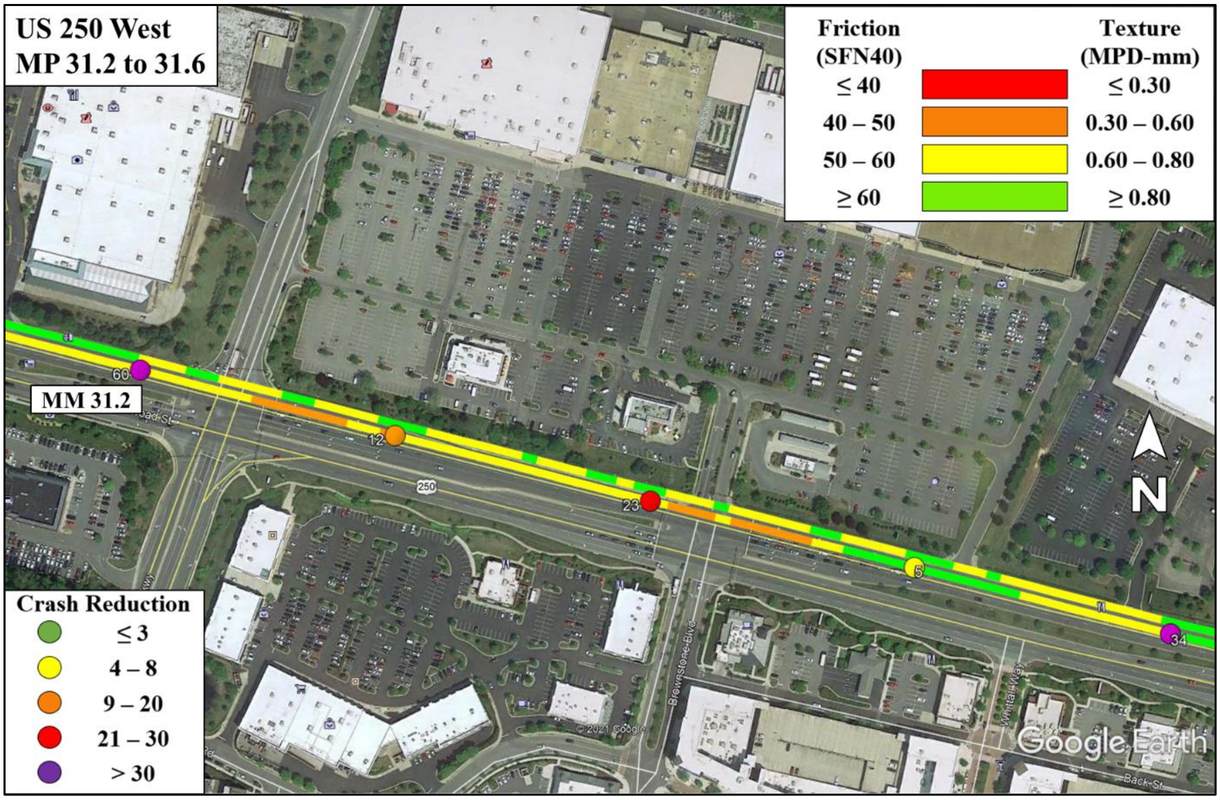


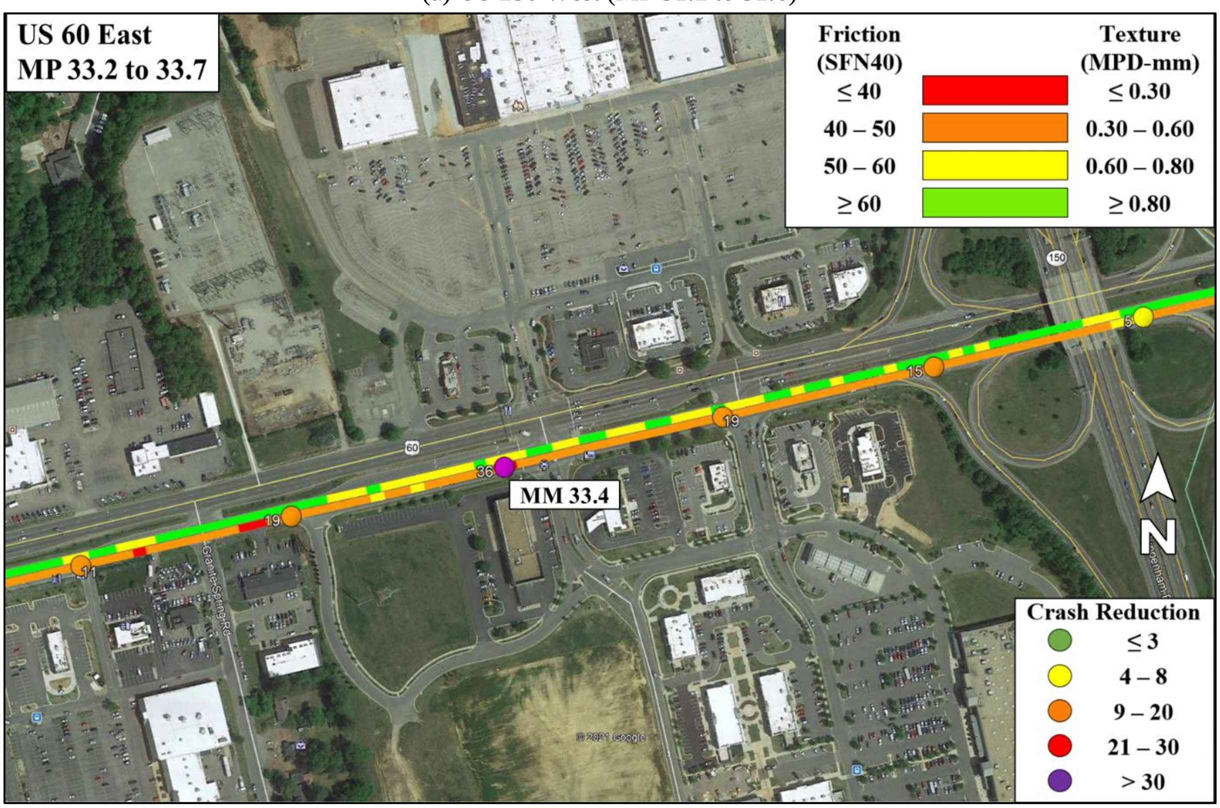
Figure 9. Suggested Friction Enhancement Treatments with the Top 15 BCR in District 4

The two sections that have the highest BCR are US 250 West at MP 31.2 and US 60 East at MP 33.4. Figure 10 shows a 0.4-mile and a 0.5-mile stretch of roadway that include the two sections, along with 10-meter SFN40 and MPD (mm) measurements and the 0.1-mile projected crash reductions, for both travel directions. Note that the 10-meter measurements are displayed as stacked bars in each direction, with MPD on the top and the SFN40 on the bottom, and color coded as displayed in the legends.

Both locations have controlled intersections with DGAC surfaces. Before friction enhancement treatment, the expected crash counts are 76 and 42. The analysis recommends that both sections receive a MICRO treatment. After improving friction with the MICRO, the new predicted crash counts are 16 and 6, which corresponds to a potential crash reduction of 60 and 36, as the maps show.



(a) US 250 West (MP 31.2 to 31.6)



(b) US 60 East (MP 33.2 to 33.7)

Figure 10. Two Locations with the Highest Friction Enhancement Treatment BCR

Statewide Friction Enhancement Treatments

The methodology demonstrated for District 4 was also used to screen the other districts for sections for potential detailed safety analyses. The results are provided in the appendices. This section presents a summary of the statewide results produced from combining the results of the analysis performed for each district. This includes the observed and estimated crashes, predicted crash reductions, and potential friction enhancement treatment costs and total savings. The results are generated using the 3-year period, the SPF, average crash costs, and treatment strategies and costs in each district, which are found in the report (District 4) or the appendices (all other districts).

Table 21 shows the observed number of crashes for the statewide analyzed network separated by reported crash severity. It should be noted that the actual dates of the 3-year period vary by district. The total number of fatality and serious injury crashes made up over 6% of the total number of crashes.

Table 21. Statewide Crash Counts Separated by Severity (Analyzed Network)

Crash Severity	Wet and Dry	
	Observed	% Total
Fatality (K)	414	0.68%
Serious Injury (A)	3,083	5.57%
Other Injury (B & C)	17,416	23.24%
PDO (O)	46,579	70.51%
(K) + (A)	3,497	6.24%
Total	67,492	—

The SPF-EB analysis evaluated the potential benefits of the treatment options used in each district across the state, a total 38,304 0.1-mile sections. In each district, the treatments were considered potentially viable solutions for sections that meet a district's treatment implementation strategy and have a total treatment cost that is lower than the projected economic savings based on potential crash reductions computed using SPF/EB estimates for that district.

Table 22 presents a summary of the sections recommended for friction enhancement treatment that could reduce crashes with potential savings per section greater than $500,000. A total of 1,709 sections, which is about 4.5% of all analyzed sections across the state, met the criteria. Most of the friction enhancement treatments are DGAC and HFST (29% and 27%). A similar percentage of sections (14%, 14%, and 16%) would receive either a THMACO, SMA, or MICRO treatment. Less than 1% of the treated sections would receive PCCP CDG.

Table 22. Statewide Number of Recommended 0.1-Mile Friction Enhancement Treatment Sections with BCR > 1 and Savings > $500,000

Savings per Section >	Number of 0.1-Mile Friction Enhancement Treatment Sections						
	DGAC	THMACO	SMA	MICRO	PCCP w/CDG	HFST	Total
$5.0 M	4	0	0	2	0	0	6
$4.0 M	1	0	0	3	0	2	6
$3.0 M	8	1	1	10	0	5	25
$2.0 M	28	11	6	23	0	18	86
$1.0 M	158	59	67	68	1	101	454
$0.5 M	301	160	168	171	4	328	1,132
Total	500	231	242	277	5	454	1,709

Table 23 shows that treating 1,709 sections costs over $42 million but may potentially reduce as many as 12,949 crashes (19.5%) with the SPF-EB method, saving more than $1.7 billion over 3 years. This large projected savings can be obtained from treating a relatively small percentage of sections.

If the reductions of fatal crashes and serious injuries in the 1,709 sections are proportional to the total number of crashes, as shown in Table 21, this could result in a potential reduction of 88 fatalities and 721 serious injuries in the analyzed statewide network over 3 years.

Table 23. Statewide Potential Crash Reductions and Total Cost Savings Benefits for the 0.1-Mile Recommended Friction Enhancement Treatment Sections

Savings per Section >	0.1-Mile Sections	Predicted Crash Reductions	Total Treatment Cost	Total Savings
$5.0 M	6	269	$83,683	$39,281,997
$4.0 M	6	180	$129,042	$26,890,772
$3.0 M	25	594	$494,300	$85,752,551
$2.0 M	86	1,413	$1,746,113	$204,446,152
$1.0 M	454	4,625	$11,136,212	$613,602,926
$0.5 M	1,132	5,867	$28,413,626	$782,176,426
Total	1,709	12,949	$42,002,975	$1,752,150,825

Note: The crash reductions are the total predicted over a 3-year period that varied by district.

The sections identified by the screening methodology could require a detailed section investigation. To obtain the benefits, the district's safety and maintenance personnel can review the sections with high potential savings from friction enhancement treatment and conduct detailed safety analyses on those that are deemed most critical. If the need for a friction enhancement treatment is confirmed, the resulting projects can be included in the district's paving schedule, the Highway Safety Improvement Program, and/or other construction project development.

Summary of Findings with Discussion

This project surveyed 7,000 miles of the CoSS with a CFME. The collected data were complemented with existing VDOT data to perform a network-level safety analysis of the corridors. The following points summarize the findings for the Pavement Friction Management demonstration project conducted in collaboration with VDOT:

1. The data analysis, consistent with previous projects (de León Izeppi et al. 2017 & 2019), demonstrated that pavement friction is significantly related to roadway crashes. The data granularity required to establish that relationship supports the use of CFME to implement a statewide PFM in Virginia to reduce fatal and serious injury crashes.
2. The methodology proposed in the report builds on previous experience and provides guidance on how to implement a statewide PFM. This effort requires participation and collaboration from the Traffic Engineering, Materials, and Maintenance Divisions. The application of the methodology was demonstrated in detail for one district, but the results for all others are provided in the appendices.
3. After filtering the data, the analyzed network made up 5,796.6 miles (82.8%) of the measured network. Mileage differences were due to invalid friction, macrotexture dropouts, or no GPS connectivity. The final network analyzed was further reduced to 3,830.4 miles (54.7%) when measurements were outside of VDOT maintenance jurisdiction or pavement surface changes (maintenance) occurred within the 3-year window of available crash data.
4. The VDOT statewide screening identified 1,709 sections with a BCR greater than 1.0 and a savings greater than $0.5 million. From those, 577 sections have savings greater than $1.0 million, and 1,132 sections have savings between $0.5 and $1.0 million. The analysis suggests that friction enhancement treatments could potentially reduce up to 12,949 of the predicted crashes on the analyzed network. The analysis showed that the costs are about $42 million with potential economic savings over $1.75 billion for a statewide BCR of 42 to 1. However, due to the limited design life of many of these treatments, life-cycle costs should be studied.
5. The complete set of CFME raw and processed data and all the results of each district’s individual analysis are available for further analysis by the Traffic Engineering, Maintenance, and Materials Division personnel. The appendices contain a complete set of results for friction (SFN) and macrotexture (MPD) for all districts and individual district results for the benefit-cost analysis.

CONCLUSIONS

- *The results of the demonstration suggest that the statewide adoption of the methodology can help reduce a significant number of crashes and associated fatalities and injuries.* The network-level assessment of the CoSS demonstrated the benefits and practicality of adopting a proactive, systemic pavement friction management approach to screen for sections that may benefit from friction enhancement treatment and a detailed section investigation.

- *Each district can utilize the data collected in this project to focus detailed safety analyses and design for safety improvement with collaboration with the Traffic Engineering, Maintenance, and Materials Divisions.* The project surveyed a significant proportion of the CoSS, screened the network, and identified many sections in which friction enhancement treatment could result in high potential return on investment.

RECOMMENDATIONS

1. *VDOT's Traffic Engineering, Maintenance, and Materials Divisions should collaborate to continue the implementation of the methodology proposed.*

2. *The VDOT districts should review the sections with high potential savings from friction enhancement treatment and conduct detailed safety analyses on those that are deemed most critical.*

IMPLEMENTATION AND BENEFITS

Implementation

Regarding Recommendation 1, a new phase of implementation support (Phase 3) will work cooperatively with Traffic Engineering, Maintenance, and Materials Divisions to develop policies and procedures to guide both project- and network-level testing, analysis, and reporting using CFME. These policies and procedures will include frequency of testing, how that testing will be administered (in-house versus vendor service), what division(s) should lead the various components of the program, and the source(s) of funding needed to support Phase 3 implementation. The Phase 3 implementation project began in early May 2021, and a multidisciplinary team representing all the partner divisions has already begun to meet. This group, led by the Traffic Engineering Division, expects to complete a draft policy and procedures guide by June 2022 with adoption by June 2023.

The Phase 3 support plan also includes several division-specific activities that address Recommendation 1:

a) Researchers will work with the Non-Destructive Testing (NDT) Section of the Materials Division to develop procedures for both project- and network-level testing and reporting using Virginia's newly acquired CFME vehicle. This task includes initial shared operation of the VDOT CFME between VTTI and VDOT with a transition to VDOT operations by Year 2. An approved set of standard operating procedures and testing proficiency by VDOT technicians is anticipated by May 2023.

b) Development of safety analysis and networking screening procedures will continue in cooperation with the Safety Office in the Traffic Engineering Division. This work is expected to track closely with new guidance under development by AASHTO. The VDOT project champion sits on the AASHTO project panel for this new "Guide for Pavement Friction," and the VTTI research team is the primary technical resource for that work. The new AASHTO guide is expected in August 2022.

c) The Materials and Traffic Engineering Divisions, in collaboration with Center for Sustainable and Resilient Infrastructure, will develop screening procedures that will address the use of speed, crashes, and other information to evaluate possible friction and macrotexture enhancement treatments.

d) Finally, Phase 3 support will include subcontracted assistance to create a data table and import procedures for friction and related safety data as collected on the VDOT network. This task will be conducted in close cooperation with the Office of Pavement Management within VDOT's Maintenance Division. The new safety data should be available in VDOT's Pavement Management System by June 2022.

Regarding Recommendation 2, the Phase 3 project also provides one-on-one support to VDOT districts as they gain familiarity with the data and related analysis. Researchers will work individually with field safety and maintenance staff to use this analysis to balance safety improvements with pavement preservation and improvement needs. The application of the network analysis will be complemented by specific case studies to help practitioners better understand the newly available data and how to use it. One-on-one support with district safety and pavement engineers has already begun and is expected to continue through the duration of the Phase 3 project until June 2023.

Benefits

The benefits of applying the proposed methodology are clear. For the network evaluated (CoSS) alone, the analysis suggested potential economic savings of more than \$1.7 billion (BCR $\approx$ 43) over 3 years.

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APPENDIX A: DISTRICT 2 RESULTS

The tables for District 2 also incorporate the data for I-77 in District 1. District 1 was not included in the analysis because of issues that prevented geometric data and GPS coordinate acquisition for a portion of the surveyed mileage (33%). This portion of the data will be collected as part of the Implementation Project Phase 3.

The I-77 corridor in the District 1 surveyed network makes up approximately 62.3 miles of the interstate pavement of the total surveyed mileage reported in Table A1. The surveyed network also includes slurry seals, which are only reported in District 2, but were built in 2018, and, therefore, were not included in the analyzed network. This has been noted under Table A1 and Table A3.

Table A1. Miles by Pavement Surface Mix for the District 2 Surveyed Network

	Miles Surveyed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	116.8	0.0	118.9	58.8	0.9	295.4
Primary	443.3	0.0	2.7	110.6	0.4	(557.0) 561.3
Total	560.1	0.0	121.6	169.4	1.3	(852.4) 856.7

Notes: The totals in parentheses are for identified mix types only and do not include sections with slurry seals. See Table A3 notes.

The analyzed network in Table A2 includes 47 miles of I-77 from District 1. The analyzed network is 74.4% of the surveyed roadway.

