CHARACTERIZING ROAD SAFETY PERFORMANCE USING PAVEMENT FRICTION

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U.S. Department of Transportation
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ZERO IS OUR GOAL
A SAFE SYSTEM IS HOW WE GET THERE

Foreword

This report documents the development of safety performance functions (SPFs) that include friction and macrotexture on a variety of roadway facility types and categories (i.e., segments, intersections, curves, and ramps). The main objectives were: (1) the development of Crash Modification Factors (CMFs), or Crash Modification Functions (CMFx) that make it possible to evaluate the effect of pavement friction changes on safety performance, which can then inform the cost effectiveness of pavement friction improvements; and (2) the establishment of performance or investigatory thresholds for friction based on roadway type and category. The analysis confirmed a strong statistical association between pavement surface frictional properties (friction and macrotexture) and crash rates; lower crash rates were observed with higher friction and macrotexture.

The findings from this report support road agency efforts toward the institutionalization of Pavement Friction Management, one of the FHWA Proven Safety Countermeasures. The results may be used by road agencies to inform safety analyses at both the system/network and site/project levels to evaluate the impact and cost-effectiveness of pavement friction enhancement strategies and treatments.

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16. Abstract

This report documents the development of safety performance functions (SPFs) that include friction and macrotexture on a variety of roadway facility types and categories (i.e., segments, intersections, curves, and ramps). The main objectives were: (1) the development of crash modification factors (CMFs), or crash modification functions (CMFx) that make it possible to evaluate the effect of pavement friction changes on safety performance, which can then inform the cost-effectiveness of pavement friction improvements; and (2) the establishment of performance or investigatory thresholds for friction based on roadway type and category.

The analysis confirmed a strong statistical association between pavement surface frictional properties (friction and macrotexture) and crash rates; lower crash rates were observed with higher friction and macrotexture were developed for total crashes on different roadway facility types. The Safety Performance Functions (SPFs), which included friction and macrotexture measurement, were developed for total crashes using traditional negative binomial models. Friction was found to have a statistically significant effect for predicting total crashes on all the roadway facility types; and macrotexture was found to have a statistically significant effect for predicting total crashes on all roadway facility types except rural two-lane/two-way roads. These SPFs were then used to develop CMF/CMFx for relatively straight segments without events (tangents) and with areas of higher friction demand (curves and intersections) on each type of facility. The CMFx obtained are reasonable, generally follow the expected trends, and show that potential reduction of up to 30 percent of total crashes can be achieved with a 10-point increase in SFN40. Finally, illustrative friction investigatory thresholds were also defined for the various roadway facility and site types. As expected, the investigatory levels are higher for higher friction demand sites, such as curves, ramp and access points, and intersections.

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SI* (MODERN METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
		Length		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		Area		
in²	square inches	645.2	square millimeters	mm²
ft²	square feet	0.093	square meters	m²
yd²	square yards	0.836	square meters	m²
ac	Acres	0.405	hectares	ha
mi²	square miles	2.59	square kilometers	km²
		Volume (volumes greater than 1,000L shall be shown in m³)		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft³	cubic feet	0.028	cubic meters	m³
yd³	cubic yards	0.765	cubic meters	m³
		Mass		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		Temperature (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
		Illumination		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m²	cd/m²
		Force and Pressure or Stress		
lbf	poundforce	4.45	newtons	N
lbf/in²	poundforce per square inch	6.89	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When You Know	Multiply By	To Find	Symbol
		Length		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		Area		
mm²	square millimeters	0.0016	square inches	in²
m²	square meters	10.764	square feet	ft²
m²	square meters	1.195	square yards	yd²
Ha	hectares	2.47	acres	ac
km²	square kilometers	0.386	square miles	mi²
		Volume		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m³	cubic meters	35.314	cubic feet	ft³
m³	cubic meters	1.307	cubic yards	yd³
		Mass		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		Temperature (exact degrees)		
°C	Celsius	1.8c+32	Fahrenheit	°F
		Illumination		
lx	lux	0.0929	foot-candles	fc
cd/m²	candela/m²	0.2919	foot-Lamberts	fl
		Force and Pressure or Stress		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in²

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

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List of Abbreviations

AADT	average annual daily traffic
AASHTO	American Association of State Highway and Transportation Officials
AIC	Akaike information criterion
CFME	continuous friction measuring equipment
CFR	Code of Federal Regulations
CMF	crash modification factor
CMF_X	crash modification function
CPFM	continuous pavement friction measurement
CSC	characteristic skid coefficient
CSTI	Center for Sustainable Transportation Infrastructure
DGAC	dense-graded asphalt
DOT	Department of Transportation
EB	empirical Bayes
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
GAM	Generalized Additive Model
GLM/GLPM	Generalized Linear Model/Generalized Partial Linear Model
GPF	Guide for Pavement Friction
HFST	high friction surface treatment
HSM	Highway Safety Manual
IFI	International Friction Index
KABCO	Killed, Injury Level A, Injury Level B, Injury Level C, No Injury
LFC	longitudinal friction coefficient
LRS	Linear reference system
LWST	locked wheel skid trailer
MPD	mean profile depth
MTD	mean texture depth
MVMT	million vehicle miles traveled
NB	negative binomial
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NZTA	New Zealand Transport Agency
OGFC	open-graded friction course
PFMP	pavement friction management program
RMS	root mean square
SCRIM	Sideway-force Coefficient Routine Investigation Machine
SE	standard error
SFC	sideway force coefficient
SFN/SFN40	Sideway Force Number (with speed adjusted to 40 mph
SMA	stone matrix asphalt
SPF	Safety Performance Function
SR	SCRIM reading (Skid Resistance)
UK	United Kingdom
US	United States

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CHAPTER 1. Introduction

1.1 Previous Research

This current project continues the work documented in "PFM Program Utilizing Continuous Friction Measurement Equipment and State-of-the-Practice Safety Analysis Demonstration Project – Final Report," (FHWA-RC-20-0009), which demonstrated a pavement friction management plan (PFMP) in four States (Florida, Indiana, Texas, and Washington) using pavement friction, texture, and crash data. That project proposed that pavement friction, also referred to as skid resistance, is best determined based on continuous measurements that are related to road surface microtexture and macrotexture. In each State, the research team:

- Divided the highway networks into groups according to friction needs (friction demand categories).
- Collected friction, texture, crash, traffic, and other data.
- Analyzed the data to explore investigatory threshold levels for pavement friction and texture.
- Demonstrated proven continuous friction and macrotexture measurement equipment for network-level data collection.

1.2 Current Research

This report documents the development of safety performance functions (SPFs) that include friction and macrotexture for a variety of roadway facility types and categories (i.e., segments, intersections, curves, and ramps) for each category, as applicable. Per the *Highway Safety Manual* (HSM), negative binomial (NB) regression modeling is the state-of-the-practice for estimating SPFs (AASHTO, 2010). This report also includes the development of Crash Modification Factors (CMFs), or Crash Modification Functions (CMFx) implied by the newly developed SPFs corresponding to the continuous pavement friction measurement (CPFM) data.

The objectives of this work were twofold: first, to develop SPFs and CMFs/CMFx that make it possible to evaluate the effect of pavement friction changes on safety performance, which can then inform the cost-effectiveness of pavement friction improvements; second, to establish performance or investigatory thresholds for managing friction based on roadway type and category.

1.3 Review of Friction-related SPFs and CMFs

A search of the available literature related to SPFs and CMFs that links measured skid resistance to expected crashes turned up relatively few materials. The limited research available does indicate, as expected, that higher skid resistance measurements are associated with lower crash rates, particularly wet-road-related collisions.