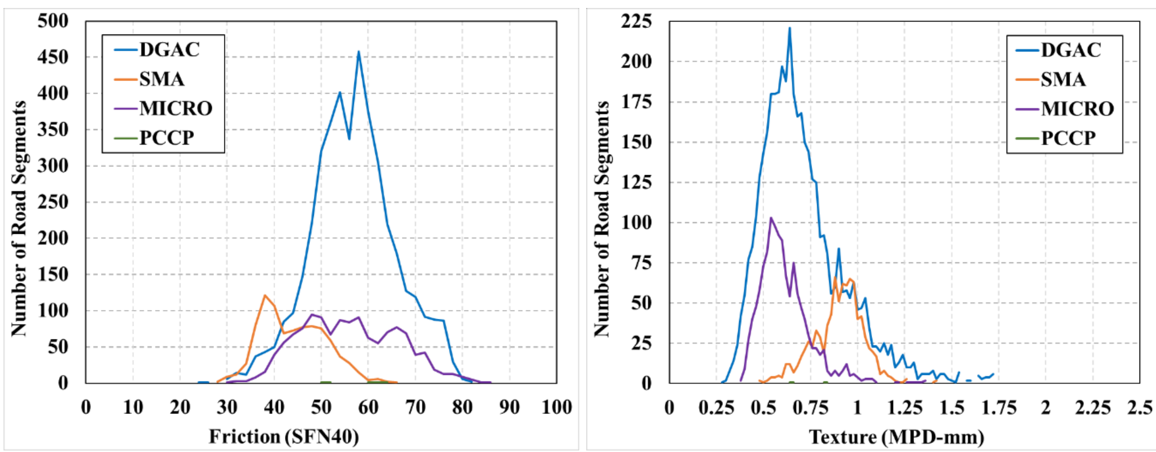
Table A2. Miles, Lane-miles, and Average AADT by Pavement Surface Mix for District 2 Analyzed Network

	Miles Analyzed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	91.3	—	88.5	42.6	0.7	223.1
Primary	330.6	—	0.0	83.4	0.3	414.3
Total	421.9	—	88.5	126.0	1.0	637.4
	Lane-Miles Analyzed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	190.7	—	191.8	91.3	1.4	475.2
Primary	660.5	—	0.0	167.9	0.6	829.0
Total	851.2	—	191.8	259.2	2.0	1,304.2
	Average AADT by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	35,999	—	43,274	46,482	36,000	42,976
Primary	15,891	—	—	12,941	10,000	15,293

Table A3. Mean and Standard Deviation for SFN40 and MPD for District 2 Surveyed and Analyzed Data

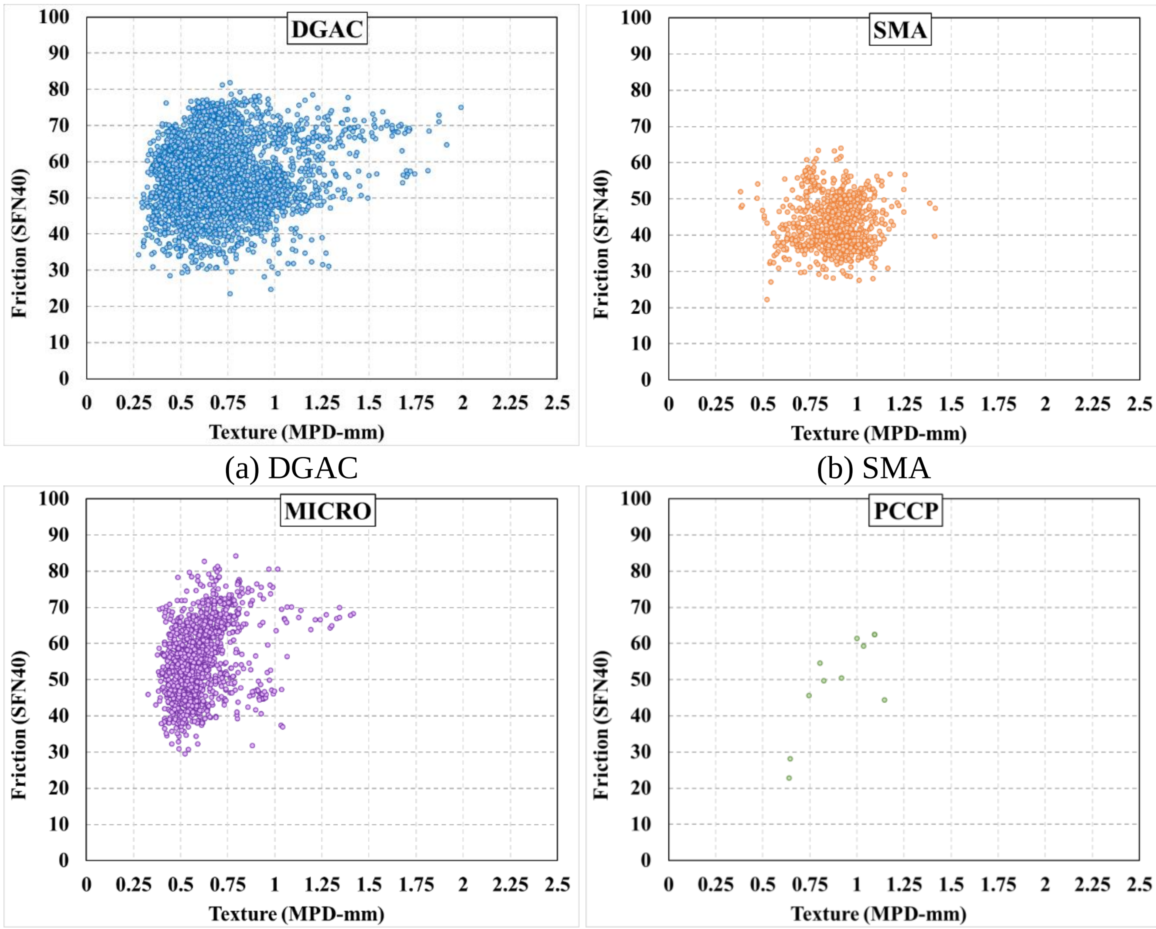
Surface Mix	Surveyed Network				Analyzed Network			
	Friction (SFN40)		Texture (MPD, in mm)		Friction (SFN40)		Texture (MPD, in mm)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DGAC	56.8	9.1	0.67	0.23	55.8	8.9	0.70	0.23
THMACO	—	—	—	—	—	—	—	—
SMA	43.6	7.1	0.86	0.16	43.0	6.8	0.89	0.14
MICRO	55.0	10.7	0.65	0.17	55.1	10.3	0.61	0.14
Slurry Seal*	0.62	7.9	0.47	0.07	—	—	—	—
PCCP	47.4	11.8	0.83	0.21	47.9	12.7	0.89	0.17
All Mixes	54.6	10.3	0.69	0.22	53.9	9.9	0.71	0.22

*Note: Slurry seals were only reported in District 2 and completed in 2018, so they are not included in the analyzed network.



(a) SFN40 (b) MPD

Figure A1. Friction (SFN40) and Texture (MPD) for District 2 Analyzed Data



(a) DGAC (b) SMA

(c) MICRO (d) PCCP

Figure A2. SFN40 vs. MPD Plots by Pavement Surface Mix (District 2 Analyzed Data

Table A4. Total and Average Crash Count per Lane per 0.1 Miles by Pavement Surface Mix for District 2 Analyzed Network

	Total Crash Count by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	775	0	1,857	751	1	3,384
Primary	3,881	0	0	561	5	4,447
Total	4,656	0	1,857	1,312	6	7,831
	Average Crash Count by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	4.1	—	9.7	8.2	0.7	7.1
Primary	5.9	—	0.0	3.3	8.3	5.4

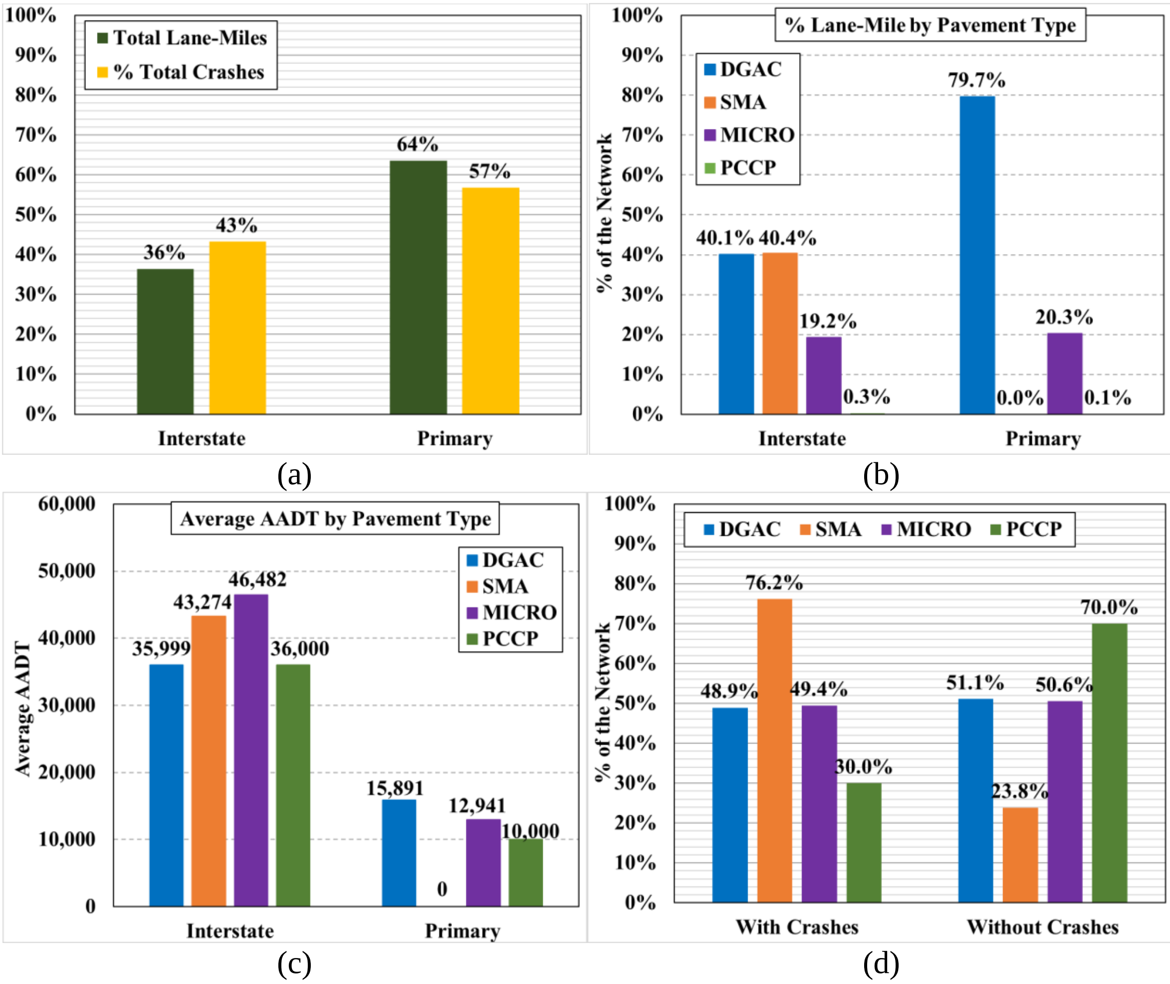


Figure A3. Network Crashes, Lane-miles, and Traffic by Pavement Surface Mix (District 2 Analyzed Data)

Table A5. Crash Counts Separated by Surface Condition and Severity for District 2 Analyzed Network

Crash Severity	Wet Crashes		Dry Crashes		Wet and Dry Crashes	
	Observed	%Wet	Observed	%Dry	Observed	%Wet+Dry
Fatality (K)	10	0.69%	43	0.67%	53	0.68%
Serious Injury (A)	67	4.63%	369	5.78%	436	5.57%
Other Injury (B & C)	360	24.86%	1,460	22.87%	1,820	23.24%
PDO (O)	1,011	69.82%	4,511	70.67%	5,522	70.51%
(K) + (A)	77	5.32%	412	6.45%	489	6.24%
Total	1,448	—	6,383	—	7,831	—

Note: Crash counts from 2017 through 2019.

The overdispersion and log-likelihood values for the District 2 SPF model are 0.687 and −8,851.

Table A6. Final SPF Coefficients for District 2 with CFME Data

Model Variables	*β*	*p*-value	Model Variables	*β*	*p*-value
Intercept	-5.810	0.00	Interaction Term(s):		
ln(AADT)	0.875	0.00	SFN40 × Route Type	—	—
Friction (SFN40)	-0.059	0.00	SFN40 × Texture	—	—
Texture (MPD, in mm)	—	—	SFN40 × Grade (%)	0.001	0.08
Divided Roadway	-0.382	0.79	SFN40 × Cross-slope (%)	—	—
Intersections & Ramp Access Points	0.781	0.00	SFN40 × Curvature (1/m)	—	—
Route Type	-0.704	0.00	SFN40 × Intersections/Ramp Access	—	—
Pavement Surface Mix			SFN40 × Divided Roadway	—	—
THMACO	—	—	SFN40 × Number of Travel Lanes	0.019	0.05
SMA	0.421	0.14	SFN40 × Pavement Surface Mix		
MICRO	0.726	0.01	*SFN40 × THMACO*	—	—
PCCP	-0.098	0.95	*SFN40 × SMA*	-0.001	0.89
Grade (%)	-0.093	0.01	*SFN40 × MICRO*	-0.013	0.01
Cross-slope (%)	—	—	*SFN40 × PCCP*	-0.012	0.74
Curvature (1/m)	54.044	0.01			
Number of Travel Lanes	-0.725	0.14			

Note: Indicator variable reference values; for route type is primary and pavement surface mix is DGAC.

Table A7. Average Cost for Friction Enhancement Treatments in District 2

Treatment Options	Cost/Lane/Mile	Cost/Lane/0.1 Mile
DGAC	$49,600	$4,960
THMACO	—	—
SMA	$86,800	$8,680
MICRO	$24,250	$2,425
PCCP w/CDG	—	—
HFST	$128,270	$12,827

Table A8. Estimated Average Friction Values (SFN40) for New Friction Enhancement Treatments in District 2

Current Surface	Surveyed SFN40 Mean	Surveyed SFN40 Standard Deviation (SD)	SFN40 Enhancement (Mean + 1.0 SD)
DGAC	55.8	8.9	65
THMACO	—	—	—
SMA	43.0	6.8	50
MICRO	55.1	10.3	65
PCCP	—	—	—
HFST	—	—	80

Table A9. Treatment Option Implementation Strategy for District 2

Interstate			
Strategy	**Current Surface Mix**	**Mix Age**	**Treatment Option**
1	DGAC	< 5 Years	MICRO
2	All Asphalt	≥ 5 Years	SMA
3	PCCP	—	SMA
Primary			
Strategy	**Current Surface Mix**	**Mix Age**	**Treatment Option**
1	DGAC	< 5 Years	MICRO
2	DGAC or MICRO	≥ 5 Years	DGAC
3	SMA	≥ 5 Years	SMA
4	PCCP	—	SMA

Note: Pavement age since 2019.

Table A10. Comprehensive Crash Costs for District 2 Analyzed Network

Crash Severity	Crash Count (2017–2019)	FHWA Cost/Crash	Comprehensive Costs
Fatality (K)	53	$11,295,402	$598,656,306
Injury A	436	$654,967	$285,565,612
Injury B	1,397	$198,492	$277,293,324
Injury C	423	$125,562	$53,112,726
PDO (O)	5,522	$11,906	$65,744,932
Total	7,831	—	$1,280,372,900

Table A11. Number of Recommended 0.1-Mile Friction Enhancement Treatment Sections with BCR > 1 and Savings > $500,000 in District 2

Savings per Section >	Number of 0.1-Mile Friction Enhancement Treatment Sections						
	DGAC	**THMACO**	**SMA**	**MICRO**	**PCCP w/CDG**	**HFST**	**Total**
$5.0 M	0	—	0	0	—	0	0
$4.0 M	0	—	0	0	—	0	0
$3.0 M	0	—	0	0	—	0	0
$2.0 M	0	—	0	0	—	1	1
$1.0 M	1	—	0	0	—	3	4
$0.5 M	20	—	0	9	—	34	63
Total	21	—	0	9	—	38	68

Table A12. Potential Crash Reductions and Total Cost Savings Benefits for the Recommended 0.1-Mile Friction Enhancement Treatment Sections in District 2

Savings per Section >	0.1-Mile Sections	Predicted Crash Reductions	Total Treatment Cost	Total Savings
$5.0 M	0	0	$0	$0
$4.0 M	0	0	$0	$0
$3.0 M	0	0	$0	$0
$2.0 M	1	15	$25,654	$2,412,670
$1.0 M	4	34	$99,709	$5,512,365
$0.5 M	63	259	$1,114,286	$41,246,444
Total	68	308	$1,239,649	$49,171,480

APPENDIX B: DISTRICT 3 RESULTS

Table B1. Miles and Lane-miles by Pavement Surface Mix for District 3 Surveyed Network

	Miles Surveyed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	0.0	0.0	0.0	0.0	0.0	0.0
Primary	453.8	0.0	0.0	45.8	23.3	522.9
	Lane-Miles Surveyed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	0.0	0.0	0.0	0.0	0.0	0.0
Primary	859.0	0.0	0.0	71.7	46.5	977.2

Table B2. Miles, Lane-miles, and Average AADT by Pavement Surface Mix for District 3 Analyzed Network

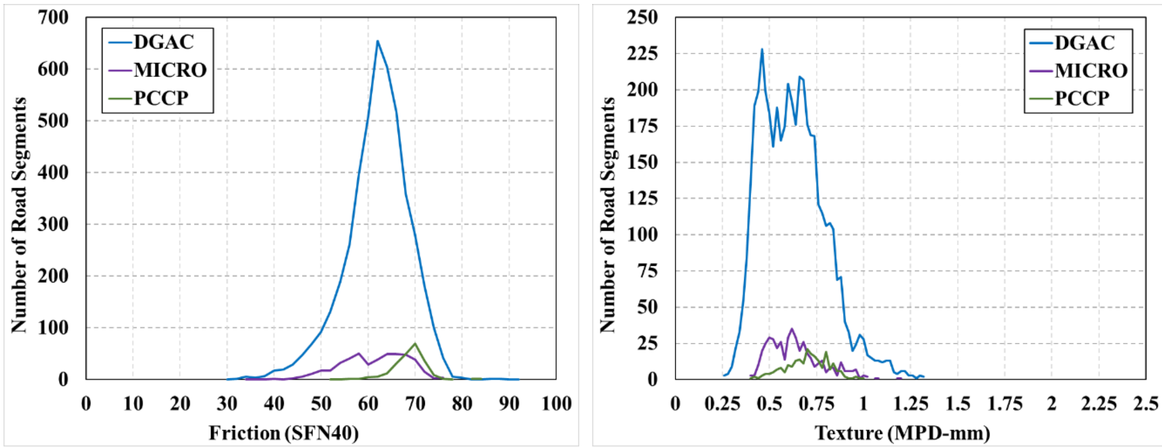
	0.1-Mile Sections Analyzed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	0.0	0.0	0.0	0.0	0.0	0.0
Primary	300.0	0.0	0.0	32.0	23.3	355.3
	Number of Lanes Analyzed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	0.0	0.0	0.0	0.0	0.0	0.0
Primary	647.9	0.0	0.0	69.2	46.6	763.7
	Average AADT by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	—	—	—	—	—	—
Primary	13,741	—	—	8,612	16,574	13,465

Notes:

1. Lane-miles are the number of travel lanes in both directions of travel for undivided roadway.
2. AADT is for direction of travel only.

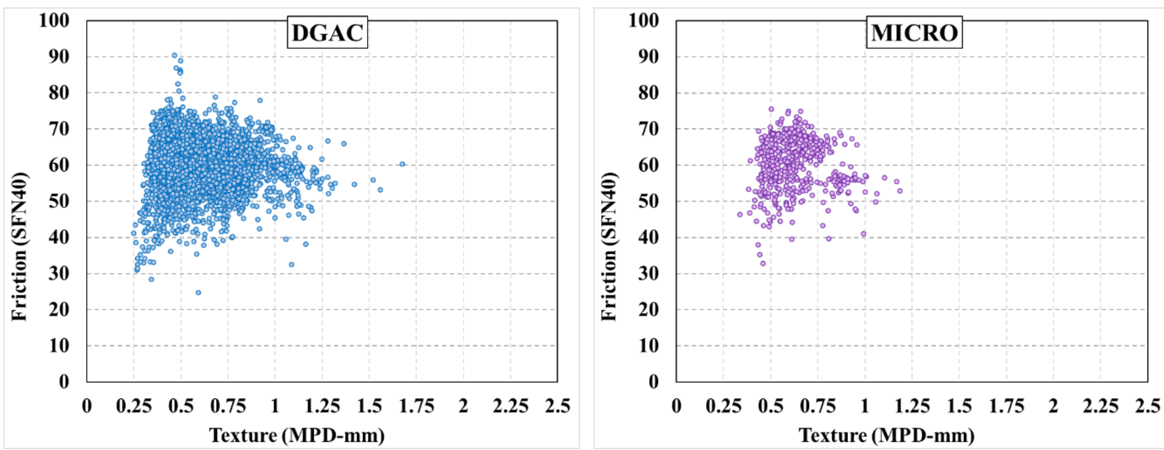
Table B3. Mean and Standard Deviation for SFN40 and MPD for District 3 Surveyed and Analyzed Data

Surface Mix	**Surveyed Network**				**Analyzed Network**			
	Friction (SFN40)		**Texture (MPD, in mm)**		**Friction (SFN40)**		**Texture (MPD, in mm)**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
DGAC	61.0	6.8	0.62	0.18	60.0	6.1	0.69	0.16
THMACO	—	—	—	—	—	—	—	—
SMA	—	—	—	—	—	—	—	—
MICRO	60.1	7.2	0.63	0.15	60.6	6.9	0.62	0.14
PCCP	67.6	4.3	0.69	0.12	67.6	4.3	0.69	0.12
All Mixes	61.2	6.9	0.62	0.17	60.5	6.3	0.68	0.16

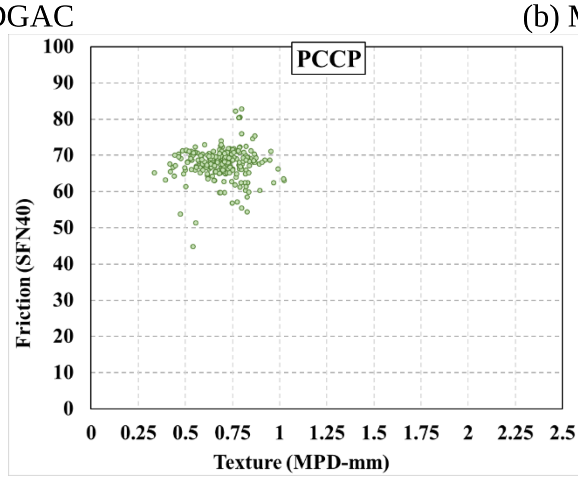


(a) SFN40 (b) MPD

Figure B1. Graphs. Friction (SFN40) and texture (MPD) for District 3 surveyed data.