Mayora and Pina (2009) studied the relationship between CPFM and injury collisions over two 5-year periods (1993–1997 and 1998–2002) on two-lane rural road segments of 500-m length in Spain. Segments including intersections were not included. Average Sideway-force Coefficient Routine Investigation Machine (SCRIM) CPFM data over a 5-year period were included in the analysis. Categories of alignment were defined for the analysis (e.g., tangent, radius > 500 m, radius 250–500 m, radius < 250 m) as well as categories of skid resistance based on the European standard of 50 km/h (e.g., SCRIM Reading (SR) ≤ 40, 40 < SR ≤ 45, 45 < SR ≤ 50, 50 < SR ≤ 55, 55 < SR ≤ 60, SCRIM > 60). Statistical tests were applied to see whether the mean crash rates differed between SCRIM categories for each alignment category tested. A before-after comparison group study was conducted to assess the benefits of skid resistance improvements done between the two 5-year periods. A group of 419 segments (500-m lengths) with an average SCRIM value of less than 50 was treated to improve the SCRIM value to more than 60. The results of crash rate analyses showed that both wet- and dry-road crash rates decreased as skid resistance increased. Wet-road crash rates were found to be significantly higher in curves than on tangents. For dry-road crashes, no differences were found between curves and tangents. The results of crash rate analyses showed that both wet- and dry-road crash rates decreased as skid resistance increased. The authors concluded that for tangents and curves with a radius less than 500 m, crash rates are significantly lower when the SCRIM value is greater than 55. For curves with a radius less than 500 m, the SCRIM value cutoff is 60. The before-after study indicates the benefits of increasing the skid resistance (measured as SR) from less than 50 to greater than 60 is a 68-percent reduction in wet-road crashes. When considering curves only, the reduction was estimated to be 84 percent.

Ivan et al. (2010) explored the relationship between wet-pavement friction and crashes to identify whether wet-pavement friction explains significant variation in crash frequency between similar locations, and whether this is particularly significant at high crash locations such as sharp curves and intersections. The amount of friction at each location was measured using the locked-wheel skid trailer (LWST) with a standard ribbed tire. These tested locations represent discrete measurements over a 60-ft length of roadway at 40 mph. NB regression models for K, A, or B crashes on the KABCO scale were developed separately for divided and undivided roadways. Additional explanatory variables considered included degree of horizontal curvature, rate of change of vertical curvature, number of intersections and driveways, pavement width, area type (rural, suburban, or urban), and speed limit. Dependent variables considered included total, wet-road, segment-related (sideswipe opposite direction, head-on fixed object, and moving object), and intersection-related (turning same direction, turning intersecting paths, sideswipe same direction, angle, rear-end, and pedestrian) crashes. The model results indicated that wet-pavement friction is most associated with increased crashes under conditions where there would be a demand for increased braking — that is, in curves and near driveways.

Cenek et al. (2011) developed Poisson log-linear regression models for run-off-road crashes on curves on rural two-lane roads. These models included the 50^{th}-percentile SCRIM CPFM data within each curve and confirmed that run-off-road crashes decrease as the CPFM increases.

Labi (2011) developed a CMF for crashes on rural two-lane roads through regression modeling that included the pavement friction measured with a LWST with a standard smooth tire at discrete 60-ft length pavement sections at 40 mph. The CMF is determined using the friction number before treatment, X, and the friction number after treatment, Y, for various classes of severity. As an example, the CMF for ABC crashes on the KABCO scale is:

$$CMF = exp^{(-0.01640(Y-X))} \qquad (1)$$

Pratt et al. (2014) similarly developed a CMF for the skid number reading (LWST with a smooth tire at discrete 60-ft length of roadway sections at 40 mph) using regression modeling. The CMF applies to horizontal curves on rural two-lane roads and all crash types. As an example, the CMF for KABCO crashes on the KABCO scale is:

$$CMF = exp^{(-0.0032(SK-40))} \qquad (2)$$

A report from the Scottish Road Research Board (2020) examined the relationship between wet-road crashes per million kilometers traveled and the SCRIM-measured characteristic skid coefficient (CSC). Piecewise linear regression models were fit to the data, which for some road types showed no discernible pattern, but for others did show an increased crash risk at low skid coefficient values.

Wallbank et al. (2016) developed generalized linear regression models with an NB error distribution to predict all crashes and wet-condition crashes on several categories of rural roadways. The models indicated that crash risk is reduced as SCRIM CPFM increases, particularly on segments with curves and grades. It was found that for wet-condition crashes skid resistance is more predictive of crashes, while for all crash types a measurement of texture depth was more predictive. As an example, the model for wet-condition crashes on motorways is:

$$Wet\_Crashes = (length)exp^{(-20.53-0.16*\text{Texture Depth}-1.51*\text{Skid Resistance})}AADT^{1.19} \qquad (3)$$

De León Izeppi et al. (2019) collected and analyzed approximately 4,000 miles of SCRIM CPFM data and recommended a methodology for identifying sections of roadway with high rates of friction-related crashes using SPFs and an empirical Bayes (EB) methodology that considered friction, macrotexture, geometric data, traffic, and crash counts. The report showed that the high resolution of CPFM (10-m data for network-level analysis) is sensitive to identifying potential friction problems on road sections with a high friction demand, such as curves and intersections.

Finally, in an evaluation by Merritt et al. (2020) of the safety effects of high-friction surface treatments, univariate categorical analysis and CMF/CMFx development indicated that there was a logical and consistent relationship between CMFs and three variables: friction improvement as measured by the percentage of high-friction surface treatment (HFST) friction increase, average annual daily traffic (AADT), and the expected crash frequency before treatment. It was found that the greater the percentage increase in friction, the greater was the observed decrease in crash frequency.

1.4 Review of Friction Investigatory Levels

The investigatory level for friction is the value below which crash risk increases significantly. This level can be used to identify sites where the skid resistance of pavement may be inadequate for the given road type, context, and expected traffic maneuvers. Pavement friction values lower than this threshold indicate the potential need for site review and possible consideration of treatments to improve friction.

In Australia, New Zealand, and the United Kingdom (UK), investigatory levels of friction are routinely monitored to ensure adequate pavement-friction properties and potentially reduce friction-related crash risk (Highways England, 2019; NZTA, 2013; Pratt and Neaylon, 2011). The UK introduced the first set of friction investigatory levels in 1988 and updated over time (Roe and Caudwell, 2008; Highways England, 2019). The friction management policy is found in CS 228 Pavement Inspection and Assessment. Other countries, such as Australia and the New Zealand, establish standards and specifications that provide recommendations and guidelines for local agencies to adopt/adapt to their local districts.

The standards for friction management in Australia and New Zealand were originally designed based on those from the UK and later adapted to the environment and roadway conditions in the two respective countries (Owen, 2014; Pratt and Neaylon, 2011). The first standard of the New Zealand policy, known as the T10 specification, was published in 1997 (NZTA, 2013). The final version of the T10 specification was published in 2013. The latest version of the recommended standards for motorway safety in Australia were published in a 2011 report, known as AP-R374-11 (Pratt and Neaylon, 2011).

CHAPTER 2. Methodology

The overall analysis framework is presented in Figure 1. This framework illustrates that there are many factors that influence the outcome variables (crashes) and that all these factors and outcomes are considered in developing SPFs. The SPFs are mathematical equations that predict the outcome variable (crashes) using the known values of the predictor variables. From these SPFs, CMFs/CMFx can be derived.

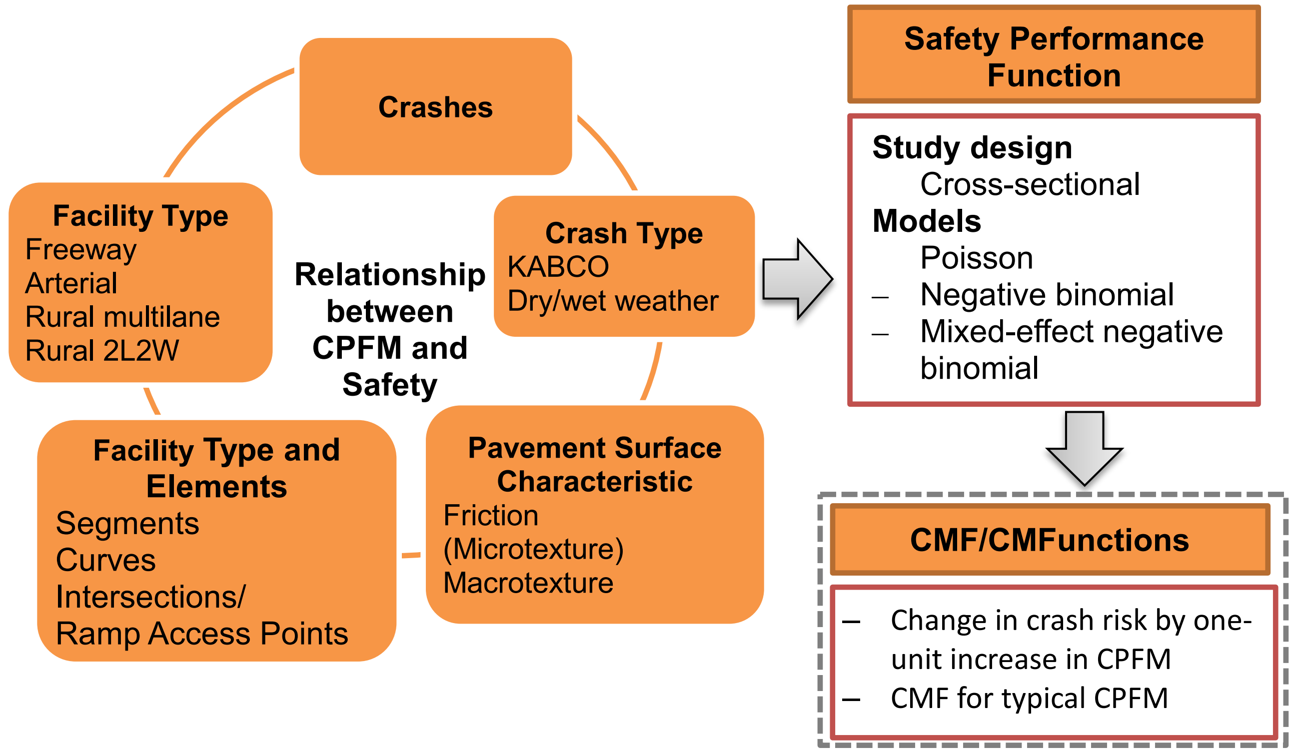


Figure 1. Illustration. Analysis framework (Source: CSTI/Arora and Associates, P.C.).

The cross-sectional approach is based on a prescribed time period under the assumption that the CMF/CMFx can be estimated as the ratio of the average crash frequency for sites with different values of a variable, assuming the values of all other variables remain constant. The reduction in crashes can be based on the increase of CPFM, based on the measurements of microtexture and macrotexture in accordance with AASHTO TP-143.

When estimating CMFs/CMFx from regression models, it is important to consider potential errors that may arise for several reasons, including inappropriate functional form, omitted variable bias, or correlation of variables. It is common practice to use generalized linear modeling (GLM) techniques, assuming an NB error structure, to estimate multivariable crash prediction models (AASHTO, 2010). However, it is difficult to account for all factors that affect safety using such modeling techniques.

For example, intersections with left-turn lanes also tend to have illumination. If a crash prediction model is used to estimate a CMF for left-turn lanes, and the presence of illumination is not accounted for in the model, the difference in model predictions with and without left-turn lanes could be partly due to illumination differences. Ironically, it is precisely because a variable is found to be correlated with another variable that it may be omitted during the model fitting exercise. Including correlated variables could, in fact, lead to effects that are counterintuitive (e.g., illumination increases nighttime crashes). In this report, the illumination analogy is equivalent to obtaining friction measurements without collection of pavement macrotexture.

Another reason the effect of an element that may affect safety cannot be captured in a model is because the sample used to develop the model is too small, or there is little or no variation in the element. For example, the effect of illumination cannot be captured if all locations in a sample are illuminated. Again, in this report, the effect of pavement friction levels cannot be captured if there is little or no variation of microtexture and macrotexture. These two variables are interrelated, which occasionally results in confounding effects in the model coefficients (collinearity).

In evaluating CMFs derived from a cross-sectional study, Gross et al. (2010) identified the following questions for consideration:

- Does the direction of effect (i.e., expected decrease or increase) in crashes meet expectations?
- Does the magnitude of the effect seem reasonable?
- Are the parameters of the model estimated with statistical significance?

These challenges may be mitigated by undertaking a rigorous before-after study, but this was not possible because of the unavailability of appropriate data. Thus, this study employed a cross-sectional approach to develop CMFs/CMFx.

2.1 SPF Estimation Methods

For this study, the research team tried (a) Poisson regression with mixed-effect, (b) NB regression with mixed-effect, and (c) NB regression without mixed-effect, to develop the SPFs that link the crash frequency with exposure and risk factors, including friction. When applying NB regression over time, it is assumed that the observed crashes for a site will follow a Poisson process around a long-term mean (the SPF estimate) that varies between similar locations in accordance with a gamma distribution. Crash counts in each period for sites with the same estimated long-term mean will follow an NB distribution.

To estimate the models, the crash, geometric, and friction data were organized by 0.1-mi sections, which accounted for crash data location accuracy and consistency with the segmentation typically used within many pavement management systems, where CPFM is collected every 10 m, and then a representative unit value is obtained from the lowest three-point moving average in a 0.1-mi section.

The NB SPF estimation theory is as follows. Let Y_{ij} denote the crash counts on the j^{th} segment of a road section i. The distribution assumption is shown in equation (4):

$$Y_{ij} \sim NB(\lambda_{ij}, \gamma) \qquad (4)$$

Where $E[Y_{ij}] = \lambda_{ij}$ is the expected number of crashes and γ is the overdispersion parameter of the NB model to accommodate extra-Poisson variation. As it happens, this overdispersion parameter is fundamental to the EB methodology for before-after evaluations and is one of several SPF goodness-of-fit parameters.

The functional form of the SPF establishes the relationship between the explanatory and dependent variables. As noted earlier, an incorrect functional form can result in biased and inconsistent parameter estimates, so it makes sense that the selection of a functional form is critical to developing a reliable CMF/CMFx.

Most SPFs apply a GLM functional form as shown in equation (5). In this equation, the expected number of crashes is linked with the traffic volume, road characteristics, and friction number through a log-link function:

$$\log \lambda_{ij} = \beta_0 + \beta_1 X_{friction,ij} + \beta_2 \log(traffic\ volume) + \beta_3 X_{3,ij}, \dots + \beta_p X_{p,ij} + \alpha_{ij}, \qquad (5)$$

where β_s are the regression coefficients, $X_{friction,ij}$ is the friction number for segment ij, and the logarithm of traffic volume is included as an exposure term. Other factors are included as exponential terms ($X_{3,ij}$ *to* $X_{p,ij}$).

While the shape of the exponential curve is somewhat flexible, it does not permit relationships that have turning points (inflections or clear changes in slopes). In some cases, this may give rise to misleading conclusions about the effects of safety treatments (Hauer, 2004). For this research, the most appropriate model forms were investigated using the Akaike's information criterion (AIC).

Hierarchical model forms were also considered. In a hierarchical modeling framework, as applied in road safety context by Chen and Persaud (2014), the parameter estimate for an explanatory variable may vary by group, for example, for sites from different States, or vary in a more complex way by being a function of other explanatory variables. Hierarchical models are used for analyzing data that are characterized by correlated responses within hierarchical clusters. Not considering the potential hierarchical structure of the data (the potential of a complex correlation structure) may lead to poorly estimated coefficients and associated standard errors, particularly when they are modeled using a traditional count-data modeling approach. For this reason, specific SPFs were developed for different road categories.

As segments on the same road section share many similar characteristics that are not easily quantified, it is likely that crash counts along these segments are correlated with each other. Spatial correlation is explored using a random-effect term, α_{ij}, to incorporate such correlation. The random-effect term can take many different forms, from the simple, within-section correlation to spatial correlation over larger distance. The within-section correlation takes the form of $\alpha_{ij} = \alpha_i \sim$ *Normal* $(0,\sigma)$, such that all segments on the same section share the same normally distributed random terms. In the context of this study, the research team considers spatial correlation between segments (see Lord and Mannering, 2010).

Multi-state, multi-corridor, high-resolution data leads to a complicated correlation structure and heterogeneity. A hierarchical, mixed-effect model is recommended with several levels of correlation structure for the macro-State-level, corridor-level (i.e., routes), to micro-level spatial correlation (segments close to each other). The correlation is mainly attributed to the shared characteristics at various levels. For example, all roads in the same State share a similar design standard, management, maintenance route, and State-level traffic management and regulation. At the micro level, segments close to each other share similar characteristics due to their similar spatial locations. The multi-level model can accommodate such correlations by either a Bayesian or frequentist approach. The basic model structure, however, is based on the formulation discussed above.