(a) DGAC (b) MICRO



(c) PCCP

Figure B2. SFN40 vs. MPD Plots by Pavement Surface Mix (District 3 Surveyed Data)

Table B4. Total and Average Crash Count per Lane per 0.1 Miles by Pavement Surface Mix for District 3 Analyzed Network

	Total Crash Count by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	0	0	0	0	0	0
Primary	1,593	0	0	129	100	1,822
	Average Crash Count by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	—	—	—	—	—	—
Primary	2.5	—	—	1.9	2.1	2.4

Notes:

1. Total crashes include both directions of travel for undivided roadway.
2. Average crashes per lane-mile computed using lane counts for both directions of travel on undivided roadway.

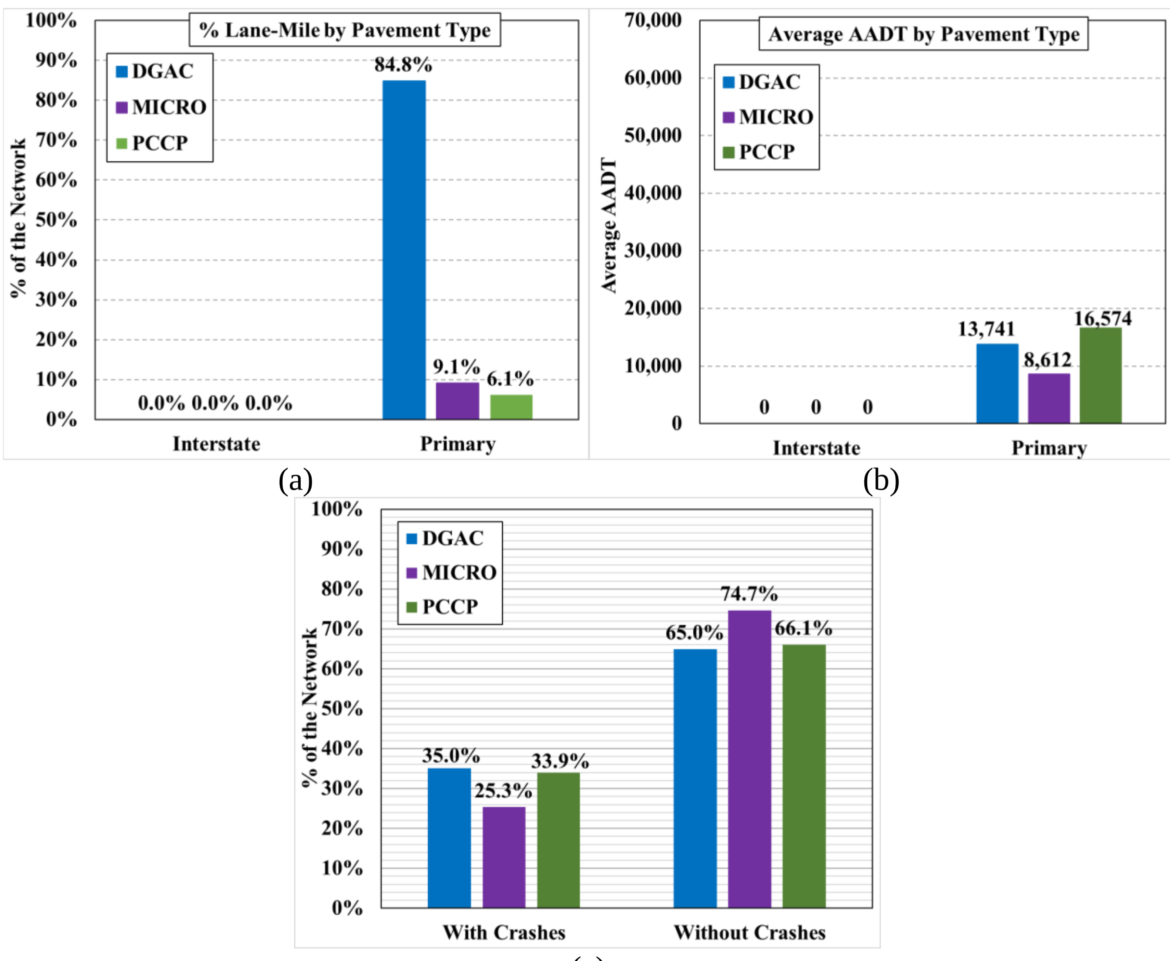


Figure B3. Network Crashes, Lane-miles, and Traffic by Pavement Surface Mix (District 3 Analyzed Data)

Table B5. Crash Counts Separated by Surface Condition and Severity for District 3 Analyzed Network

Crash Severity	Wet Crashes		Dry Crashes		Wet and Dry Crashes	
	Observed	%Wet	Observed	%Dry	Observed	%Wet+Dry
Fatality (K)	4	1.09%	19	1.31%	23	1.26%
Serious Injury (A)	23	6.25%	117	8.05%	140	7.68%
Other Injury (B & C)	82	22.28%	345	23.73%	427	23.44%
PDO (O)	259	70.38%	973	66.92%	1,232	67.62%
(K) + (A)	27	7.34%	136	9.35%	163	8.95%
Total	368	—	1,454	—	1,822	—

Note: Crash counts from 2017 through 2019.

The overdispersion and log-likelihood values for the District 3 SPF model are 0.563 and −3,243.

Table B6. Final SPF Coefficients for District 3 with CFME Data

Model Variables	*β*	*p*-value	Model Variables	*β*	*p*-value
Intercept	-6.478	0.00	Interaction Term(s):		
ln(AADT)	0.626	0.00	SFN40 × Route Type	—	—
Friction (SFN40)	0.004	0.81	SFN40 × Texture	-0.039	0.08
Texture (MPD, in mm)	1.956	0.13	SFN40 × Grade (%)	0.003	0.09
Divided Roadway	—	—	SFN40 × Cross-slope (%)	—	—
Intersections & Ramp Access Points	2.011	0.00	SFN40 × Curvature (1/m)	—	—
Route Type	—	—	SFN40 × Intersections/Ramp Access	-0.026	0.00
Pavement Surface Mix			SFN40 × Divided Roadway	—	—
THMACO	—	—	SFN40 × Number of Travel Lanes	—	—
SMA	—	—	SFN40 × Pavement Surface Mix		
MICRO	—	—	*SFN40 × THMACO*	—	—
PCCP	—	—	*SFN40 × SMA*	—	—
Grade (%)	-0.197	0.06	*SFN40 × MICRO*	—	—
Cross-slope (%)	—	—	*SFN40 × PCCP*	—	—
Curvature (1/m)	147.628	0.00			
Number of Travel Lanes	-0.164	0.00			

Note: Indicator variable reference value for route type is primary and pavement surface mix is DGAC.

Table B7. Average Cost for Friction Enhancement Treatments in District 3

Treatment Option	Cost/Lane/Mile	Cost/Lane/0.1 Mile
DGAC	$50,660	$5,066
THMACO	—	—
SMA	—	—
MICRO	$19,440	$1,944
PCCP w/CDG	$42,240	$4,224
HFST	$128,270	$12,827

Table B8. Estimated Average Friction Values (SFN40) for New Friction Enhancement Treatments in District 3

Current Surface	Surveyed SFN40 Mean	Surveyed SFN40 Standard Deviation (SD)	SFN40 Enhancement (Mean + 1.0 SD)
DGAC	61.0	6.8	70
THMACO	—	—	—
SMA	—	—	—
MICRO	60.1	7.2	65
PCCP	67.6	4.3	70 (w/CDG)
HFST	—	—	80

Table B9. Treatment Option Implementation Strategy for District 3

Interstate and Primary			
Strategy	**Current Surface Mix**	**Mix Age**	**Treatment Option**
1	DGAC	< 8 Years	MICRO
2	DGAC or MICRO	≥ 8 Years	DGAC
3	PCCP	≥ 8 Years	PCCP w/CDG

Note: Pavement age since 2019.

Table B10. Comprehensive Crash Costs for District 3 Analyzed Network

Crash Severity	Crash Count (2017–2019)	FHWA Cost/Crash	Comprehensive Costs
Fatality (K)	23	$11,295,402	$259,794,246
Injury A	140	$654,967	$91,695,380
Injury B	365	$198,492	$72,449,580
Injury C	62	$125,562	$7,784,844
PDO (O)	1,232	$11,906	$14,668,192
Total	1,822	—	$446,392,242

Table B11. Number of Recommended 0.1-Mile Friction Enhancement Treatment Sections with BCR > 1 and Savings > $500,000 in District 3

Savings per Section >	Number of 0.1-Mile Friction Enhancement Treatment Sections						
	DGAC	**THMACO**	**SMA**	**MICRO**	**PCCP w/CDG**	**HFST**	**Total**
$5.0 M	0	—	—	0	0	0	0
$4.0 M	0	—	—	0	0	0	0
$3.0 M	0	—	—	0	0	0	0
$2.0 M	0	—	—	0	0	0	0
$1.0 M	2	—	—	0	0	1	3
$0.5 M	5	—	—	2	0	2	9
Total	7	—	—	2	0	3	12

Table B12. Potential Crash Reductions and Total Cost Savings Benefits for the Recommended 0.1-Mile Friction Enhancement Treatment Sections in District 3

Savings per Section >	0.1-mile Sections	Predicted Crash Reductions	Total Treatment Cost	Total Savings
$5.0 M	0	0	$0	$0
$4.0 M	0	0	$0	$0
$3.0 M	0	0	$0	$0
$2.0 M	0	0	$0	$0
$1.0 M	3	16	$45,918	$3,780,254
$0.5 M	9	24	$109,744	$5,674,641
Total	12	39	$155,662	$9,454,895

APPENDIX C: DISTRICT 5 RESULTS

Table C1. Miles and Lane-miles by Pavement Surface Mix for District 5 Surveyed Network

	Miles Surveyed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	58.9	49.9	144.9	12.5	55.3	321.5
Primary	347.1	0.0	63.8	25.8	25.4	(462.1) 851.2
Total	406.0	49.9	208.7	38.3	80.7	(783.6) 1,172.7
	Lane-Mile Surveyed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	135.6	115.9	380.1	25.0	188.3	844.9
Primary	796.7	0.0	213.0	64.2	51.0	(1,124.9) 2,076.2
Total	932.3	115.9	593.1	89.2	239.3	(1,969.8) 2,921.1

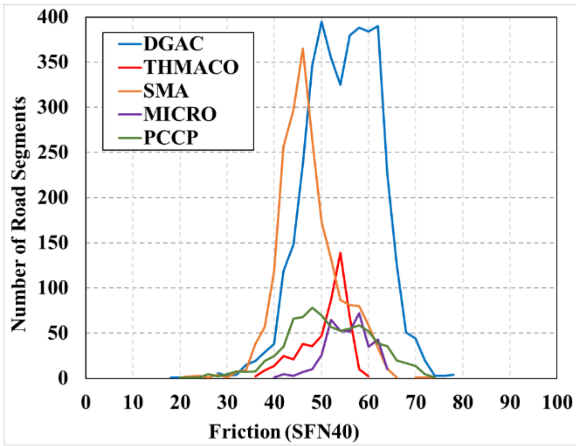
Notes: The totals in parentheses are for identified mix types only.

Table C2. Miles, Lane-miles, and Average AADT by Pavement Surface Mix for District 5 Analyzed Network

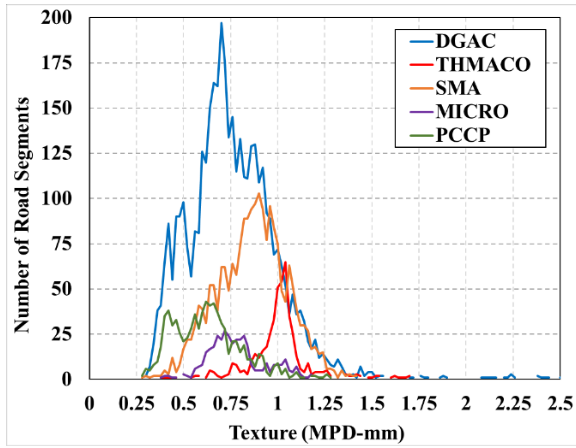
	Miles Analyzed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	43.7	49.4	90.3	12.5	54.5	250.4
Primary	298.2	0.0	29.3	25.8	22.9	376.2
Total	341.9	49.4	119.6	38.3	77.4	626.6
	Lane-Miles Analyzed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	101.3	113.9	258.4	25.0	185.1	683.7
Primary	687.4	0.0	110.4	64.2	45.7	907.7
Total	788.7	113.9	368.8	89.2	230.8	1,591.4
	Average AADT by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	59,449	63,324	104,038	36,228	110,264	86,194
Primary	14,276	—	12,452	8,496	19,274	14,042

Table C3. Mean and Standard Deviation for SFN40 and MPD for District 5 Surveyed and Analyzed Data

Surface Mix	**Surveyed Network**				**Analyzed Network**			
	Friction (SFN40)		**Texture (MPD, in mm)**		**Friction (SFN40)**		**MPD (texture)**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
DGAC	53.6	7.4	0.77	0.29	53.3	6.9	0.79	0.27
THMACO	49.8	4.9	1.00	0.19	49.7	4.9	1.01	0.18
SMA	46.2	6.2	0.86	0.19	44.7	5.4	0.83	0.19
MICRO	54.5	4.7	0.77	0.15	54.5	4.7	0.77	0.15
PCCP	50.7	9.1	0.63	0.20	50.9	9.2	0.61	0.19
All Mixes	51.1	7.7	0.79	0.26	51.1	7.5	0.79	0.25

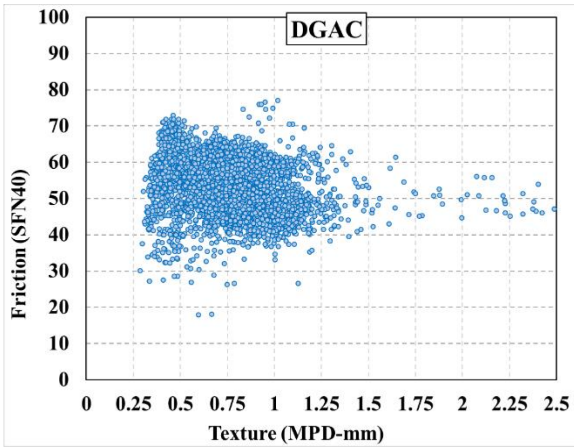


(a) SFN40

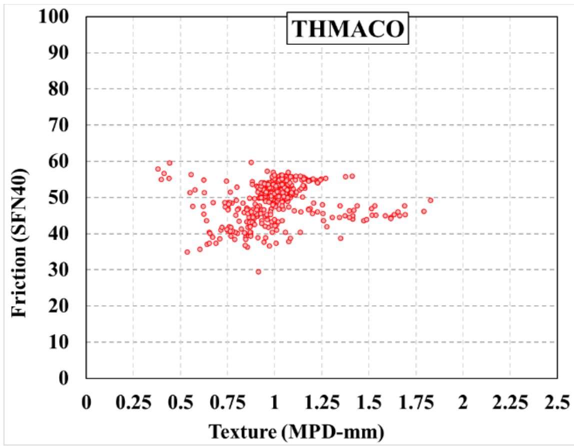


(b) MPD

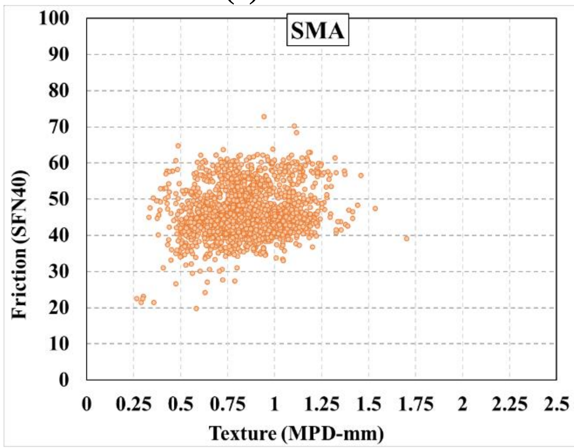
Figure C1. Friction (SFN40) and Texture (MPD) for District 5 Surveyed Data



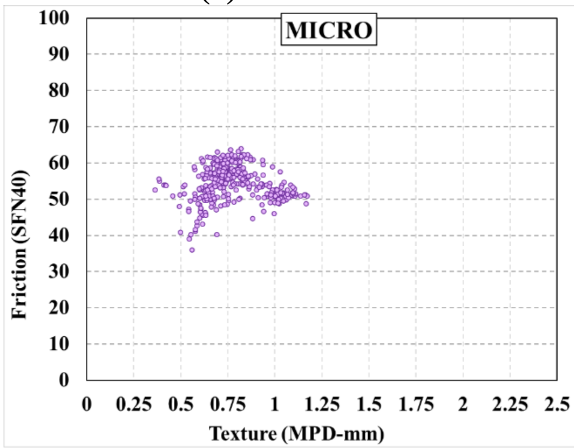
(a) DGAC



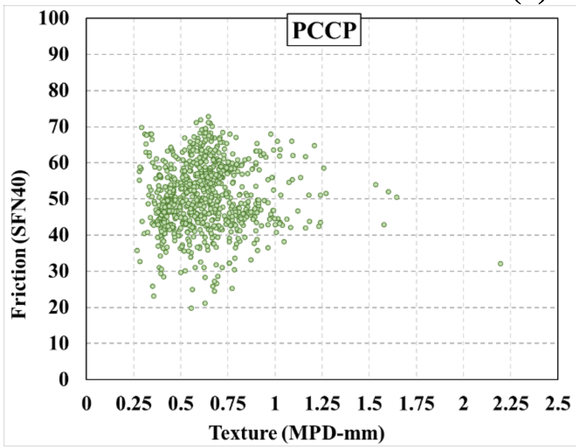
(b) THMACO



(c) SMA



(d) MICRO



(e) PCCP

Figure C2. SFN40 vs. MPD Plots by Pavement Surface Mix (District 5 Surveyed Data)

Table C4. Total and Average Crash Count per Lane per 0.1 Mile by Pavement Surface Mix for District 5 Analyzed Network

	Total Crash Count by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	1,049	1,027	4,080	60	1,830	8,046
Primary	2,342	0	119	49	173	2,683
Total	3,391	1,027	4,199	109	2,003	10,729
	Average Crash Count by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	10.4	9.0	15.8	2.4	9.9	11.8
Primary	3.4	—	1.1	0.8	3.8	3.0

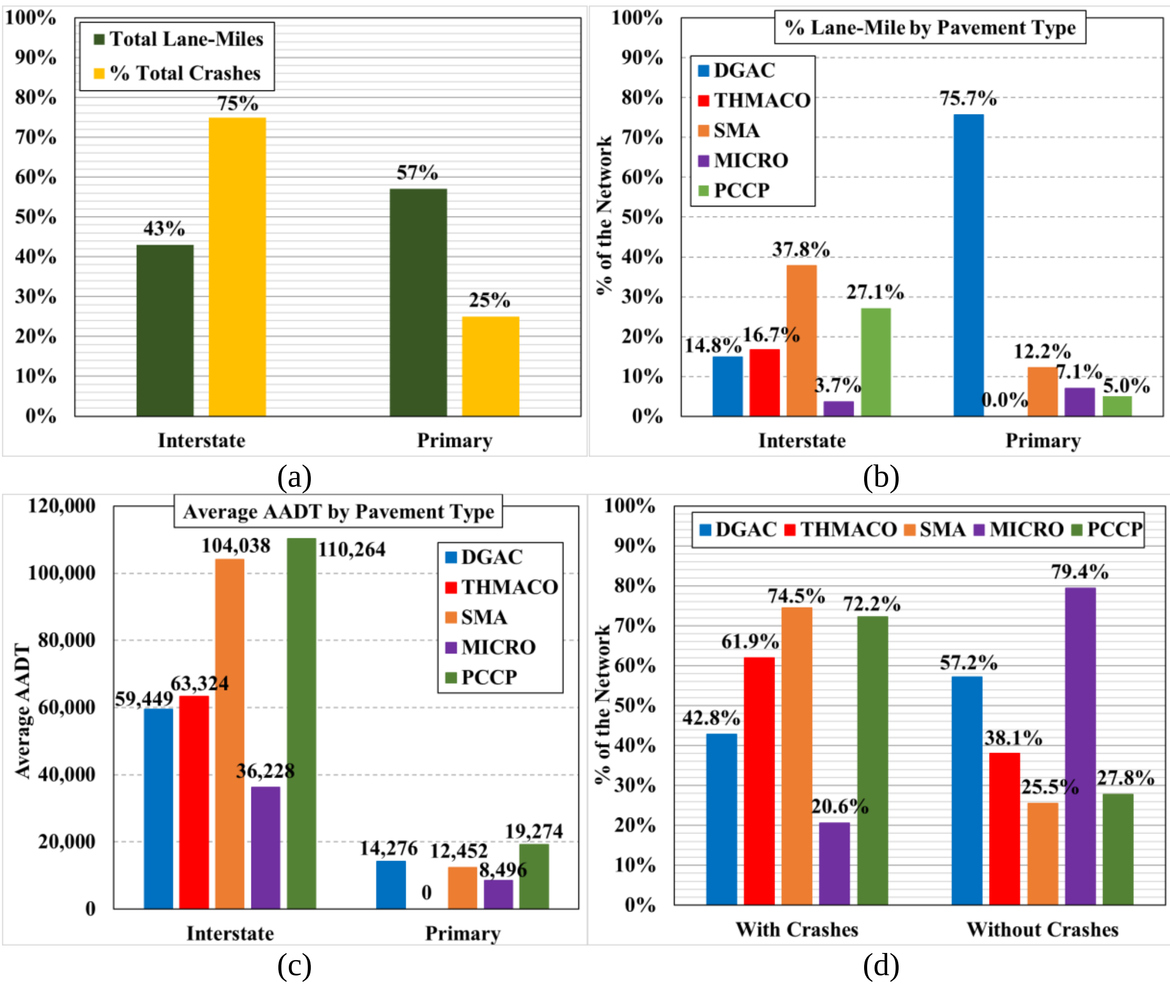


Figure C3. Network Crashes, Lane-miles, and Traffic by Pavement Surface Mix (District 5 Analyzed Data)

Table C5. Crash Counts Separated by Surface Condition and Severity for District 5 Analyzed Network

Crash Severity	Wet Crashes		Dry Crashes		Wet and Dry Crashes	
	Observed	%Wet	Observed	%Dry	Observed	%Wet+Dry
Fatality (K)	13	0.59%	70	0.82%	83	0.77%
Serious Injury (A)	76	3.46%	477	5.59%	553	5.15%
Other Injury (B & C)	671	30.56%	2,463	28.86%	3,134	29.21%
PDO (O)	1,436	65.39%	5,523	64.73%	6,959	64.86%
(K) + (A)	89	4.05%	547	6.41%	636	5.93%
Total	2,196	—	8,533	—	10,729	—

Note: Crash counts from 2017 through 2019.

The overdispersion and log-likelihood values for the District 5 SPF model are 0.442 and −8,951.

Table C6. Final SPF Coefficients for District 5 with CFME Data

Model Variables	*β*	*p*-value	Model Variables	*β*	*p*-value
Intercept	-11.509	0.00	Interaction Term(s):		
ln(AADT)	1.270	0.00	SFN40 × Route Type	0.030	0.00
Friction (SFN40)	-0.013	0.11	SFN40 × Texture	—	—
Texture (MPD, in mm)	—	—	SFN40 × Grade (%)	-0.004	0.11
Divided Roadway	0.594	0.17	SFN40 × Cross-slope (%)	—	—
Intersections & Ramp Access Points	0.953	0.00	SFN40 × Curvature (1/m)	—	—
Route Type	-1.939	0.00	SFN40 × Intersections/Ramp Access	-0.008	0.10
Pavement Surface Mix			SFN40 × Divided Roadway	-0.019	0.03
THMACO	0.852	0.10	SFN40 × Number of Travel Lanes	—	—
SMA	-0.846	0.02	SFN40 × Pavement Surface Mix		
MICRO	-5.496	0.00	*SFN40 × THMACO*	-0.025	0.02
PCCP	-1.005	0.00	*SFN40 × SMA*	0.016	0.03
Grade (%)	0.127	0.23	*SFN40 × MICRO*	0.088	0.00
Cross-slope (%)	—	—	*SFN40 × PCCP*	0.015	0.02
Curvature (1/m)	239.232	0.00			
Number of Travel Lanes	-0.128	0.00			

Note: Indicator variable reference value for route type is primary and pavement surface mix is DGAC.

Table C7. Average Cost for Friction Enhancement Treatments in District 5

Treatment Option	Cost/Lane/Mile	Cost/Lane/0.1 Mile
DGAC	$57,614	$5,761
THMACO	$29,322	$2,932
SMA	$89,508	$8,951
MICRO	$16,960	$1,696
PCCP w/CDG	$77,440	$7,744
HFST	$128,270	$12,827

Table C8. Estimated Average Friction Values (SFN40) for New Friction Enhancement Treatments in District 5

Current Surface	Surveyed SFN40 Mean	Surveyed SFN40 Standard Deviation (SD)	SFN40 Enhancement (Mean + 1.0 SD)
DGAC	53.6	7.4	60
THMACO	49.8	4.9	55
SMA	46.2	6.2	50
MICRO	54.5	4.7	60
PCCP	50.7	9.1	60 (w/CDG)
HFST	—	—	80

Table C9. Treatment Option Implementation Strategy for District 5

Interstate and Primary			
Strategy	**Current Surface Mix**	**Mix Age**	**Treatment Option**
1	All Asphalt	≤ 5 Years	MICRO
2	DGAC	≥ 10 Years	DGAC
3	All Asphalt	> 6 Years; ≤ 10 Years	THMACO
4	SMA	> 10 Years	SMA
5	PCCP	—	PCCP w/CDG

Note: Pavement age since 2019.

Table C10. Comprehensive Crash Costs for District 5 Analyzed Network

Crash Severity	Crash Count (2017–2019)	FHWA Cost/Crash	Comprehensive Costs
Fatality (K)	83	$11,295,402	$937,518,366
Injury A	553	$654,967	$362,196,751
Injury B	2,568	$198,492	$509,727,456
Injury C	566	$125,562	$71,068,092
PDO (O)	6,959	$11,906	$82,853,854
Total	10,729	—	$1,963,364,519

Table C11. Number of Recommended 0.1-Mile Friction Enhancement Treatment Sections with BCR > 1 and Savings > $500,000 in District 5

Savings per Section >	Number of 0.1-Mile Friction Enhancement Treatment Sections						
	DGAC	**THMACO**	**SMA**	**MICRO**	**PCCP w/CDG**	**HFST**	**Total**
$5.0 M	0	0	0	0	0	0	0
$4.0 M	0	0	0	0	0	0	0
$3.0 M	0	0	0	0	0	0	0
$2.0 M	0	0	0	0	0	0	0
$1.0 M	0	0	0	3	0	0	3
$0.5 M	5	2	0	32	0	3	42
Total	5	2	0	35	0	3	45

Table C12. Potential Crash Reductions and Total Cost Savings Benefits for Recommended 0.1-Mile Friction Enhancement Treatment Sections in District 5

Savings per Section >	0.1-Mile Sections	Predicted Crash Reductions	Total Treatment Cost	Total Savings
$5.0 M	0	0	$0	$0
$4.0 M	0	0	$0	$0
$3.0 M	0	0	$0	$0
$2.0 M	0	0	$0	$0
$1.0 M	3	18	$15,264	$3,362,785
$0.5 M	42	152	$294,249	$27,607,718
Total	45	171	$309,513	$30,970,503

APPENDIX D: DISTRICT 6 RESULTS

Table D1. Miles and Lane-miles by Pavement Surface Mix for District 6 Surveyed Network

	Miles Surveyed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	0.0	4.1	87.8	0.0	0.1	92.0
Primary	279.3	12.6	29.4	54.9	2.6	378.8
Total	279.3	16.7	117.2	54.9	2.7	470.8
	Lane-Miles Surveyed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	0.0	12.3	263.4	0.0	0.3	276.0
Primary	529.9	25.2	59.8	109.8	5.2	729.9
Total	529.9	37.5	323.2	109.8	5.5	1,005.9

Table D2. Miles, Lane-miles, and Average AADT by Pavement Surface Mix for District 6 Analyzed Network

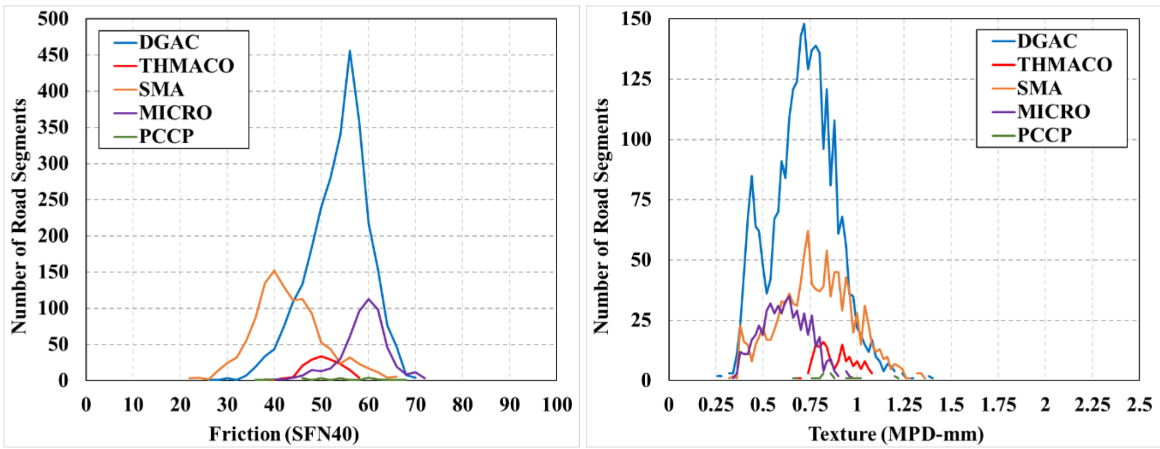
	Miles Analyzed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	0.0	4.1	78.0	0.0	0.1	82.2
Primary	209.6	2.9	18.8	27.2	2.2	260.7
Total	209.6	7.0	96.8	27.2	2.3	342.9
	Lane-Mile Analyzed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	0.0	12.3	234.0	0.0	0.3	246.6
Primary	488.3	11.2	38.5	54.4	5.0	597.4
Total	488.3	23.5	272.5	54.4	5.3	844.0
	Average AADT by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	—	103,000	116,466	—	149,000	115,834
Primary	12,187	4,800	28,907	8,492	26,909	13,049

Notes:

1. Lane-miles are the number of travel lanes in both directions of travel for undivided roadway.
2. AADT is for direction of travel only.

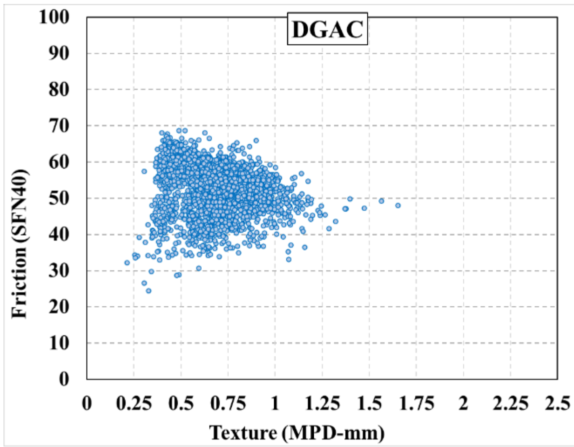
Table D3. Mean and Standard Deviation for SFN40 and MPD for District 6 Surveyed and Analyzed Data

Surface Mix	Surveyed Network				Analyzed Network			
	Friction (SFN40)		Texture (MPD, in mm)		Friction (SFN40)		MPD (texture)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DGAC	52.6	6.3	0.71	0.18	52.3	6.0	0.74	0.16
THMACO	49.2	4.0	0.87	0.11	47.2	3.8	0.88	0.12
SMA	42.1	7.5	0.78	0.20	42.5	7.6	0.79	0.21
MICRO	57.9	5.2	0.61	0.13	59.6	4.8	0.68	0.11
PCCP	52.7	9.5	0.95	0.21	54.1	9.3	0.97	0.22
All Mixes	50.5	8.3	0.72	0.19	50.0	8.2	0.76	0.18

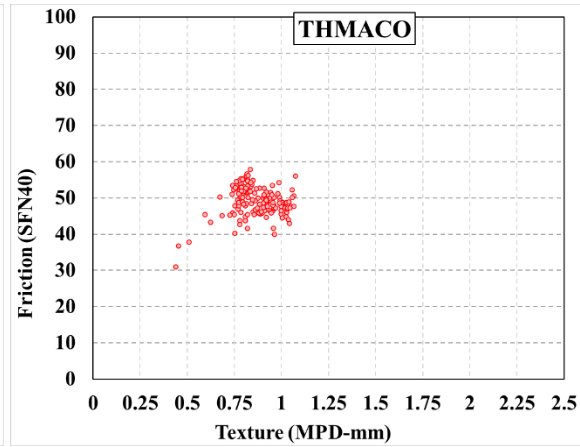


(a) SFN40 (b) MPD

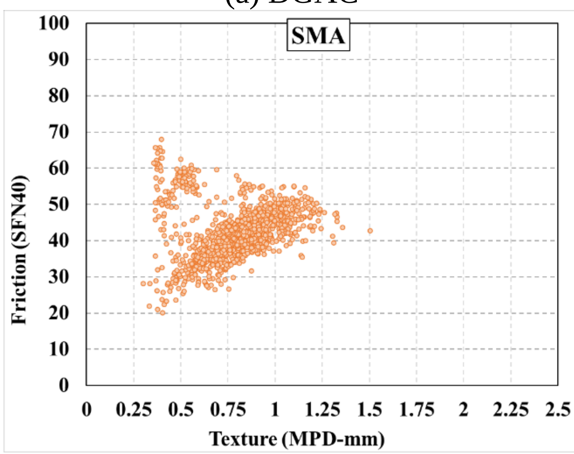
Figure D1. Friction (SFN40) and Texture (MPD) for District 6 Surveyed Data



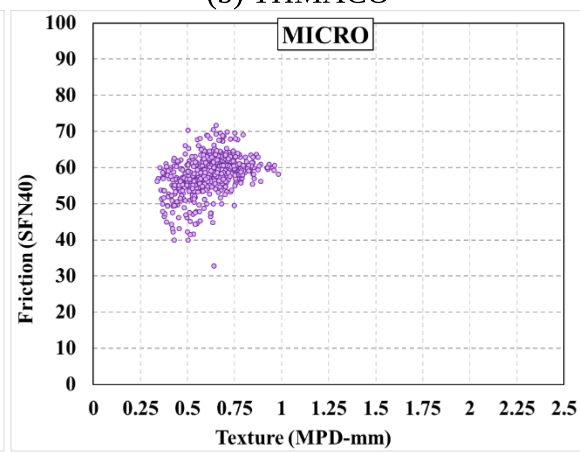
(a) DGAC



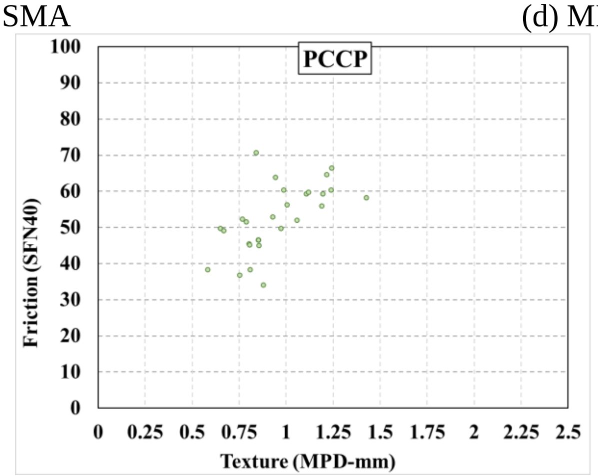
(b) THMACO



(c) SMA



(d) MICRO



(e) PCCP

Figure D2. SFN40 vs. MPD Plots by Pavement Surface Mix (District 6 Surveyed Data)

Table D4. Total and Average Crash Count per Lane per 0.1 Miles by Pavement Surface Mix for District 6 Analyzed Network

	Total Crash Count by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	0	68	3,564	0	4	3,636
Primary	2,605	15	444	92	28	3,184
Total	2,605	83	4,008	92	32	6,820
	Average Crash Count by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	—	5.5	15.2	—	13.3	14.7
Primary	5.3	1.3	11.5	1.7	5.6	5.3

Notes:
1. Total crashes include both directions of travel for undivided roadway.
2. Average crashes per lane-mile computed using lane counts for both directions of travel on undivided roadway.