2.2 SPF Stratification

Many factors can contribute to crash risk, including functional class, facility types and elements, and pavement surface characteristics. The confounding and interacting effects caused by these factors can lead to biased estimations. In developing the cross-sectional regression models, it is ideal to develop separate models so that each group is as identical as possible, except for the treatment under consideration. However, this can be challenging when sample sizes are too small, which can necessitate combining groups, e.g., site types. Where this happens, such that a group is not homogeneous, a group classification categorical variable(s) may be considered for inclusion in the SPF as a multiplier or as an interaction term, if found to be statistically significant. As noted earlier, the quality of fit for the functional form of the SPFs proposed in this study was investigated with the AIC method.

2.3 Deriving CMFs/CMFx from SPFs

The CMFs/CMFx were derived from the estimated SPFs. The effects on safety from the friction measurements were used to estimate the reduction in crashes for every 10-unit increase in the CPFM. Equation (6) shows an example of a CMF-derived model form in equation (5), where β_1 is the regression coefficient for the friction or macrotexture measurements. Equation (7) shows the corresponding calculation for the standard error of the CMF based on the delta methodology presented in Park et al. (2016) and applied by Anarkooli et al. (2021). Depending on the coding method for the friction variable, $X_{friction}$, the CMF can be interpreted differently. For the continuous CPFM, the CMF represents the change to crash risk when friction increases by 10-units of sideway force number with speed adjusted to 40 mph according to AASHTO TP 143 (SFN40). For dichotomized, $X_{friction}$, the CMF represents the crash frequency between two levels of CPFM.

$$CMF = \exp\left(\beta_1\left(CPFM_{after} - CPFM_{before}\right)\right) \qquad (6)$$

$$SE(CMF) = \left(CPFM_{after} - CPFM_{before}\right) \times \exp\left(\beta_1\left(CPFM_{after} - CPFM_{before}\right)\right) SE(\beta_1) \qquad (7)$$

2.4 Identification of Friction Investigatory Thresholds

The research team employed two approaches to identify the investigatory level, including the change point-based method and a more practical graphical assessment based on observation of crash rates for different friction levels.

The model-based method assumes a nonlinear functional form of the SPF and friction number relationship. The investigatory level is the point at which the slope of the curve changes and below which decreasing friction is associated with a rapid increase in crash risk. This approach provided a wide range of thresholds, especially for roadway facility types with relatively small sample sizes, which was not considered acceptable. Thus, only the results from the graphical assessment are included in this report.

CHAPTER 3. Data Collection

The friction, macrotexture, and roadway geometry data were collected with SCRIM CPFM equipment (de León Izeppi et al. 2019). Multiple databases were used to collect the following data: crashes, traffic volume, geospatial referencing (linear reference system [LRS] roadway points and GPS), etc. The CPFM data were collected every 10 m with a sideway-force friction device (AASHTO TP 143, 2021), and summarized into homogeneous 0.1-mi road segments, curves, and intersections, to match the common pavement management systems used in the United States (US). All the CPFM data were collected with the same device, which was calibrated in 2015 and 2019. These small segments are the basic analysis unit for SPF and CMF development.

3.1 Variables

The CMFs were developed by the research team using 3 years of collected crash data, including information on KABCO severity and wet/dry pavement condition, which were used to specify the dependent variables for modeling. The team also accounted for any surface changes applied to each section during the time-period of the collected crash and CPFM data. Sections that received interventions in the 3 years before testing were eliminated from the analysis.

The variables directly or indirectly relevant to safety that were considered in the SPF development are listed below:

1. Average annual daily traffic (AADT).
2. Roadway classification (Table 1).
3. Pavement surface mix:
    a. Asphalt: Dense Graded, Open Graded (or Porous) Friction Course, Stone Matrix Asphalt (SMA), Microsurfacing, Chip Seal.
    b. Concrete: Tined, Ground, Grooved, Other (burlap, etc.).
    c. The age of the road surface type (years).
4. Available continuously collected data:
    a. Friction (SFN40): Minimum SR adjusted for speed to 40 mph from a 90-ft moving average on a 0.1-mi. segment.
    b. Macrotexture (mean profile depth, MPD): Average MPD for each 0.1-mi. segment.
    c. Cross-slope and/or superelevation (%: Average of the absolute value of percentage for a 0.1-mi segment).
    d. Vertical Grade (%): Average percentage for a 0.1-mi segment.
    e. Curvature (1/R): The inverse of the average of the absolute value of the curve radius (R) for a 0.1-mi segment.
5. Crashes
    a. Total crashes.
    b. Dry crashes: crashes when the pavement condition specified is dry.
    c. Wet crashes: crashes when the pavement condition specified is wet.
    d. Fatal and Injury Crashes.

Table 1. Road classification scheme.[1]

Roadway Facility Type	Site Type	Description
Freeways and Ramps	Roadway Segment (Urban and Rural)	Tangents with R > 2,000 ft
	Ramp Access Points	Roadway access to on-/off-ramps
	Curves	R < 2,000 ft
Urban and Suburban Arterial	Roadway Segment	Divided tangents with R > 2,000 ft
		Undivided tangents with R > 2,000 ft
	Intersections	Signalized and unsignalized stop-controlled, including ramp access points.
	Curves	R < 2,000 ft
Rural Multilane Highway	Roadway Segment	Divided, tangent with 4+ lanes and R > 2,000 ft
		Undivided, tangent with 4+ lanes and R > 2,000 ft
	Intersections	Signalized and unsignalized stop-controlled
	Curves	R < 2,000 ft
Rural 2-lane 2-way Roads	Roadway Segment	Undivided, 2-lane tangent roadway with R > 2,000 ft
	Intersections	Signalized and unsignalized stop-controlled
	Curves	R< 2,000 ft

3.2 Highway Network Mileage

Table 2 shows the mileage of the highway network based on 0.1-mi road segments (tangent, ramp access points, curves, and intersections) with CPFM and crash data for each facility and site type that were considered. The network in this study includes 55,677 0.1-mi roadway segments in five States separated into the 14 facility and site types from Table 1. For illustration purposes, Figure 2 shows the trend of crash rates per 100 million vehicle miles traveled (100 MVMT) for interstate tangent sites. The figure shows that the rate increases for lower friction values.

The international community that has extensive experience with continuous friction data collection and analysis recognizes that seasonal variations occur that impact the friction measurements. There are procedures to adjust friction test results for analysis. The data in this study does not have a seasonal adjustment, but it is recognized that a seasonal adjustment would have enhanced the data analysis. It is expected that as the US gains experience with CPFM data collection, seasonal adjustment will become a standard practice.

[1] Curves have been added to the site types to account for the additional demand for friction while driving on curves. They represent segments of roadway with a horizontal radius lower than 2,000 ft. The rationale for this classification was taken from the recommendations of Friction Demand Site Categories in the UK (Highways England, Design Manual for Roads and Bridges, Volume 7, Section 3, CS 228, Revision 1, Pavement, Inspection and Assessment. Skidding Resistance (formerly HD 28/15 – Withdrawn), Crown, United Kingdom, 2020). In this recommendation, curves were segments of roads with a radius lower than 500 m; the interpretation in this report was that 2,000 ft provides a more conservative estimate for use in the United States.

Table 2. Number of 0.1-mi segments analyzed by State and facility and site type.

Facility and Site Types	Florida	North Dakota	Texas	Virginia	Washington	Total
Freeway Segments	2,742	4,677	2,108	11,924	2,571	24,022
Freeway Ramp Access Points	410	281	560	1,291	541	3,083
Freeway Curves	15	0	25	186	71	297
Divided Urban Arterial Segments	1,076	97	542	1,793	28	3,536
Undivided Urban Arterial Segments	318	27	757	392	82	1,576
Urban Arterial Intersections	1,582	27	983	1,848	87	4,527
Urban Arterial Curves	35	9	50	116	2	212
Divided Rural Multilane Segments	0	1,930	170	6,416	27	8,543
Undivided Rural Multilane Segments	0	0	902	643	52	1,597
Rural Multilane Highway Intersections	6	140	338	2,009	6	2,499
Rural Multilane Highway Curves	0	12	51	244	19	326
Rural 2-lane, 2-way Segments	214	2,181	1,926	1,482	970	6,773
Rural 2-lane, 2-way Intersections	35	68	363	445	168	1,079
Rural 2-lane, 2-way Curves	4	82	127	252	225	690
Total	**6,027**	**9,250**	**8,342**	**27,750**	**4,308**	**55,677**

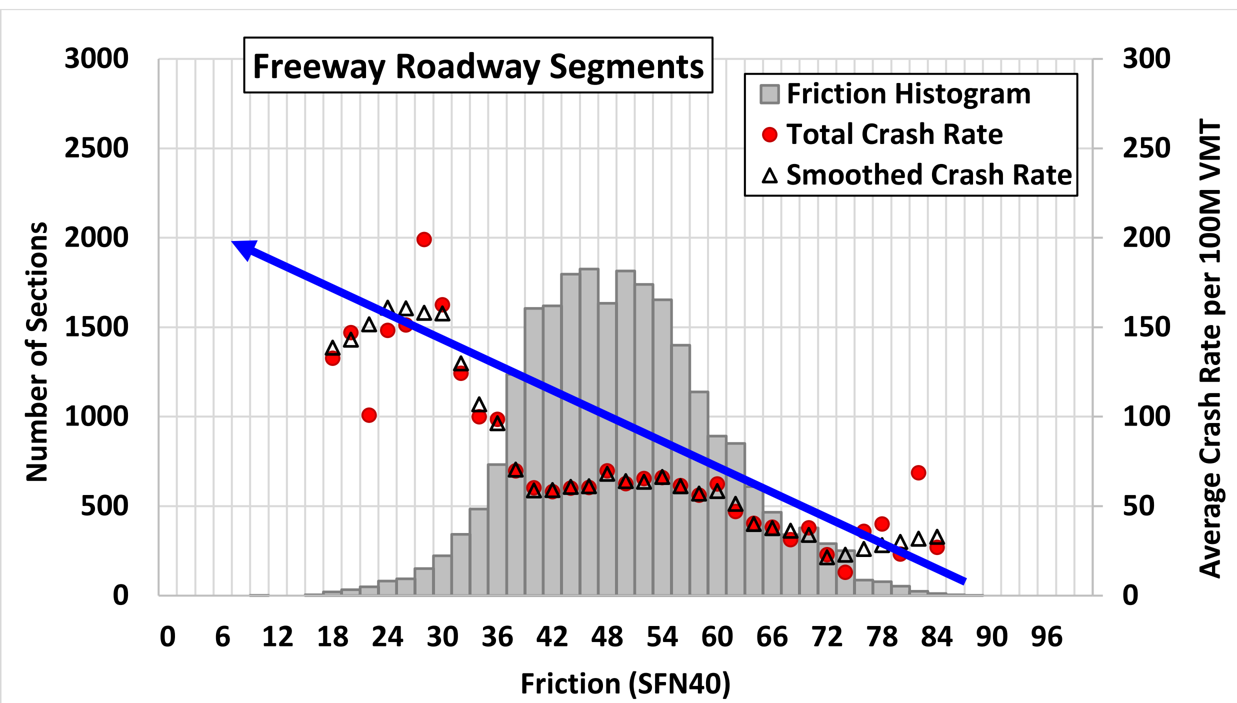


Figure 2. Graphs. Distribution of friction values and crash rates for interstate tangent sites (Source: FHWA).

3.3 Crash Data

Table 3 shows the distribution of crashes for each facility and site type and State. Some site types have a relatively small number of crashes.

Table 3. Distribution of crashes by State, facility, and site type.

Facility and Site Types	Florida	North Dakota	Texas	Virginia	Washington	Total
Freeway Segments	6,278	923	26,537	27,995	19,949	81,682
Freeway Ramp Access Points	2,523	152	8,511	6,093	9,292	26,571
Freeway Curves	50	0	272	590	914	1,826
Divided Urban Arterial Segments	2,375	53	2,759	3,846	14	9,047
Undivided Urban Arterial Segments	105	9	1,341	850	115	2,420
Urban Arterial Intersections	10,930	195	6,463	10,328	552	28,468
Urban Arterial Curves	30	8	94	165	1	298
Divided Rural Multilane Highway Segments	0	173	115	2,652	9	2,949
Undivided Rural Multilane Highway Segments	0	0	343	465	6	814
Rural Multilane Highway Intersections	7	92	427	2,448	3	2,977
Rural Multilane Highway Curves	0	2	39	190	9	240
Rural 2-lane, 2-way Segments	51	100	547	467	430	1,595
Rural 2-lane, 2-way Intersections	46	19	275	479	193	1,012
Rural 2-lane, 2-way Curves	9	12	47	75	74	217
Total	**22,404**	**1,738**	**47,770**	**56,643**	**31,561**	**160,116**

CHAPTER 4. Results

This chapter presents the results for the hierarchical mixed-effect and fixed-effect crash models. Analysis was performed using all the crash data, for fatal and serious-injury crashes, and for each surface condition (dry/wet).

4.1 Hierarchical Standard and Mixed-Effect SPF Regression Modeling

This section uses the data from all five States to develop three different SPF regression model types: (a) Poisson mixed-effect, (b) NB mixed-effect, and (c) NB without mixed-effect. The analysis is presented for the three model types for all roadway site types combined. This is followed by the analysis for each individual roadway site type using only the NB without mixed-effect model type.

4.1.1 All Roadway Types

The three models in this section were developed for all roadway functional classifications. Table 4 lists the estimated regression coefficients (β) and *p*-value the variables in each model, in addition to the AIC and overdispersion parameters. The full set of regression coefficients and *p*-values for State and functional classification in the NB model without mixed-effect is shown Table 5. Both the friction and macrotexture are significant ($p < 0.05$) for all three models.

Table 4. Poisson and NB hierarchical mixed-effect SPF models – all facility and site types.

Parameters	Poisson with Mixed -Effect		NB with Mixed -Effect		NB without Mixed- Effect	
	β	***p*-value**	**β**	***p*-value**	**β**	***p*-value**
Intercept, β_0	-11.2038	<0.0001	-10.6554	<0.0001	-10.9950	<0.0001
ln (AADT)	1.2950	<0.0001	1.2260	<0.0001	1.2263	<0.0001
Friction (SFN40)	-0.0139	<0.0001	-0.0105	<0.0001	-0.0105	<0.0001
Texture (MPD-mm)	-0.1622	<0.0001	-0.2401	<0.0001	-0.2400	<0.0001
Grade (%)	0.0095	<0.0001	-	-	-	-
Curvature (1/m)	107.9594	<0.0001	175.0743	<0.0001	175.3708	<0.0001
Overdispersion	n/a		1.1616		1.1609	
AIC	300,108		177,997		177,907	

The AIC is similar for both fixed-effect and mixed-effect NB models. The AIC is significantly lower than for the Poisson mixed-effect. Based on AIC, the NB models are better than Poisson mixed-effect for modeling crash counts for all facility and site types. Furthermore, the regression coefficients for friction and macrotexture are the same for both NB models; therefore, the fixed-effect NB was selected for modeling all facility and site types.

Table 5. NB SPF model without mixed-effect – all facility and site types – categorical variables only.

Parameters	β	*p*-value
Intercept, β_0	-10.9950	<0.0001
ln (AADT)	1.2263	<0.0001
Friction (SFN40)	-0.0105	<0.0001
Texture (MPD-mm)	-0.2400	<0.0001
Curvature (1/m)	175.3708	<0.0001
State 1	-0.5334	<0.0001
State 2	-0.8369	<0.0001
State 3	Reference Variable	
State 4	0.3549	<0.0001
State 5	0.5515	<0.0001
Freeway Segment	Reference Variable	
Freeway Ramp	0.3878	<0.0001
Freeway Curve	0.1658	0.0308
Divided Urban Arterial Segment	0.6481	<0.0001
Undivided Urban Arterial Segment	0.3066	<0.0001
Urban Arterial Intersection	1.7696	<0.0001
Urban Arterial Curve	0.1242	0.2365
Divided Rural Multilane Highway Segment	0.3541	<0.0001
Undivided Rural Multilane Highway Segment	-0.0281	0.5710
Rural Multilane Highway Intersection	1.1440	<0.0001
Rural Multilane Highway Curve	0.6511	<0.0001
Rural 2-lane, 2-way Road Segment	0.4116	<0.0001
Rural 2-lane, 2-way Road Intersection	1.3876	<0.0001
Rural 2-lane, 2-way Road Curve	0.6410	<0.0001

In both plots, the models tend to overestimate the number of crashes for the locations with a low predicted crash frequency, probably due to the considerable number of segments with zero observed crashes. However, the plots show that both models are better when predicting sites with higher crash frequencies.