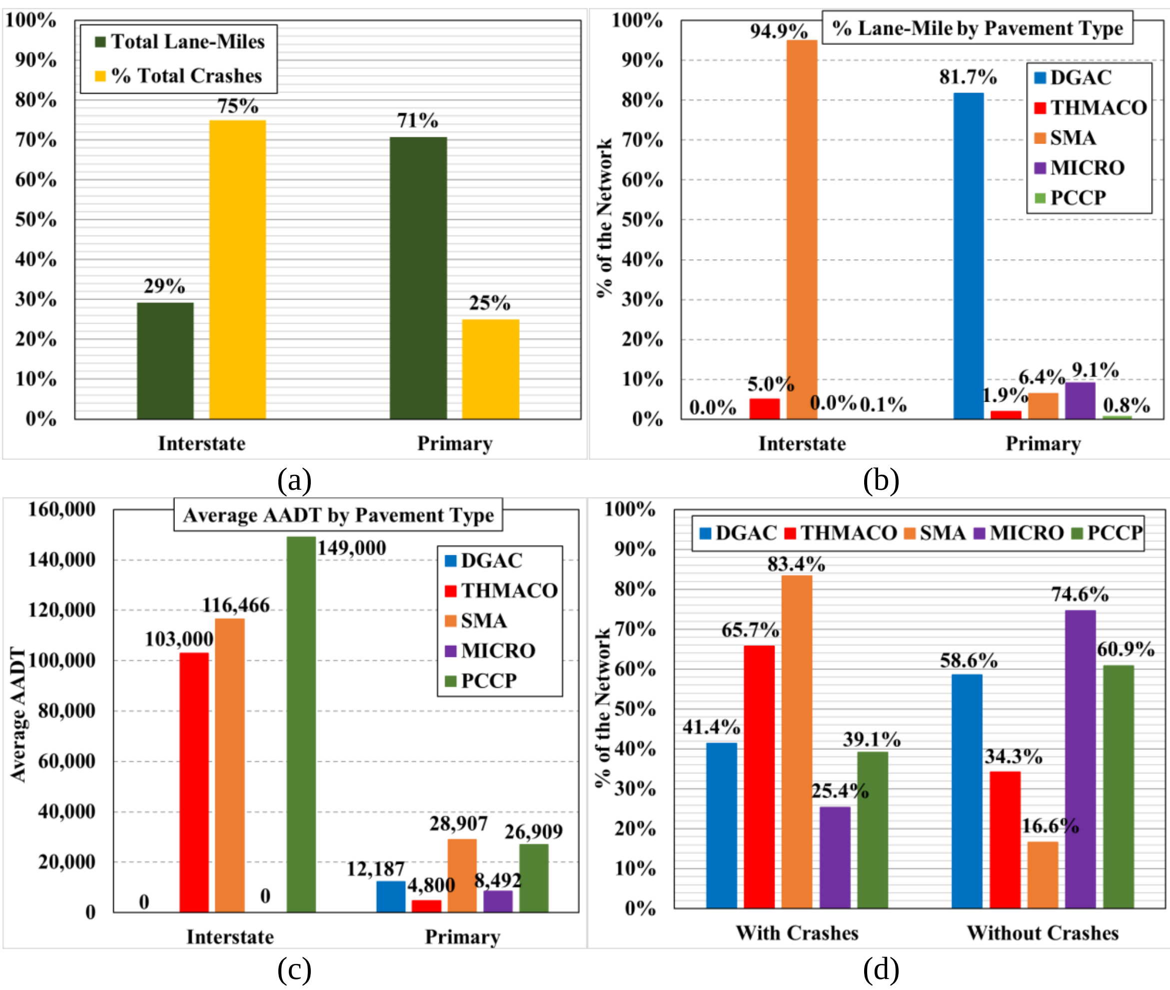


Figure D3. Network Crashes, Lane-miles, and Traffic by Pavement Surface Mix (District 6 Analyzed Data)

Table D5. Crash Counts Separated by Surface Condition and Severity for District 6 Analyzed Network

Crash Severity	Wet Crashes		Dry Crashes		Wet and Dry Crashes	
	Observed	%Wet	Observed	%Dry	Observed	%Wet+Dry
Fatality (K)	6	0.49%	39	0.70%	45	0.66%
Serious Injury (A)	54	4.40%	246	4.40%	300	4.40%
Other Injury (B & C)	275	22.39%	1,246	22.28%	1,521	22.30%
PDO (O)	893	72.72%	4,061	72.62%	4,954	72.64%
(K) + (A)	60	4.89%	285	5.10%	345	5.06%
Total	1,228	—	5,592	—	6,820	—

Note: Crash counts from 2017 through 2019.

The overdispersion and log-likelihood values for the District 6 SPF model are 0.524 and −5,007.

Table D6. Final SPF Coefficients for District 6 with CFME Data

Model Variables	*β*	*p*-value	Model Variables	*β*	*p*-value
Intercept	-5.735	0.00	Interaction Term(s):		
ln(AADT)	0.897	0.00	SFN40 × Route Type	—	—
Friction (SFN40)	-0.046	0.00	SFN40 × Texture	-0.050	0.00
Texture (MPD, in mm)	1.440	0.08	SFN40 × Grade (%)	—	—
Divided Roadway	-1.710	0.00	SFN40 × Cross-slope (%)	—	—
Intersections & Ramp Access Points	0.721	0.00	SFN40 × Curvature (1/m)	—	—
Route Type	-0.854	0.00	SFN40 × Intersections/Ramp Access	—	—
Pavement Surface Mix			SFN40 × Divided Roadway	0.021	0.04
THMACO	-2.378	0.17	SFN40 × Number of Travel Lanes	—	—
SMA	-0.183	0.62	SFN40 × Pavement Surface Mix		
MICRO	-3.938	0.01	*SFN40 × THMACO*	0.044	0.24
PCCP	-1.790	0.24	*SFN40 × SMA*	0.006	0.44
Grade (%)	—	—	*SFN40 × MICRO*	0.070	0.01
Cross-slope (%)	—	—	*SFN40 × PCCP*	0.028	0.37
Curvature (1/m)	—	—			
Number of Travel Lanes	0.209	0.00			

Note: Indicator variable reference value for route type is primary and pavement surface mix is DGAC.

Table D7. Average Cost for Friction Enhancement Treatments in District 6

Treatment Option	Cost/Lane/Mile	Cost/Lane/0.1 Mile
DGAC	—	—
THMACO	$43,428	$4,343
SMA	—	—
MICRO	$18,438	$1,844
PCCP w/CDG	—	—
HFST	$128,270	$12,827

Table D8. Estimated Average Friction Values (SFN40) for New Friction Enhancement Treatments in District 6

Current Surface	Surveyed SFN40 Mean	Surveyed SFN40 Standard Deviation (SD)	SFN40 Enhancement (Mean + 1.0 SD)
DGAC	—	—	—
THMACO	49.2	4.0	55
SMA	—	—	—
MICRO	57.9	5.2	65
PCCP	—	—	—
HFST	—	—	80

Table D9. Treatment Option Implementation Strategy for District 6

Interstate			
Strategy	**Current Surface Mix**	**Mix Age**	**Treatment Option**
1	All Surfaces	≥ 5 Years	THMACO
Primary			
Strategy	**Current Surface Mix**	**Mix Age**	**Treatment Option**
1	All Surfaces	≥ 5 Years; < 8 Years	MICRO
2	All Surfaces	≥ 8 Years	THMACO

Note: Pavement age since 2019.

Table D10. Comprehensive Crash Costs for District 6 Analyzed Network

Crash Severity	Crash Count (2017–2019)	FHWA Cost/Crash	Comprehensive Costs
Fatality (K)	45	$11,295,402	$508,293,090
Injury A	300	$654,967	$196,490,100
Injury B	1,218	$198,492	$241,763,256
Injury C	303	$125,562	$38,045,286
PDO (O)	4,954	$11,906	$58,982,324
Total	6,820	—	$1,043,574,056

Table D11. Number of Recommended 0.1-Mile Friction Enhancement Treatment Sections with BCR > 1 and Savings > $500,000 in District 6

Savings per Section >	Number of 0.1-Mile Friction Enhancement Treatment Sections						
	DGAC	THMACO	SMA	MICRO	PCCP w/CDG	HFST	Total
$5.0 M	—	0	—	0	—	0	0
$4.0 M	—	0	—	0	—	0	0
$3.0 M	—	1	—	1	—	1	3
$2.0 M	—	11	—	5	—	1	17
$1.0 M	—	59	—	5	—	35	99
$0.5 M	—	158	—	29	—	103	290
Total	—	229	—	40	—	140	409

Table D12. Potential Crash Reductions and Total Cost Savings Benefits for the Recommended 0.1-Mile Friction Enhancement Treatment Sections in District 6

Savings per Section >	0.1-Mile Sections	Predicted Crash Reductions	Total Treatment Cost	Total Savings
$5.0 M	0	0	$0	$0
$4.0 M	0	0	$0	$0
$3.0 M	3	63	$62,572	$9,545,725
$2.0 M	17	273	$221,167	$41,596,507
$1.0 M	99	879	$2,127,126	$132,442,291
$0.5 M	290	1,364	$6,063,165	$202,655,154
Total	409	2,580	$8,474,030	$386,239,677

APPENDIX E: DISTRICT 7 RESULTS

Table E1. Miles by Pavement Surface Mix for District 7 Surveyed Network

	Miles Surveyed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	1.4	10.2	91.6	25.3	0.0	128.5
Primary	144.1	0.0	48.4	89.9	0.1	(282.5) 285.3
Total	145.5	10.2	140.0	115.2	0.1	(411.0) 413.8

Notes: The totals in parentheses are for identified mix types only.

Table E2. Miles, Lane-miles, and Average AADT by Pavement Surface Mix for District 7 Analyzed Network

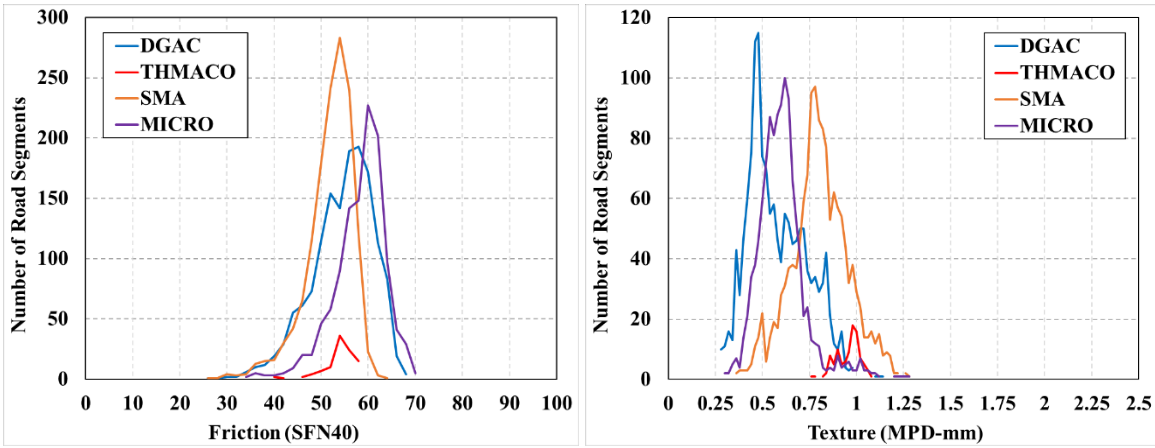
	Miles Analyzed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	1.4	10.2	66.1	25.3	0.0	103.0
Primary	74.8	0.0	42.1	35.0	0.0	151.9
Total	76.2	10.2	108.2	60.3	0.0	254.9
	Lane-Miles Analyzed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	2.8	20.4	132.2	50.6	0.0	206.0
Primary	164.8	0.0	84.0	70.1	0.0	318.9
Total	167.6	20.4	216.2	120.7	0.0	524.9
	AADT by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	39,000	47,029	40,521	38,583	—	40,669
Primary	20,572	—	32,285	23,796	—	24,561

Notes:

1. Lane-miles are the number of travel lanes in both directions of travel for undivided roadway.
2. AADT is for direction of travel only.

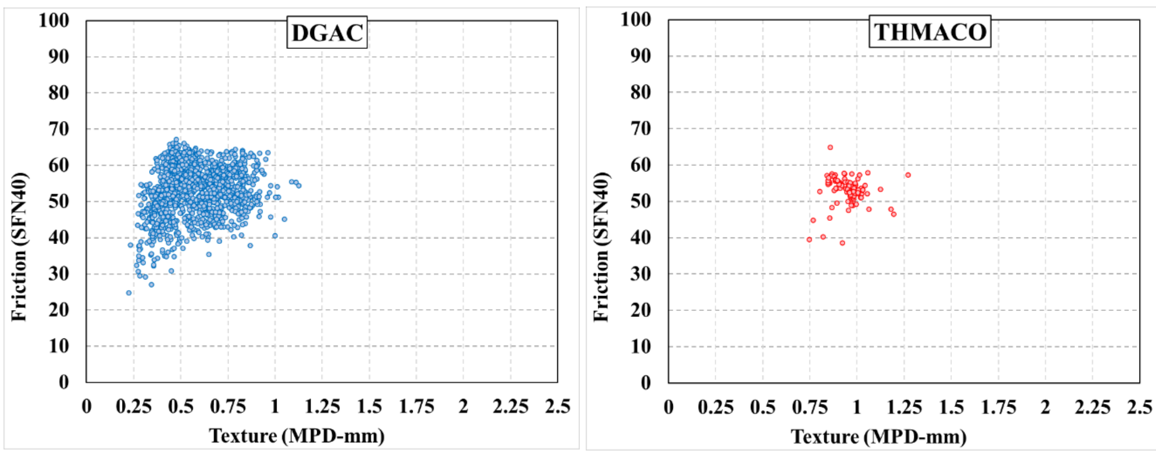
Table E3. Mean and Standard Deviation for SFN40 and MPD for District 7 Surveyed and Analyzed Data

Surface Mix	Surveyed Network				Analyzed Network			
	Friction (SFN40)		Texture (MPD, in mm)		Friction (SFN40)		Texture (MPD, in mm)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DGAC	53.5	6.6	0.57	0.16	52.8	6.0	0.67	0.14
THMACO	52.9	3.8	0.95	0.08	52.9	3.8	0.95	0.08
SMA	50.8	5.1	0.79	0.16	50.9	4.8	0.81	0.16
MICRO	57.2	5.4	0.60	0.13	57.9	4.8	0.58	0.11
PCCP	—	—	—	—	—	—	—	—
All Mixes	53.6	6.3	0.66	0.19	53.2	5.8	0.72	0.17

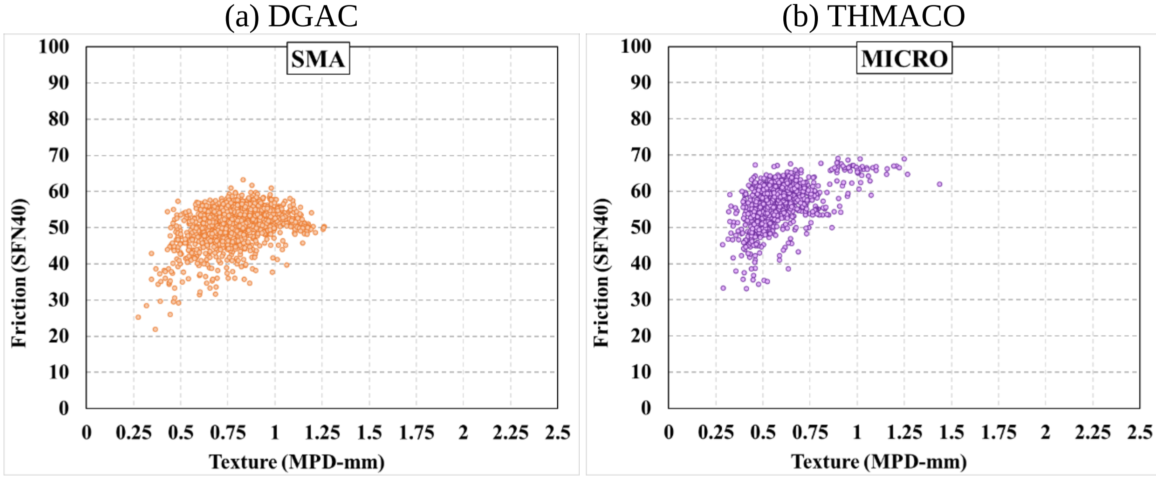


(a) SFN40 (b) MPD

Figure E1. Friction (SFN40) and Texture (MPD) for District 7 Surveyed Data



(a) DGAC (b) THMACO



(c) SMA (d) MICRO

Figure E2. SFN40 vs. MPD Plots by Pavement Surface Mix (District 7 Surveyed Data)

Table E4. Total and Average Crash Count per Lane per 0.1 Miles by Pavement Surface Mix for District 7 Analyzed Network

	Total Crash Count by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	15	165	786	154	0	1,120
Primary	1,397	0	578	328	0	2,303
Total	1,412	165	1,364	482	0	3,423
	Average Crash Count by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	5.4	8.1	5.9	3.0	—	5.4
Primary	8.5	—	6.9	4.7	—	7.2

Notes:

1. Total crashes include both directions of travel for undivided roadway.
2. Average crashes per lane-mile computed using lane counts for both directions of travel on undivided roadway.

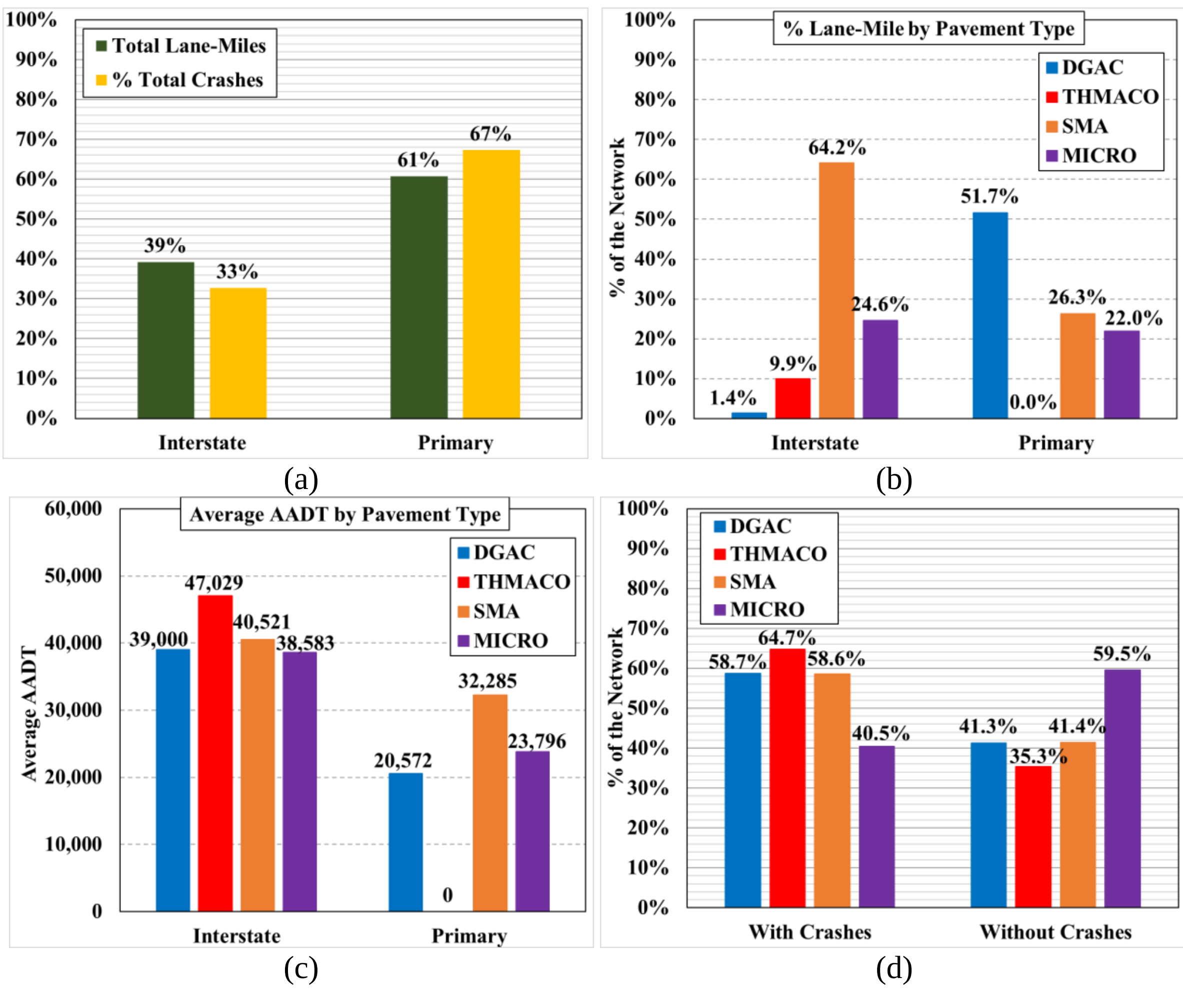


Figure E3. Network Crashes, Lane-miles, and Traffic by Pavement Surface Mix (District 7 Analyzed Data)

Table E5. Crash Counts Separated by Surface Condition and Severity for District 7 Analyzed Network

Crash Severity	Wet Crashes		Dry Crashes		Wet and Dry Crashes	
	Observed	%Wet	Observed	%Dry	Observed	%Wet+Dry
Fatality (K)	1	0.14%	26	0.96%	27	0.79%
Serious Injury (A)	29	3.99%	154	5.71%	183	5.35%
Other Injury (B & C)	200	27.51%	663	24.59%	863	25.21%
PDO (O)	497	68.36%	1,853	68.73%	2,350	68.65%
(K) + (A)	30	4.13%	180	6.68%	210	6.13%
Total	727	—	2,696	—	3,423	—

Note: Crash counts from 2017 through 2019.

The overdispersion and log-likelihood values for the District 7 SPF model are 0.672 and −3,644.

Table E6. Final SPF Coefficients for District 7 with CFME Data

Model Variables	*β*	*p*-value	Model Variables	*β*	*p*-value
Intercept	-9.630	0.00	Interaction Term(s):		
ln(AADT)	0.897	0.00	SFN40 × Route Type	—	—
Friction (SFN40)	0.018	0.48	SFN40 × Texture	—	—
Texture (MPD, in mm)	-0.396	0.04	SFN40 × Grade (%)	—	—
Divided Roadway	-0.529	0.00	SFN40 × Cross-slope (%)	—	—
Intersections & Ramp Access Points	0.856	0.00	SFN40 × Curvature (1/m)	—	—
Route Type	—	—	SFN40 × Intersections/Ramp Access	—	—
Pavement Surface Mix			SFN40 × Divided Roadway	—	—
THMACO	-0.461	0.77	SFN40 × Number of Travel Lanes	-0.032	0.00
SMA	-0.365	0.51	SFN40 × Pavement Surface Mix		
MICRO	1.294	0.08	*SFN40 × THMACO*	0.008	0.79
PCCP	—	—	*SFN40 × SMA*	0.003	0.79
Grade (%)	—	—	*SFN40 × MICRO*	-0.029	0.03
Cross-slope (%)	—	—	*SFN40 × PCCP*	—	—
Curvature (1/m)	101.539	0.10			
Number of Travel Lanes	1.842	0.00			

Note: Indicator variable reference value for route type is primary and pavement surface mix is DGAC.

Table E7. Average Cost for Friction Enhancement Treatments in District 7

Treatment Option	Cost/Lane/Mile	Cost/Lane/0.1 Mile
DGAC	$43,030	$4,303
THMACO	—	—
SMA	$86,040	$8,604
MICRO	$16,960	$1,696
PCCP w/CDG	—	—
HFST	$128,270	$12,827

Table E8. Estimated Average Friction Values (SFN40) for New Friction Enhancement Treatments in District 7

Current Surface	Surveyed SFN40 Mean	Surveyed SFN40 Standard Deviation (SD)	SFN40 Enhancement (Mean + 1.0 SD)
DGAC	53.5	6.6	60
THMACO	—	—	—
SMA	50.8	5.1	55
MICRO	57.2	5.4	65
PCCP	—	—	—
HFST	—	—	80

Table E9. Treatment Option Implementation Strategy for District 7

Interstate			
Strategy	**Current Surface Mix**	**Mix Age**	**Treatment Option**
1	All Surfaces	≥ 5 Years; < 10 Years	MICRO
2	All Surfaces	≥ 10 Years	SMA
Primary			
Strategy	**Current Surface Mix**	**Mix Age**	**Treatment Option**
1	DGAC	< 8 Years	MICRO
2	DGAC or MICRO	≥ 8 Years	DGAC
3	SMA	≥ 10 Years	SMA

Note: Pavement age since 2019.

Table E10. Comprehensive Crash Costs for District 7 Analyzed Network

Crash Severity	Crash Count (2017–2019)	FHWA Cost/Crash	Comprehensive Costs
Fatality (K)	27	$11,295,402	$304,975,854
Injury A	183	$654,967	$119,858,961
Injury B	450	$198,492	$89,321,400
Injury C	413	$125,562	$51,857,106
PDO (O)	2,350	$11,906	$27,979,100
Total	3,423	—	$593,992,421

Table E11. Number of Recommended 0.1-Mile Friction Enhancement Treatment Sections with BCR > 1 and Savings > $500,000 in District 7

Savings per Section >	Number of 0.1-Mile Friction Enhancement Treatment Sections						
	DGAC	**THMACO**	**SMA**	**MICRO**	**PCCP w/CDG**	**HFST**	**Total**
$5.0 M	0	—	0	0	—	0	0
$4.0 M	1	—	0	0	—	0	1
$3.0 M	1	—	0	0	—	1	2
$2.0 M	5	—	0	0	—	4	9
$1.0 M	9	—	0	5	—	4	18
$0.5 M	25	—	0	9	—	24	58
Total	41	—	0	14	—	33	88

Table E12. Potential Crash Reductions and Total Cost Savings Benefits for the Recommended 0.1-Mile Friction Enhancement Treatment Sections in District 7

Savings per Section >	0.1-Mile Sections	Predicted Crash Reductions	Total Treatment Cost	Total Savings
$5.0 M	0	0	$0	$0
$4.0 M	1	24	$17,212	$4,149,978
$3.0 M	2	38	$55,693	$6,612,328
$2.0 M	9	121	$171,382	$20,789,232
$1.0 M	18	140	$251,147	$24,112,225
$0.5 M	58	240	$995,426	$40,691,956
Total	88	564	$1,490,860	$96,355,719

APPENDIX F: DISTRICT 8 RESULTS

Table F1. Miles and Lane-miles by Pavement Surface Mix for District 8 Surveyed Network

	Miles Surveyed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	107.8	0.0	294.0	57.7	0.7	460.2
Primary	152.7	0.0	0.0	51.5	0.0	204.2
Total	260.5	0.0	294.0	109.2	0.7	664.4
	Lane-Miles Surveyed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	215.6	0.0	595.8	115.4	1.4	928.2
Primary	215.0	0.0	0.0	61.2	0.0	276.2
Total	430.6	0.0	595.8	176.6	1.4	1,204.4

Table F2. Miles, Lane-miles, and Average AADT by Pavement Surface Mix for District 8 Analyzed Network

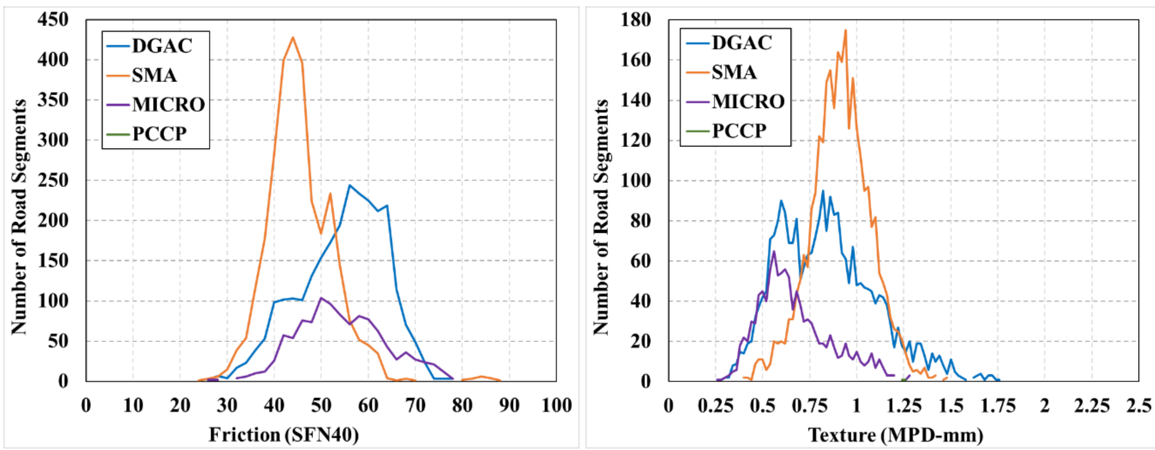
	Miles Analyzed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	89.2	0.0	206.6	25.6	0.7	322.1
Primary	117.4	0.0	0.0	9.5	0.0	126.9
Total	206.6	0.0	206.6	35.1	0.7	449.0
	Lane-Miles Analyzed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	178.4	0.0	421.0	51.2	1.4	652.0
Primary	239.5	0.0	0.0	19.0	0.0	258.5
Total	417.9	0.0	421.0	70.2	1.4	910.5
	Average AADT by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	27,784	—	44,111	44,465	32,857	39,593
Primary	11,387	—	—	6,959	—	11,056

Notes:

1. Lane-miles are the number of travel lanes in both directions of travel for undivided roadway.
2. AADT is for direction of travel only.

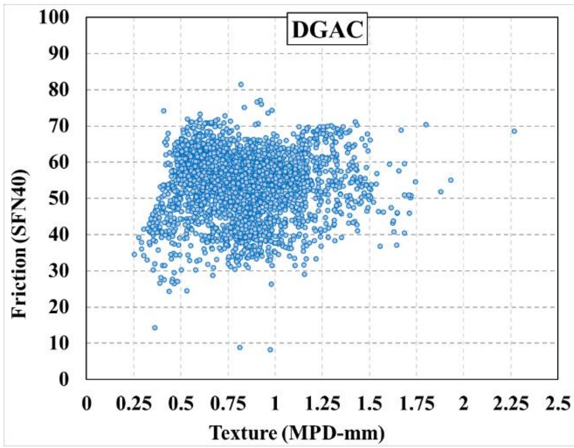
Table F3. Mean and Standard Deviation for SFN40 and MPD for District 8 Surveyed and Analyzed Data

Surface Mix	Surveyed Network				Analyzed Network			
	Friction (SFN40)		Texture (MPD, in mm)		Friction (SFN40)		Texture (MPD, in mm)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DGAC	53.5	9.2	0.83	0.26	52.5	9.2	0.89	0.26
THMACO	—	—	—	—	—	—	—	—
SMA	44.6	7.0	0.90	0.16	45.2	7.8	0.90	0.17
MICRO	53.4	9.4	0.66	0.19	50.6	7.7	0.60	0.15
PCCP	52.7	8.9	0.87	0.34	52.7	8.9	0.87	0.34
All Mixes	49.6	9.4	0.84	0.23	49.0	9.2	0.87	0.23

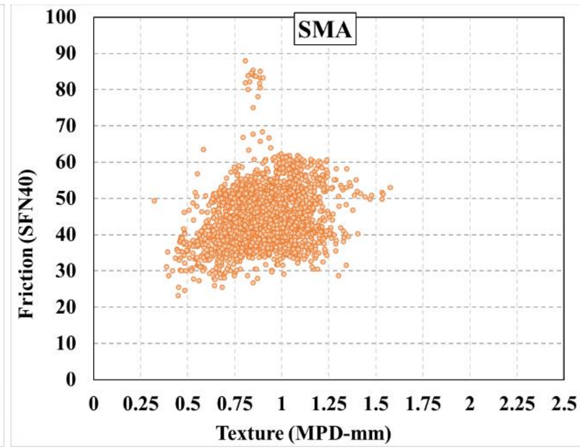


(a) SFN40 (b) MPD

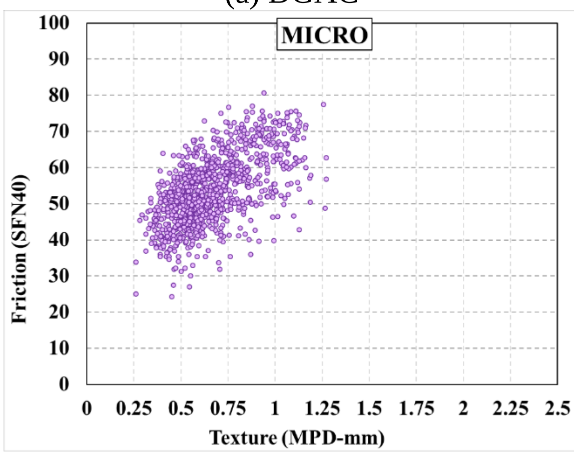
Figure F1. Friction (SFN40) and Texture (MPD) for District 8 Surveyed Data



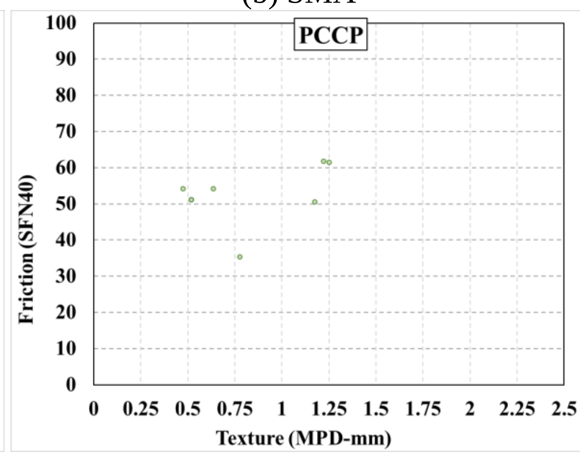
(a) DGAC



(b) SMA



(c) MICRO



(d) PCCP

Figure F2. SFN40 vs. MPD Plots by Pavement Surface Mix (District 8 Surveyed Data)

Table F4. Total and Average Crash Count per Lane per 0.1 Miles by Pavement Surface Mix for District 8 Analyzed Network

	Total Crash Count by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	750	0	2,125	232	6	3,113
Primary	972	0	0	59	0	1,031
Total	1,722	0	2,125	291	6	4,144
	Average Crash Count by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	4.2	—	5.0	4.5	4.3	4.8
Primary	4.1	—	—	3.1	—	4.0

Notes:

1. Total crashes include both directions of travel for undivided roadway.
2. Average crashes per lane-mile computed using lane counts for both directions of travel on undivided roadway.

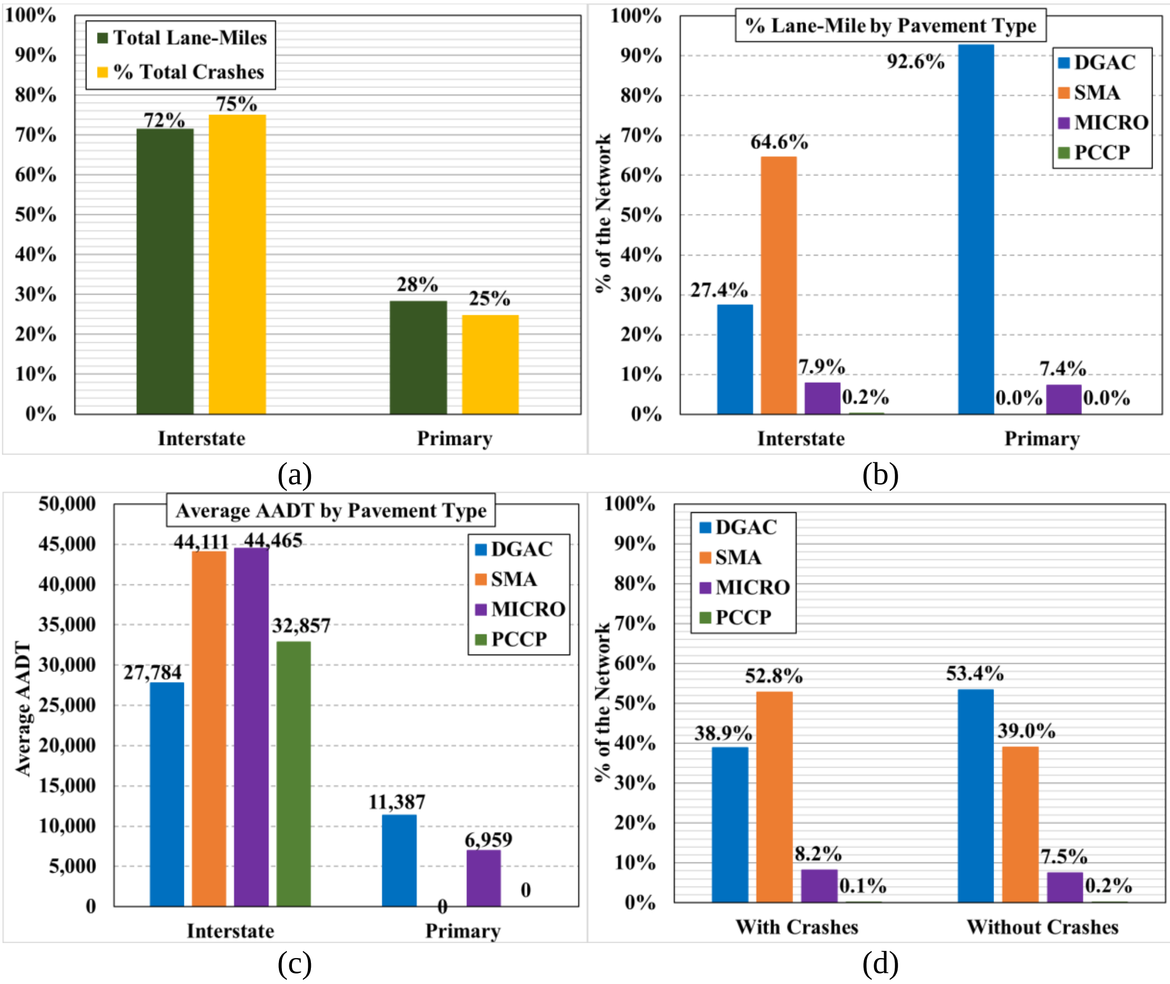


Figure F3. Network Crashes, Lane-miles, and Traffic by Pavement Surface Mix (District 8 Analyzed Data)

Table F5. Crash Counts Separated by Surface Condition and Severity for District 8 Analyzed Network

Crash Severity	Wet Crashes		Dry Crashes		Wet and Dry Crashes	
	Observed	%Wet	Observed	%Dry	Observed	%Wet+Dry
Fatality (K)	3	0.33%	42	1.30%	45	1.09%
Serious Injury (A)	37	4.06%	190	5.88%	227	5.48%
Other Injury (B & C)	171	18.75%	703	21.75%	874	21.09%
PDO (O)	701	76.86%	2,297	71.07%	2,998	72.35%
(K) + (A)	40	4.39%	232	7.18%	272	6.56%
Total	912	—	3,232	—	4,144	—

Note: Crash counts from 2017 through 2019.

The overdispersion and log-likelihood values for the District 8 SPF model are 0.422 and −5,570.

Table F6. Final SPF Coefficients for District 8 with CFME Data

Model Variables	*β*	*p*-value	Model Variables	*β*	*p*-value
Intercept	-4.232	0.00	Interaction Term(s):		
ln(AADT)	0.584	0.00	SFN40 × Route Type	0.032	0.00
Friction (SFN40)	-0.029	0.00	SFN40 × Texture	-0.018	0.08
Texture (MPD, in mm)	0.522	0.29	SFN40 × Grade (%)	—	—
Divided Roadway	0.291	0.00	SFN40 × Cross-slope (%)	—	—
Intersections & Ramp Access Points	0.524	0.00	SFN40 × Curvature (1/m)	8.047	0.00
Route Type	-1.962	0.00	SFN40 × Intersections/Ramp Access	—	—
Pavement Surface Mix			SFN40 × Divided Roadway	—	—
THMACO	—	—	SFN40 × Number of Travel Lanes	—	—
SMA	-0.055	0.85	SFN40 × Pavement Surface Mix		
MICRO	-1.209	0.03	*SFN40 × THMACO*	—	—
PCCP	5.672	0.04	*SFN40 × SMA*	-0.002	0.80
Grade (%)	-0.022	0.01	*SFN40 × MICRO*	0.019	0.08
Cross-slope (%)	-0.041	0.00	*SFN40 × PCCP*	-0.117	0.04
Curvature (1/m)	-284.849	0.02			
Number of Travel Lanes	—	—			

Note: Indicator variable reference value for route type is primary and pavement surface mix is DGAC.

Table F7. Average Cost for Friction Enhancement Treatments in District 8

Treatment Option	Cost/Lane/Mile	Cost/Lane/0.1 Mile
DGAC	$43,030	$4,303
THMACO	—	—
SMA	$86,040	$8,604
MICRO	$16,960	$1,696
PCCP w/CDG	—	—
HFST	$128,270	$12,827

Table F8. Estimated Average Friction Values (SFN40) for New Friction Enhancement Treatments in District 8

Current Surface	Surveyed SFN40 Mean	Surveyed SFN40 Standard Deviation (SD)	SFN40 Enhancement (Mean + 1.0 SD)
DGAC	53.5	9.2	65
THMACO	—	—	—
SMA	44.6	7.0	50
MICRO	53.4	9.4	65
PCCP	—	—	—
HFST	—	—	80

Table F9. Treatment Option Implementation Strategy for District 8

Interstate			
Strategy	**Current Surface Mix**	**Mix Age**	**Treatment Option**
1	DGAC	≤ 5 Years	MICRO
2	All Asphalt	> 5 Years	SMA
Primary			
Strategy	**Current Surface Mix**	**Mix Age**	**Treatment Option**
1	DGAC	≤ 8 Years	MICRO
2	DGAC or MICRO	> 8 Years	DGAC

Note: Pavement age since 2019.