The NB without mixed-effect and mixed-effect NB models have similar AICs (much better than the Poisson) and produce very similar or identical regression coefficients for friction and macrotexture. Equivalent results were observed after stratification. Therefore, only the results for the NB regression model without mixed-effect are reported for the remaining roadway functional classifications. Furthermore, the regression coefficients for both friction and macrotexture are statistically significant at a 95-percent confidence level (p-values < 0.05).

4.1.2 Freeways

Table 6 lists the NB without mixed-effect coefficients (β and *p*-value), overdispersion, and AIC for the freeway fixed-effect NB model. This table shows that both friction and macrotexture are statistically significant at the 95-percent confidence level.

Table 6. NB model – freeways.

Parameters	β	Standard Error	95% CI Lower	95% CI Upper	*p*-value
Intercept, β_0	-13.2201	0.1618	-13.5372	-12.9029	<0.0001
ln (AADT)	1.4180	0.0128	1.3930	1.4431	<0.0001
Friction (SFN40)	-0.0031	0.0010	-0.0050	-0.0012	0.0013
Texture (MPD-mm)	-0.1175	0.0299	-0.1760	-0.0590	0.0001
Curvature (1/m)	312.1713	26.3390	260.5468	363.7957	<0.0001
State 1	-1.0801	0.0328	-1.1444	-1.0158	<0.0001
State 2	-0.8676	0.0517	-0.9690	-0.7662	<0.0001
State 3	Reference Variable				
State 4	-0.6636	0.0251	-0.7128	-0.6144	<0.0001
State 5	0.3187	0.0330	0.2539	0.3835	<0.0001
Segments	Reference Variable				
Ramp Access Points	0.3362	0.0235	0.0235	0.3823	<0.0001
Curves	-0.0170	0.0870	0.0870	0.1536	0.8449
Overdispersion	1.0146				
AIC	98,441				

4.1.3 Urban and Suburban Arterials

Table 7 lists the fixed-effects (β and *p*-value), overdispersion, and AIC for the fixed-effect NB model for urban and suburban arterials. In this case again, both the friction and the macrotexture are statistically significant at the 95-percent confidence level.

4.1.4 Rural Multilane Highways

Table 8 lists the fixed-effects (β and *p*-value), the overdispersion, and the AIC for the fixed-effect NB model for rural multilane highways. In this case, friction is statistically significant at the 95-percent confidence level but not macrotexture, which is significant at the 90-percent level, with a direction of effect that is consistent with that for freeways and urban and suburban arterials.

Table 7. NB model – urban and suburban arterials.

Parameters	β	Standard Error	95% CI Lower	95% CI Upper	*p*-value
Intercept, β_0	-6.3395	0.2369	-6.8038	-5.8752	<0.0001
ln (AADT)	0.8893	0.0216	0.8469	0.9316	<0.0001
Friction (SFN40)	-0.0282	0.0016	-0.0313	-0.0251	<0.0001
Texture (MPD-mm)	-0.2363	0.0368	-0.3085	-0.1641	<0.0001
Grade (%)	-0.0256	0.0097	-0.0446	-0.0067	0.0079
State 1	-0.1650	0.0367	-0.2370	-0.0930	<0.0001
State 2	-0.1012	0.1318	-0.3596	0.1572	0.4429
State 3	Reference Variable				
State 4	-0.1289	0.0360	-0.1995	-0.0583	0.0003
State 5	0.5295	0.0984	0.3367	0.7224	<0.0001
Divided Segments	Reference Variable				
Undivided Segments	-0.3111	0.0457	-0.4008	-0.2215	<0.0001
Intersections	0.9898	0.0291	0.9327	1.0469	<0.0001
Curves	-0.2807	0.1045	-0.4855	-0.0758	0.0072
Overdispersion	1.2318				
AIC	44,402				

Table 8. NB model – rural multilane highways.

Parameters	β	Standard Error	95% CI Lower	95% CI Upper	*p-value*
Intercept, β_0	-7.3199	0.3211	-7.9493	-6.6905	<0.0001
ln (AADT)	0.8878	0.0299	0.8291	0.9464	<0.0001
Friction (SFN40)	-0.0265	0.0018	-0.0301	-0.0229	<0.0001
Texture (MPD-mm)	-0.1645	0.0764	-0.3142	-0.0147	0.0313
Curvature (1/m)	315.3585	27.1809	262.0838	368.6332	<0.0001
State 1	1.2137	0.5675	0.1014	2.3261	0.0325
State 2	-0.4364	0.0933	-0.6192	-0.2536	<0.0001
State 3	Reference Variable				
State 4	0.3902	0.0547	0.2830	0.4975	<0.0001
State 5	0.3524	0.2363	-0.1107	0.8155	0.1358
Overdispersion	1.0225				
AIC	23,148				

4.1.5 Rural Two-Lane, Two-Way Roads

Table 9 shows the fixed-effects (β and *p*-value), the overdispersion, and AIC for the fixed-effect NB model for rural two-lane, two-way roadways. The friction is statistically significant at the 95-percent confidence level. The results show that the *p*-value for macrotexture is not statistically significance at the 95-percent confidence level. Furthermore, the positive sign for the regression coefficient contradicts the expectation that higher macrotexture results in lower crashes.

Table 9. NB model – rural 2-lane, 2-way roadway.

Parameters	β	Standard Error	95% CI Lower	95% CI Upper	*p*-value
Intercept, β_0	-7.3174	0.3595	-8.0220	-6.6129	<0.0001
ln (AADT)	0.8246	0.0380	0.7501	0.8991	<0.0001
Friction (SFN40)	-0.0202	0.0024	-0.0249	-0.0155	<0.0001
State 1	0.4842	0.1387	0.2123	0.7560	0.0005
State 2	-0.4451	0.1147	-0.6700	-0.2202	0.0001
State 3	Reference Variable				
State 4	0.5962	0.0703	0.4584	0.7340	<0.0001
State 5	1.1315	0.0852	0.9644	1.2985	<0.0001
Segments	Reference Variable				
Intersections	0.9125	0.0621	0.7908	1.0342	<0.0001
Curves	0.3566	0.0953	0.1698	0.5434	0.0002
Overdispersion	1.4116				
AIC	10,572				

4.1.6 Alternative Modeling Approaches

Two alternative modeling approaches were also tested. The first approach consisted of using a generalized partial linear model (GPLM), a special case of a generalized additive model (GAM). This approach was not adopted as the CMF estimations for different values of SFN40 lie within the GLM standard errors, which implies that the non-linearity in the safety effects is not statistically meaningful. The second approach explores the use of alternative SPFs that allow the development of CMFs for a change in friction to vary depending on the level of friction before the change. This approach was not adopted as the friction coefficients obtained are considerably higher than those obtained using the traditional approach and are not recommended for implementation.

4.2 Crash Modification Factors/Functions (CMFs/CMFx)

Estimating CMFs and CMFx that capture the variability inherent in CMFs using cross-sectional models is akin to developing SPFs and observing how the predicted crash frequency differs by a variation in the feature of interest. This section reports the CMFx computed using equation (6) and the NB model coefficients for each roadway facility and site type (segments, junctions, curves, and others). Functions are included only when the measurement of interest is statistically significant at a 95-percent level of confidence for that facility type/category. For example, if friction is significant, but macrotexture is not, then only the CMFx for friction is included.

4.2.1 CMFs for Friction Improvements

Table 10 presents the friction improvement regression coefficient (β_1) for each CMFx for each roadway facility and site type, the resulting CMFs for a 10-unit increase in friction (SFN40), and the estimated percentage crash reductions using equation (6). For some site types, the friction coefficients were not statistically significant in the NB analysis, and they were omitted. The standard error for the 10-unit increase CMF was calculated using equation (7).

Table 10. CMF and percent crash reduction for a 10-unit increase in SFN40.[1,2]

Roadway Facility	Site Type	CMFx regression coefficient (β_1)	CMF for 10-Unit SFN40 Increase	Standard Error (CMF)	% Crash Reduction
All Facilities	All Site Types	-0.0105	0.901	0.0064	9.9
Freeways	All Freeways Site Types	-0.0031	0.969	0.0093	3.1
	Tangent Segments	-0.0023	0.977	0.0103	2.3
	Ramp Access Points	-0.0135	0.874	0.0219	12.6
	Curves	-0.0169	0.844	0.0611	15.6
Urban Arterials	All Urban Arterials Site Types	-0.0282	0.754	0.0118	24.6
	Divided Tangent Segments	-0.0288	0.754	0.0221	25.0
	Undivided Tangent Segments	-0.0230	0.794	0.0286	20.6
	Intersections	-0.0357	0.700	0.0161	30.1
	Curves	-0.0281	0.755	0.0625	24.5
Rural Multilane Highways	All Rural Multilane Highways Site Types	-0.0265	0.767	0.0142	23.3
	Divided Tangent Segments	-0.0168	0.846	0.0238	15.4
	Undivided Tangent Segments	-0.0094	0.910	0.0318	9.0
	Intersections	-0.0344	0.709	0.0218	29.1
	Curves	-0.0187	0.829	0.0731	17.1
Rural – 2-Lane 2-Way Road	All R2L-2W Roads Site Types	-0.0202	0.817	0.0196	18.3
	Tangent Segments	-0.0096	0.909	0.0243	9.1
	Intersections	-0.0188	0.829	0.0386	17.1
	Curves	-0.0188	0.829	0.0593	17.1

[1] The CMF values were obtained using equation (6), with the corresponding regression coefficients for β_1 provided in this table, and assuming a 10-point increase in SFN40 value.
[2] The CMFx and CMF corresponding to the Curve site types were developed based on a relatively small number of segments.

4.2.1.1 CMFx by Roadway Facility Type

Figure 3 compares the crash modification functions for the various roadway facility types. The impact of friction on crashes is relatively small on freeways but quite significant on urban arterials and rural multilane highways. In these types of facilities, a 10-point increase in SFN40 can result in a 23- to 25-percent reduction in crashes.

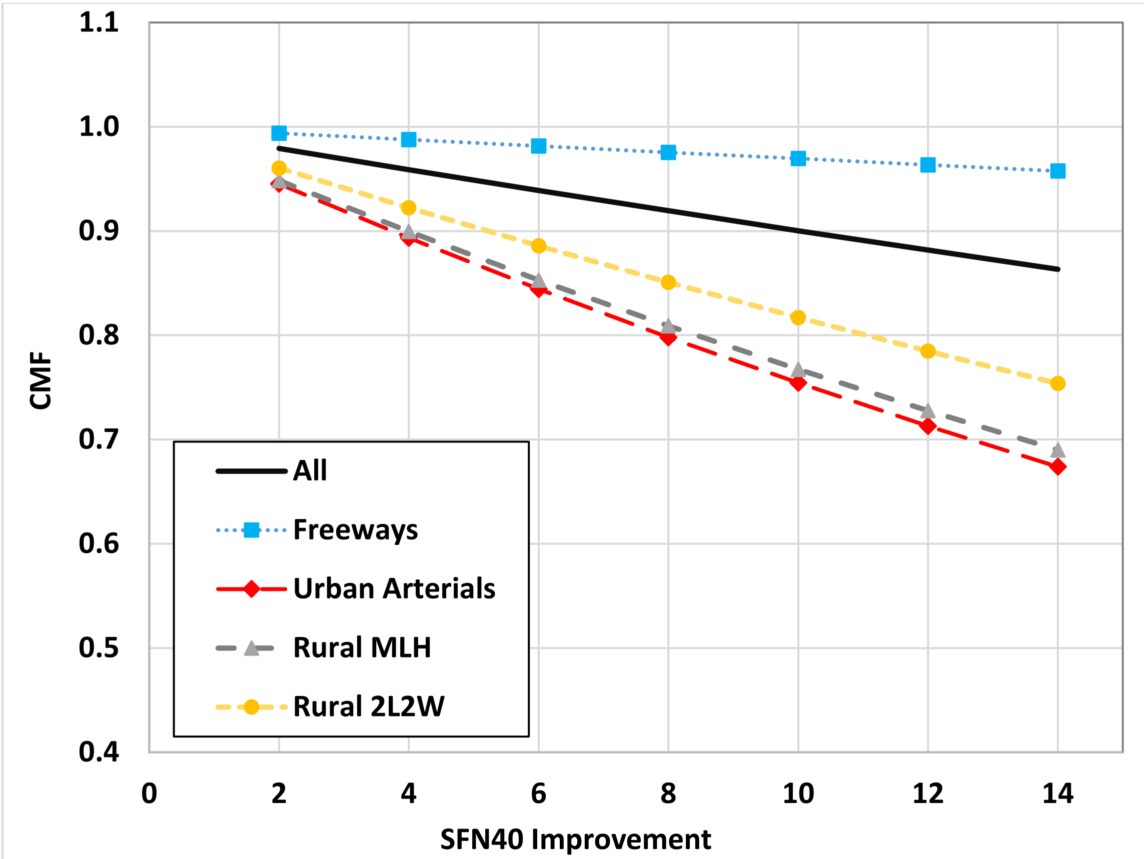


Figure 3. Graph. Comparison of CMFx for friction on different roadway facility types (Source: FHWA).

4.2.1.2 SPF and CMFx by Crash Type

A similar approach was conducted by breaking down the analysis by crash type and developing separate SPFs for wet and dry crashes, as well as fatal (K) and fatal and serious injury (K+A) crashes. This analysis used data from four States, as the detailed crash breakdown was not readily available for Texas. The effect of friction on fatal (K) and fatal and serious injury (K+A) crashes observed is highly variable and thus these results are not reported. The variability in the estimated model coefficients for the different facility types can probably be attributed to the smaller sample size. The resulting CMFx regression coefficients (β_1) and CMF for 10-unit increase in friction (SFN40) using equation (6), and the estimated percentage crash reductions by surface condition are presented in Table 11, and Figure 4 through Figure 7. As expected, the figures show that in all cases friction has a higher impact on wet crashes than on dry crashes.

Table 11. CMF and percent crash reduction by surface condition for a 10-unit increase in SFN40.[1]

Roadway Facility	Surface Condition	CMFx regression coefficient (β_1)	CMF for 10-unit SFN40 increase [(1)]	Standard Error CMF	% Crash reduction
Expressways	Total Wet	-0.0270	0.763	0.0109	23.7
	Total Dry	-0.0135	0.873	0.0078	12.6
Freeways	Total Wet	-0.0088	0.916	0.0152	8.4
	Total Dry	-0.0023	0.977	0.0106	2.3
Urban Arterials	Total Wet	-0.0479	0.619	0.0198	38.1
	Total Dry	-0.0348	0.706	0.0150	29.4
Rural Multilane Highways	Total Wet	-0.0251	0.778	0.0179	22.2
	Total Dry	-0.0251	0.778	0.0178	22.2
Rural 2-lane, 2-way Road	Total Wet	-0.0467	0.627	0.0575	37.3
	Total Dry	-0.0354	0.702	0.0343	29.8

[1] *The CMF values were obtained using equation (6), with the corresponding regression coefficients for β_1 provided in this table, and assuming a 10-point increase in SFN40 value.*