Table F10. Comprehensive Crash Costs for District 8 Analyzed Network

Crash Severity	Crash Count (2017–2019)	FHWA Cost/Crash	Comprehensive Costs
Fatality (K)	45	$11,295,402	$508,293,090
Injury A	227	$654,967	$148,677,509
Injury B	774	$198,492	$153,632,808
Injury C	100	$125,562	$12,556,200
PDO (O)	2,998	$11,906	$35,694,188
Total	4,144	—	$858,853,795

In District 8, the highest potential savings per section are just over $500,000. There are two sections in this category, US 50 East at MP 2.0 and SR 7 East at MP 8.3. Both sections have a DGAC and their combined estimated, pre-treatment crash count is approximately four over 3 years. In the analysis, these two sections receive a MICRO. The total cost at each site is $3,392 but the total savings are $510,180 and $501,836.

Table F11. Number of Recommended 0.1-Mile Friction Enhancement Treatment Sections with BCR > 1 and Savings > $500,000 in District 8

Savings per Section >	Number of 0.1-Mile Friction Enhancement Treatment Sections						
	DGAC	**THMACO**	**SMA**	**MICRO**	**PCCP w/CDG**	**HFST**	**Total**
$500 k	0	—	0	2	—	0	2
$400 k	0	—	0	9	—	0	9
$300 k	0	—	0	40	—	3	43
$200 k	0	—	0	127	—	18	145
$100 k	0	—	0	143	—	103	246
Total	0	—	0	321	—	124	445

Table F12. Potential Crash Reductions and Total Cost Savings Benefits for Recommended 0.1-Mile Friction Enhancement Treatment Sections in District 8

Savings per Section >	0.1-Mile Sections	Predicted Crash Reductions	Total Treatment Cost	Total Savings
$500 k	2	5	$6,784	$1,012,016
$400 k	9	19	$33,920	$3,945,137
$300 k	43	71	$226,210	$14,566,598
$200 k	145	176	$906,124	$35,635,793
$100 k	246	192	$3,147,770	$36,708,592
Total	445	464	$4,320,808	$91,868,137

APPENDIX G: DISTRICT 9 RESULTS

Table G1. Miles and Lane-miles by Pavement Surface Mix for District 9 Surveyed Network

	Miles Surveyed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	66.4	0.0	34.9	20.4	13.5	135.2
Primary	221.9	0.0	10.0	95.1	2.4	(329.4) 336.1
Total	288.3	0.0	44.9	115.5	15.9	(464.6) 471.3
	Lane-Miles Surveyed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	247.6	0.0	117.6	79.2	53.1	497.5
Primary	532.4	0.0	26.0	190.7	6.2	(755.3) 769.9
Total	780.0	0.0	143.6	269.9	59.3	(1,252.8) 1,267.4

Notes: The totals in parentheses are for identified mix types only.

Table G2. Miles, Lane-miles, and Average AADT by Pavement Surface Mix for District 9 Analyzed Network

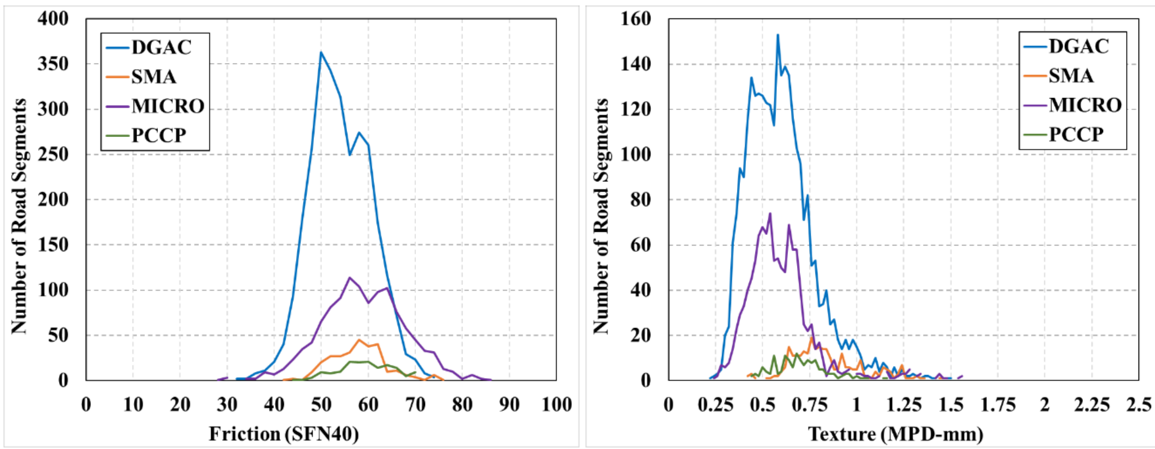
	Miles Analyzed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	40.8	0.0	16.0	16.6	13.1	86.5
Primary	142.6	0.0	5.6	45.6	2.4	196.2
Total	183.4	0.0	21.6	62.2	15.5	282.7
	Lane-Miles Analyzed by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	157.3	0.0	52.1	66.2	51.7	327.3
Primary	386.7	0.0	11.7	111.2	6.2	515.8
Total	544.0	0.0	63.8	177.4	57.9	843.1
	Average AADT by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	187,600	—	103,988	171,756	147,011	162,947
Primary	51,987	—	47,696	47,316	49,083	50,743

Notes:

1. Lane-miles are the number of travel lanes in both directions of travel for undivided roadway.
2. AADT is for direction of travel only.

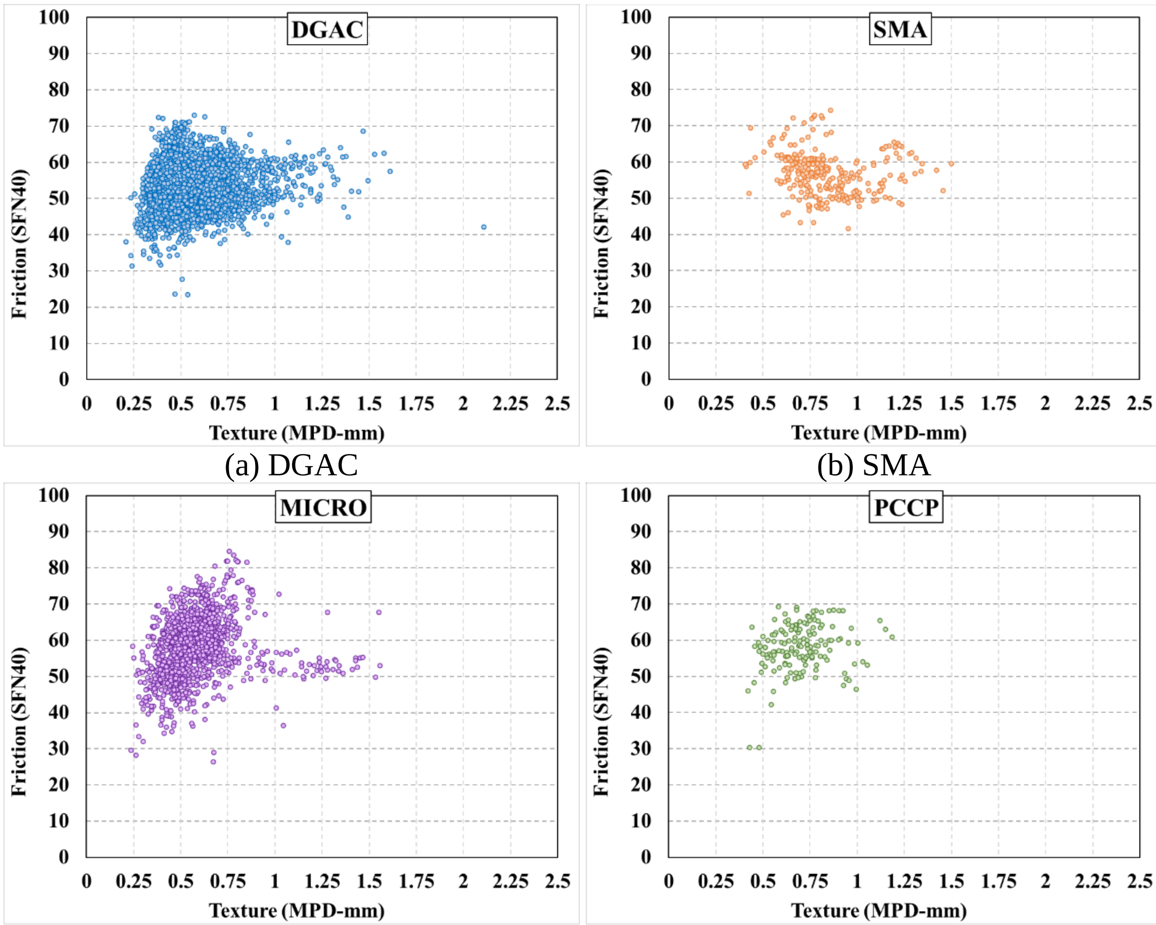
Table G3. Mean and Standard Deviation for SFN40 and MPD for District 9 Surveyed and Analyzed Data

Surface Mix	Surveyed Network				Analyzed Network			
	Friction (SFN40)		Texture (MPD, in mm)		Friction (SFN40)		Texture (MPD, in mm)	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DGAC	53.1	6.5	0.59	0.19	51.7	5.9	0.63	0.19
THMACO	—	—	—	—	—	—	—	—
SMA	56.9	5.8	0.84	0.20	57.8	5.7	0.84	0.22
MICRO	57.9	8.7	0.59	0.19	57.7	8.9	0.59	0.23
PCCP	58.1	6.5	0.70	0.15	58.1	6.5	0.70	0.15
All Mixes	54.8	7.4	0.61	0.20	53.9	7.2	0.64	0.21



(a) SFN40 (b) MPD

Figure G1. Friction (SFN40) and Texture (MPD) for District 9 Surveyed Data



(a) DGAC (b) SMA

(c) MICRO (d) PCCP

Figure G2. SFN40 vs. MPD Plots by Pavement Surface Mix (District 9 Surveyed Data)

Table G4. Total and Average Crash Count per Lane per 0.1 Miles by Pavement Surface Mix for District 9 Analyzed Network

	Total Crash Count by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	4,652	0	723	960	1,239	7,574
Primary	5,937	0	143	1,369	92	7,541
Total	10,589	0	866	2,329	1,331	15,115
	Average Crash Count by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	29.6	—	13.9	14.5	24.0	23.1
Primary	15.4	—	12.2	12.3	14.8	14.6

Notes:

1. Total crashes include both directions of travel for undivided roadway.
2. Average crashes per lane-mile computed using lane counts for both directions of travel on undivided roadway.

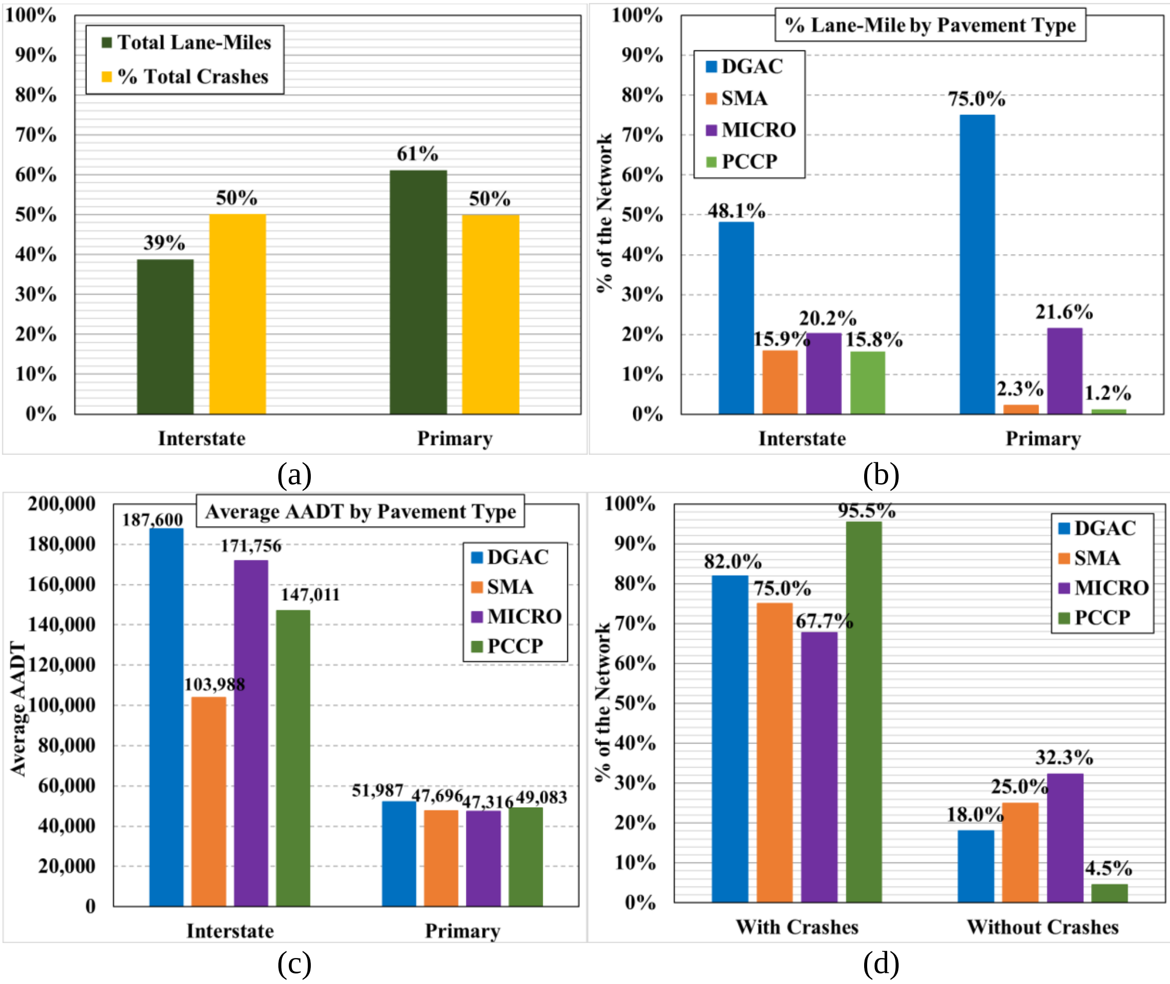


Figure G3. Network Crashes, Lane-miles, and Traffic by Pavement Surface Mix (District 9 Analyzed Data)

Table G5. Crash Counts Separated by Surface Condition and Severity for District 9 Analyzed Network

Crash Severity	Wet Crashes		Dry Crashes		Wet and Dry Crashes	
	Observed	%Wet	Observed	%Dry	Observed	%Wet+Dry
Fatality (K)	—	—	—	—	42	0.28%
Serious Injury (A)	—	—	—	—	465	3.08%
Other Injury (B & C)	—	—	—	—	4,368	28.90%
PDO (O)	—	—	—	—	10,240	67.75%
(K) + (A)	—	—	—	—	507	3.35%
Total	2,182	—	12,933	—	15,115	—

Note: Crash counts from 2015 through 2017.

Table G6. Total and Average Crash Count per Lane-mile by Pavement Surface Mix in District 9

	Total Crashes by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	4,652	-	723	960	1,239	7,574
Primary	5,937	-	143	1,369	92	7,541
Total	10,589	-	866	2,329	1,331	15,115
	Average Crashes/Lane-mile by Pavement Surface Mix					
Road Type	*DGAC*	*THMACO*	*SMA*	*MICRO*	*PCCP*	*Total*
Interstate	29.6	-	13.9	14.5	24.0	23.1
Primary	15.4	-	12.2	12.3	14.8	14.6

Notes:

1. Total crashes include both directions of travel for undivided roadway.
2. Average crashes per lane-mile computed using lane counts for both directions of travel on undivided roadway.

The overdispersion and log-likelihood values for the District 9 SPF model are 0.675 and −6,969.

Table G7. Final SPF Coefficients for District 9 with CFME Data

Model Variables	***β***	***p*-value**	**Model Variables**	***β***	***p*-value**
Intercept	-3.979	0.00	Interaction Term(s):		
ln(AADT)	0.849	0.00	SFN40 × Route Type	—	—
Friction (SFN40)	-0.089	0.00	SFN40 × Texture	—	—
Texture (MPD, in mm)	—	—	SFN40 × Grade (%)	—	—
Divided Roadway	—	—	SFN40 × Cross-slope (%)	—	—
Intersections & Ramp Access Points	1.449	0.00	SFN40 × Curvature (1/m)	—	—
Route Type	—	—	SFN40 × Intersections/Ramp Access		
Pavement Surface Mix			SFN40 × Divided Roadway	—	—
THMACO	—	—	SFN40 × Number of Travel Lanes	0.013	0.00
SMA	1.608	0.05	SFN40 × Pavement Surface Mix		
MICRO	0.567	0.11	*SFN40 × THMACO*	—	—
PCCP	-3.229	0.00	*SFN40 × SMA*	-0.030	0.05
Grade (%)	-0.026	0.01	*SFN40 × MICRO*	-0.013	0.05
Cross-slope (%)	—	—	*SFN40 × PCCP*	0.061	0.00
Curvature (1/m)	-142.650	0.00			
Number of Travel Lanes	-0.516	0.00			

Note: Indicator variable reference value for route type is primary and pavement surface mix is DGAC.

Table G8. Average Cost for Friction Enhancement Treatments in District 9

Treatment Options	Cost/Lane/Mile	Cost/Lane/0.1 Mile
DGAC	$65,875	$6,588
THMACO	—	—
SMA	$85,250	$8,525
MICRO	$18,700	$1,870
PCCP w/CDG	$42,240	$4,224
HFST	$190,000	$19,000

Notes: Based on District 4 (Richmond) treatment costs.

Table G9. Estimated Average Friction Values (SFN40) for New Friction Enhancement Treatments in District 9

Current Surface	Surveyed SFN40 Mean	Surveyed SFN40 Standard Deviation (SD)	SFN40 Enhancement (Mean + 1.0 SD))
DGAC	53.1	6.5	60
THMACO	—	—	—
SMA	56.9	5.8	65
MICRO	57.9	8.7	65
PCCP	58.1	6.5	65 (w/CDG)
HFST	—	—	80

Table G10. Treatment Option Implementation Strategy for District 9

Interstate			
Strategy	**Current Surface Mix**	**Mix Age**	**Treatment Option**
1	All Asphalt	-	SMA
2	PCCP	-	PCCP w/CDG
Primary			
Strategy	**Current Surface Mix**	**Mix Age**	**Treatment Option**
1	DGAC or SMA	< 6 Years	MICRO
2	DGAC or MICRO	≥ 6 Years	DGAC
3	SMA	≥ 6 Years	SMA
4	PCCP	≥ 6 Years	PCCP w/CDG

Notes:

11. Based on District 4 (Richmond) treatment strategy.
12. Age: Pavement age since 2018.

Table G11. Comprehensive Crash Costs for District 9 Analyzed Network

Crash Severity	Crash Count (2015–2017)	FHWA Cost/Crash	Comprehensive Costs
Fatality (K)	42	$11,295,402	$474,406,884
Injury A	465	$654,967	$304,559,655
Injury B	2,980	$198,492	$591,506,160
Injury C	1,388	$125,562	$174,280,056
PDO (O)	10,240	$11,906	$121,917,440
Total	15,115	—	$1,666,670,195

Table G12. Number of Recommended 0.1-Mile Friction Enhancement Treatment Sections with BCR > 1 and Savings > $500,000 in District 9

Savings per Section >	Number of 0.1-Mile Friction Enhancement Treatment Sections						
	DGAC	THMACO	SMA	MICRO	PCCP w/CDG	HFST	Total
$5.0 M	0	—	0	0	0	0	0
$4.0 M	0	—	0	0	0	0	0
$3.0 M	1	—	1	0	0	0	2
$2.0 M	3	—	4	0	0	1	8
$1.0 M	61	—	59	8	0	21	149
$0.5 M	118	—	139	12	0	53	322
Total	183	—	203	20	0	75	481

Table G13. Potential Crash Reductions and Total Cost Savings Benefits for Recommended 0.1-Mile Friction Enhancement Treatment Sections in District 9

Savings per Section >	0.1-Mile Sections	Predicted Crash Reductions	Total Treatment Cost	Total Savings
$5.0 M	0	0	$0	$0
$4.0 M	0	0	$0	$0
$3.0 M	2	60	$60,450	$6,528,741
$2.0 M	8	163	$271,688	$17,756,747
$1.0 M	149	1,789	$4,602,990	$192,617,461
$0.5 M	322	2,114	$10,250,648	$222,893,965
Total	481	4,126	$15,185,775	$439,796,913

APPENDIX H: TOP 15 PROPOSED FRICTION IMPROVEMENT SECTIONS

Table H1. Recommended Friction Enhancement Treatment 0.1-Mile Sections with the Top 15 BCR in District 2 (and I-77 in District 1)

No	Route ID	Rte. Type	Mix Type	Age	AADT	Lanes	Divided	MP	SFN40	MPD	Treatment	CR	Savings	BCR	Facility
1	US460W	Primary	MICRO	3	18,000	2	Yes	116.5	39.1	0.44	MICRO	5.3	$857,427	177.8	I/R
2	US460W	Primary	DGAC	4	38,000	2	Yes	76.4	34.8	1.02	MICRO	5.1	$833,475	172.9	I/R
3	US460E	Primary	DGAC	7	38,000	2	Yes	78.8	42.4	0.61	DGAC	8.8	$1,429,674	145.1	I/R
4	US460W	Primary	DGAC	4	38,000	2	Yes	76.6	39.5	0.93	MICRO	4.3	$698,059	144.9	I/R
5	US460W	Primary	DGAC	4	41,000	2	Yes	77.2	30.6	0.69	MICRO	4.1	$660,730	137.2	I/R
6	US460W	Primary	DGAC	4	23,000	2	No	66.9	47.3	0.35	MICRO	3.9	$628,574	130.6	I/R
7	US460W	Primary	DGAC	4	41,000	2	Yes	76.9	36.6	0.56	MICRO	3.4	$555,649	115.6	I/R
8	US460W	Primary	DGAC	4	18,000	2	No	66.1	40.7	0.65	MICRO	3.4	$545,969	113.6	I/R
9	US460W	Primary	DGAC	4	20,500	2	No	66.4	39.8	0.33	MICRO	3.1	$503,005	104.7	I/R Curve
10	US460W	Primary	DGAC	4	23,000	2	No	67.0	46.7	0.46	MICRO	3.1	$501,134	104.3	I/R
11	US220S	Primary	DGAC	4	32,000	2	Yes	55.0	44.9	0.56	MICRO	3.0	$482,805	100.5	I/R Curve
12	US460W	Primary	DGAC	7	35,000	2	Yes	79.9	31.5	1.25	DGAC	6.1	$986,981	100.5	DPN
13	US460E	Primary	DGAC	9	23,000	2	No	66.4	43.1	0.39	DGAC	6.1	$981,910	100.0	I/R
14	US460W	Primary	DGAC	4	21,000	2	Yes	70.6	46.2	0.37	MICRO	2.9	$469,713	97.8	I/R
15	US460W	Primary	DGAC	7	35,000	2	Yes	80.0	31.1	1.29	DGAC	5.9	$952,074	97.0	I/R

Notes:

13. Route ID: I = Interstate, US = US Route, SR = State Route.
14. Pavement Surface Mix and Treatment: DGAC = dense-graded AC, SMA = stone matrix AC; MICRO = microsurfacing, PCCP = Portland cement concrete pavement.
15. Age: Pavement age since 2019.
16. AADT = Annual average daily traffic. For the direction of travel only.
17. Lanes: Number of lanes per direction of travel.
18. MP = Starting mile-point. All of the sections are 0.1-miles long.
19. SFN40 = friction parameter, SCRIM Reading, converted to standard speed of 40 mph.
20. MPD = mean profile depth, in mm.
21. BCR = benefit-cost ratio.
22. Facility type: I/R = intersection/ramp access, Curve = any section with a radius < 2,000 feet, I/R Curve = intersections/ramp access and curve, DPN = divided primary nonevent, UPN = undivided primary nonevent, IN = interstate nonevent.

Table H2. Recommended Friction Enhancement Treatment 0.1-Mile Sections with the Top 15 BCR in District 3

No	Route ID	Mix Type	Age	AADT	Lanes	Divided	MP	SFN40	MPD	Treatment	CR	Savings	BCR	Facility
1	US29N	DGAC	7	19,500	2	Yes	61.5	34.2	0.31	MICRO	2.6	$630,084	163.1	I/R
2	US29N	DGAC	4	20,000	2	Yes	63.6	40.1	0.38	MICRO	2.5	$603,196	156.1	I/R
3	US29S	DGAC	14	13,000	2	Yes	113.5	32.6	1.09	DGAC	4.7	$1,137,453	113.3	Curve
4	US29N	DGAC	7	20,000	2	Yes	61.6	42.7	0.52	MICRO	1.8	$430,048	111.6	I/R
5	US29S	DGAC	14	13,000	2	Yes	113.6	38.2	1.16	DGAC	4.1	$1,002,779	100.0	Curve
6	US29S	DGAC	7	18,000	2	Yes	53.4	51.3	0.78	MICRO	1.5	$363,206	94.4	I/R
7	US460E	DGAC	14	38,000	2	Yes	208.5	48.7	0.76	DGAC	3.6	$874,356	87.3	I/R
8	US460E	DGAC	7	41,000	2	Yes	202.3	49.5	0.54	MICRO	1.3	$321,177	83.6	I/R
9	US460W	DGAC	7	52,000	2	Yes	202.8	41.6	0.71	MICRO	1.3	$305,687	79.6	I/R
10	US460E	DGAC	7	41,000	2	Yes	202.1	46.7	0.57	MICRO	1.2	$298,650	77.8	I/R
11	US29N	DGAC	4	20,000	2	Yes	63.4	45.7	0.45	MICRO	1.2	$298,453	77.8	I/R
12	US460W	DGAC	7	18,000	2	Yes	219.4	47.9	0.71	MICRO	1.2	$285,221	74.4	I/R
13	US60E	DGAC	4	4,000	2	No	121.6	48.1	0.57	MICRO	1.1	$277,630	72.4	I/R Curve
14	US29N	DGAC	4	20,000	2	Yes	63.9	52.6	0.46	MICRO	1.1	$275,022	71.7	I/R
15	US460E	MICRO	7	24,000	2	Yes	196.6	41.0	0.99	HFST	6.8	$1,640,021	64.9	I/R

Notes:
1. Age: Pavement age since 2019.
2. Lanes are the number of travel lanes in both directions of travel for undivided roadway.
3. AADT is for the direction of travel.
4. Crash reductions (CR) are predicted for both directions of travel for undivided roadway.

Table H3. Recommended Friction Enhancement Treatment 0.1-Mile Sections with the Top 15 BCR in District 5

No	Route ID	Mix Type	Age	AADT	Lanes	Divided	MP	SFN40	MPD	Treatment	CR	Savings	BCR	Facility
1	I64W	THMACO	4	144,000	1	Yes	285.0	46.6	0.86	MICRO	4.2	$767,424	453.5	IN
2	I64W	THMACO	4	144,000	1	Yes	284.9	46.7	0.80	MICRO	3.2	$591,106	349.5	IN
3	I64W	THMACO	4	186,000	2	Yes	284.7	35.8	0.60	MICRO	4.8	$875,949	259.2	IN
4	I64W	THMACO	4	142,000	3	Yes	282.1	39.0	0.67	MICRO	7.1	$1,302,960	257.1	I/R
5	I64W	THMACO	4	186,000	2	Yes	284.8	39.4	0.87	MICRO	4.4	$795,419	235.5	IN
6	I64W	THMACO	4	142,000	3	Yes	282.6	34.9	0.54	MICRO	5.7	$1,040,230	205.4	I/R
7	I64W	THMACO	4	151,000	3	Yes	281.5	38.6	0.71	MICRO	5.6	$1,019,595	201.4	I/R
8	I64W	THMACO	4	186,000	2	Yes	284.6	49.8	0.92	MICRO	3.7	$671,347	198.9	I/R
9	I64W	THMACO	4	137,000	2	Yes	277.9	42.2	0.98	MICRO	3.7	$671,296	198.9	IN
10	I64W	THMACO	4	142,000	3	Yes	281.9	37.3	0.65	MICRO	5.3	$970,122	191.7	IN
11	I64W	THMACO	4	137,000	2	Yes	278.0	41.8	0.97	MICRO	3.5	$636,790	188.7	I/R
12	I64W	THMACO	4	129,000	3	Yes	279.2	43.3	1.02	MICRO	5.2	$940,766	185.9	I/R Curve
13	I64W	THMACO	4	142,000	3	Yes	282.5	36.7	0.84	MICRO	5.0	$918,525	181.5	IN
14	I64W	THMACO	4	186,000	2	Yes	284.5	49.4	0.95	MICRO	3.2	$581,177	172.3	I/R
15	I64W	THMACO	4	186,000	2	Yes	284.4	41.8	0.72	MICRO	3.1	$561,047	166.4	IN

Notes:
1. Age: Pavement age since 2019.
2. AADT is for the direction of travel.

Table H4. Recommended Friction Enhancement Treatment 0.1-Mile Sections with the Top 15 BCR in District 6

No	Route ID	Rte. Type	Mix Type	Age	AADT	Lanes	Divided	MP	SFN40	MPD	Treatment	CR	Savings	BCR	Facility
1	US1S	Primary	DGAC	6	56,000	3	Yes	142.3	44.8	0.70	MICRO	14.8	$2,259,186	409.4	DPN
2	US1N	Primary	DGAC	6	27,000	4	No	143.0	50.2	0.75	MICRO	19.6	$2,986,703	406.0	I/R
3	US17N	Primary	DGAC	6	15,150	4	No	126.3	45.8	1.07	MICRO	17.1	$2,612,597	355.2	I/R
4	US1N	Primary	DGAC	6	56,000	4	No	142.9	48.5	0.68	MICRO	16.7	$2,546,243	346.2	UPN
5	US1S	Primary	DGAC	6	56,000	6	No	142.2	40.0	0.72	MICRO	20.7	$3,160,327	286.7	UPN
6	US1N	Primary	DGAC	7	18,000	4	No	156.7	39.6	0.86	MICRO	13.8	$2,101,596	286.0	I/R
7	US17S	Primary	SMA	8	41,000	2	Yes	182.2	27.6	0.59	THMACO	14.7	$2,237,090	258.6	I/R
8	US1N	Primary	DGAC	7	19,500	4	No	154.5	36.8	0.80	MICRO	11.8	$1,804,801	245.7	I/R
9	US17N	Primary	SMA	8	41,000	3	Yes	182.2	26.0	0.52	THMACO	20.9	$3,185,302	245.5	I/R
10	I95S	Interstate	SMA	11	136,000	3	Yes	143.7	33.7	0.56	THMACO	19.6	$2,982,771	229.9	I/R
11	US17S	Primary	DGAC	13	28,000	2	No	172.3	40.7	0.52	THMACO	12.9	$1,958,156	226.5	I/R
12	US1S	Primary	DGAC	6	19,000	2	Yes	158.7	40.3	0.87	MICRO	5.3	$804,153	219.1	I/R
13	US301S	Primary	DGAC	6	21,000	2	Yes	138.6	40.6	0.63	MICRO	5.3	$801,019	218.2	I/R
14	US17S	Primary	DGAC	13	23,000	2	No	171.4	43.7	0.63	THMACO	12.1	$1,846,308	213.6	I/R
15	I95S	Interstate	SMA	11	136,000	3	Yes	143.4	36.0	0.74	THMACO	17.4	$2,647,198	204.2	IN

Notes:

3. Age: Pavement age since 2019.
4. Lanes are the number of travel lanes in both directions of travel for undivided roadway.
5. AADT is for the direction of travel.
6. Crash reductions (CR) are predicted for both directions of travel for undivided roadway.

Table H5. Recommended Friction Enhancement Treatment 0.1-Mile Sections with the Top 15 BCR in District 7

No	Route ID	Rte. Type	Mix Type	Age	AADT	Lanes	Divided	MP	SFN40	MPD	Treatment	CR	Savings	BCR	Facility
1	US29N	Primary	DGAC	10	51,500	2	Yes	214.2	44.7	0.48	DGAC	17.3	$2,993,542	348.8	I/R
2	I64E	Interstate	THMACO	5	45,000	2	Yes	118.2	46.5	1.20	MICRO	6.4	$1,106,791	327.3	I/R
3	US15N	Primary	DGAC	3	30,500	2	Yes	166.6	39.0	0.53	MICRO	6.4	$1,099,356	325.1	I/R
4	I66W	Interstate	SMA	8	43,000	2	Yes	32.1	42.7	0.89	MICRO	6.2	$1,079,526	319.3	IN
5	US29N	Primary	DGAC	10	49,000	2	Yes	212.2	30.9	0.45	DGAC	15.0	$2,602,447	303.4	I/R
6	US250W	Primary	DGAC	3	11,300	2	No	85.7	42.3	0.77	MICRO	2.7	$475,427	281.3	I/R Curve
7	I66E	Interstate	SMA	9	43,000	2	Yes	32.0	39.8	0.84	MICRO	5.2	$900,726	266.5	IN
8	US29S	Primary	DGAC	6	45,000	4	Yes	141.8	43.1	0.73	MICRO	10.3	$1,775,354	262.7	I/R
9	I66W	Interstate	SMA	8	43,000	2	Yes	32.2	50.0	0.84	MICRO	5.1	$877,939	259.8	IN
10	I64E	Interstate	THMACO	5	55,000	2	Yes	118.4	39.6	0.75	MICRO	4.9	$849,051	251.3	I/R
11	US29N	Primary	DGAC	8	45,000	4	Yes	141.8	45.5	0.82	DGAC	24.0	$4,149,978	242.1	I/R
12	US29S	Primary	DGAC	6	45,000	4	Yes	142.5	44.0	0.64	MICRO	9.3	$1,602,121	237.2	I/R
13	US29S	Primary	DGAC	9	34,000	2	Yes	147.6	34.7	0.46	DGAC	11.7	$2,027,594	236.6	I/R
14	US29N	Primary	DGAC	6	18,000	2	Yes	153.4	46.9	0.63	MICRO	4.3	$736,247	218.1	I/R
15	US29N	Primary	DGAC	10	54,000	4	Yes	140.3	42.9	0.64	DGAC	17.9	$3,092,891	180.7	DPN

Notes:

1. Age: Pavement age since 2019.
2. Lanes are the number of travel lanes in both directions of travel for undivided roadway.
3. AADT is for the direction of travel.
4. Crash reductions (CR) are predicted for both directions of travel for undivided roadway.

Table H6. Recommended Friction Enhancement Treatment 0.1-Mile Sections with the Top 15 BCR in District 8

No	Route ID	Mix Type	Age	AADT	Lanes	Divided	MP	SFN40	MPD	Treatment	CR	Savings	BCR	Facility
1	US50E	DGAC	8	8,600	2	No	2.0	34.5	1.02	MICRO	2.5	$510,180	151.4	I/R Curve
2	SR7E	DGAC	8	28,000	2	Yes	8.3	44.8	0.96	MICRO	2.4	$501,836	148.9	I/R
3	US60E	DGAC	7	13,000	2	Yes	58.3	48.2	0.46	MICRO	2.4	$484,002	143.7	I/R Curve
4	SR7E	DGAC	8	28,000	2	Yes	5.8	32.8	0.55	MICRO	2.3	$468,551	139.1	DPN
5	US11N	DGAC	7	7,600	2	No	335.0	41.0	0.44	MICRO	2.3	$465,667	138.3	I/R
6	US11N	DGAC	7	7,600	2	No	334.4	39.8	0.42	MICRO	2.1	$433,633	128.8	I/R
7	SR7E	DGAC	8	28,000	2	Yes	5.7	39.6	0.46	MICRO	2.1	$428,477	127.3	I/R
8	SR7E	DGAC	8	28,000	2	Yes	5.6	46.7	0.37	MICRO	2.1	$427,645	127.1	I/R
9	SR7E	DGAC	7	28,000	2	Yes	9.2	43.7	0.64	MICRO	2.0	$420,688	125.0	I/R
10	US60E	DGAC	7	6,700	1	Yes	58.2	55.1	0.52	MICRO	1.0	$209,348	124.4	I/R
11	SR7W	DGAC	6	28,000	2	Yes	5.7	46.3	0.56	MICRO	2.0	$403,638	120.0	I/R
12	US220N	DGAC	4	3,000	2	No	149.0	44.7	1.21	MICRO	1.9	$396,303	117.8	I/R Curve
13	US60E	DGAC	7	7,100	2	No	58.0	52.7	0.43	MICRO	1.9	$388,361	115.5	I/R
14	SR7E	DGAC	8	28,000	2	Yes	6.2	50.6	0.60	MICRO	1.9	$385,004	114.5	I/R
15	US11S	DGAC	6	6,400	2	No	311.4	46.9	0.48	MICRO	1.8	$376,027	111.9	I/R

Notes:

1. Age: Pavement age since 2019.
2. Lanes are the number of travel lanes in both directions of travel for undivided roadway.
3. AADT is for the direction of travel.
4. Crash reductions (CR) are predicted for both directions of travel for undivided roadway.

Table H7. Recommended Friction Enhancement Treatment 0.1-Mile Sections with the Top 15 BCR in District 9

No	Route ID	Mix Type	Age	AADT	Lanes	Divided	MP	SFN40	MPD	Treatment	CR	Savings	BCR	Facility
1	SR234S	DGAC	5	40,000	2	Yes	20.5	35.4	0.36	MICRO	11.7	$1,290,566	346.1	I/R
2	SR7E	DGAC	4	86,000	3	Yes	60.4	41.8	0.54	MICRO	17.6	$1,933,244	345.6	I/R
3	US29N	DGAC	5	48,000	2	Yes	217.2	44.8	0.52	MICRO	10.3	$1,136,944	305.0	I/R
4	SR7E	DGAC	4	86,000	3	Yes	60.1	47.0	0.50	MICRO	13.2	$1,454,741	260.3	I/R
5	SR7W	DGAC	4	86,000	3	Yes	60.1	47.0	0.49	MICRO	12.5	$1,373,196	245.8	I/R
6	US29N	DGAC	5	48,000	3	Yes	217.6	46.7	0.58	MICRO	12.2	$1,345,111	240.8	I/R
7	US1N	DGAC	5	13,000	2	Yes	167.8	48.2	0.34	MICRO	6.7	$738,461	198.4	I/R
8	SR7W	DGAC	4	86,000	3	Yes	60.3	47.8	0.57	MICRO	9.9	$1,082,120	193.9	I/R
9	SR7E	DGAC	4	86,000	3	Yes	60.0	44.6	0.45	MICRO	9.7	$1,059,511	189.9	I/R
10	SR234N	DGAC	5	40,000	2	Yes	20.5	46.6	0.39	MICRO	6.4	$701,651	188.6	I/R
11	US29N	DGAC	5	48,000	2	Yes	217.3	44.0	0.51	MICRO	6.1	$671,150	180.5	DPN
12	SR7E	DGAC	4	86,000	3	Yes	60.2	42.9	0.54	MICRO	8.7	$950,671	170.5	I/R
13	SR28N	DGAC	8	56,000	2	Yes	29.2	34.4	0.48	DGAC	18.2	$1,989,051	152.0	I/R
14	SR7W	DGAC	5	36,000	2	Yes	66.4	45.8	0.67	MICRO	5.1	$562,319	151.4	I/R
15	SR234N	DGAC	7	41,000	2	Yes	13.5	27.8	0.51	DGAC	17.6	$1,932,504	147.7	I/R

Notes:

1. Age: Pavement age since 2018.
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3. AADT is for the direction of travel.
4. Crash reductions (CR) are predicted for both directions of travel for undivided roadway.