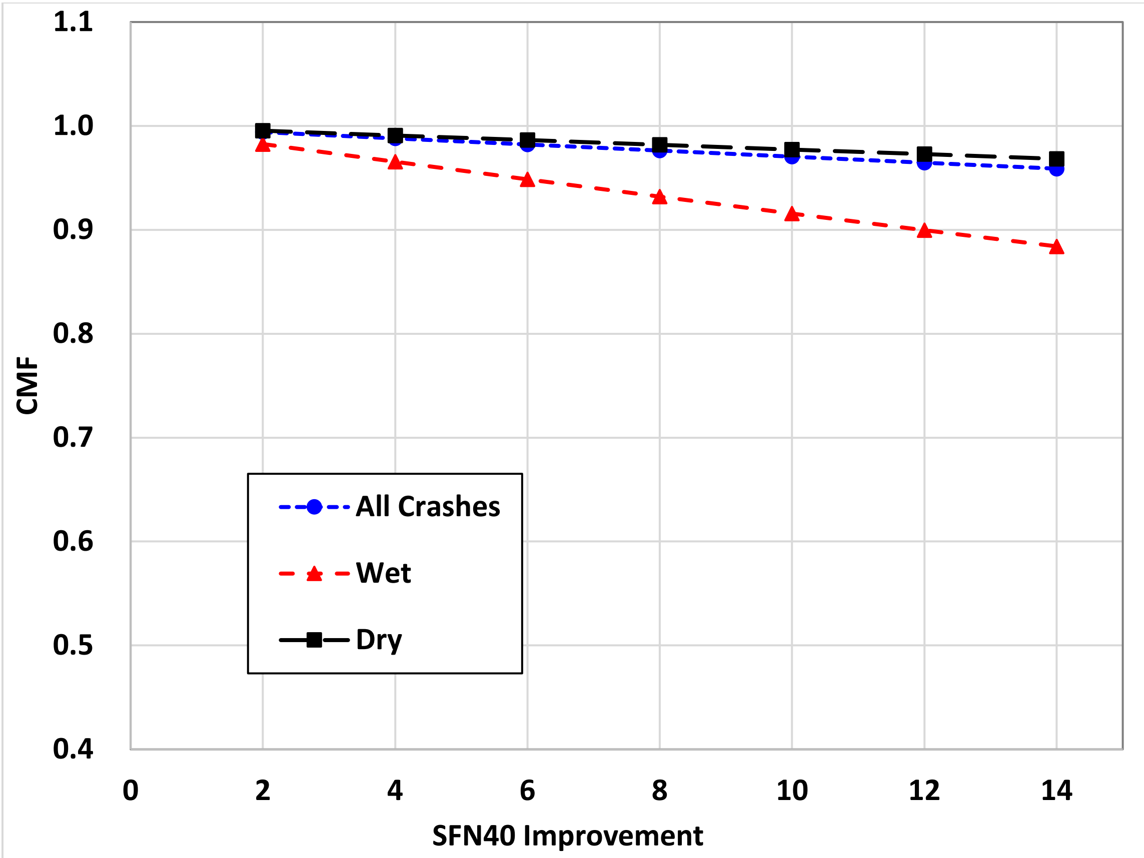


Figure 4. Graph. CMFx for friction on freeway segments by surface condition (Source: FHWA).

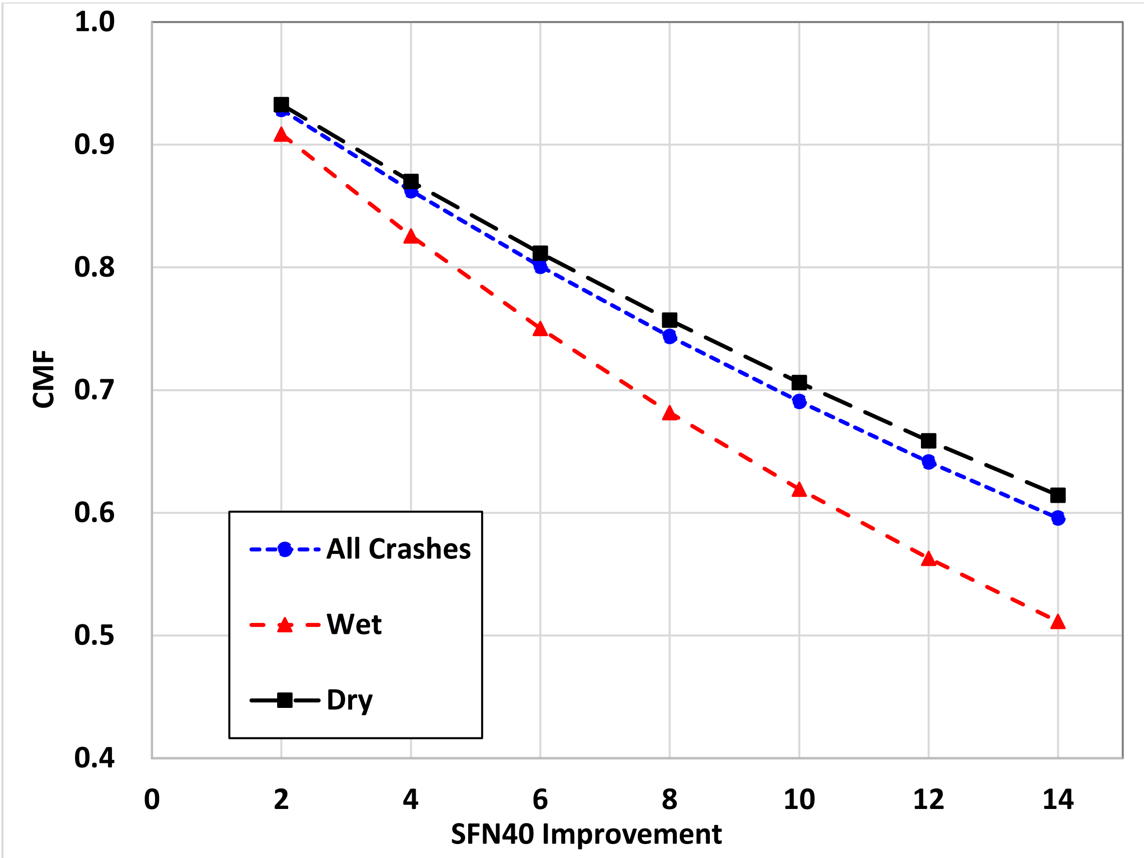


Figure 5. Graph. CMFx for friction on urban and suburban arterial highway segments by surface condition (Source: FHWA).

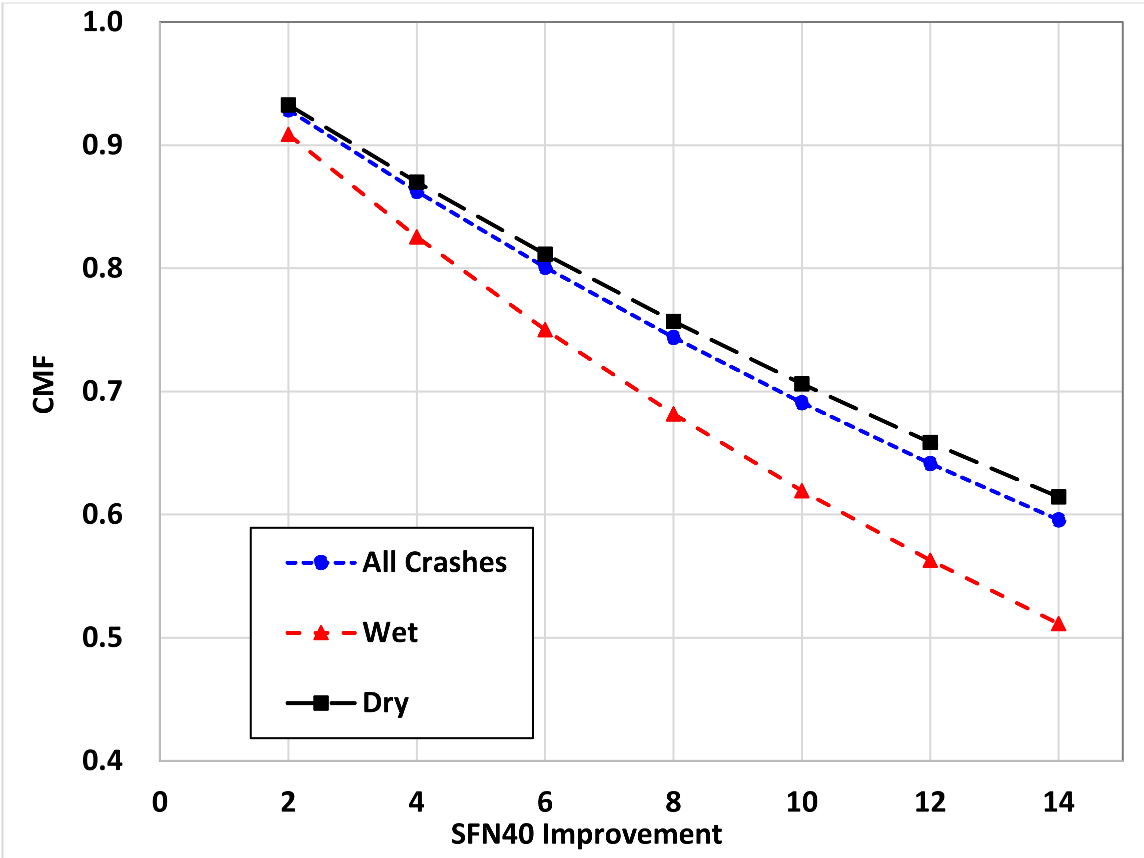


Figure 6. Graph. CMFx for friction on rural multilane highway segments by surface condition (Source: FHWA).

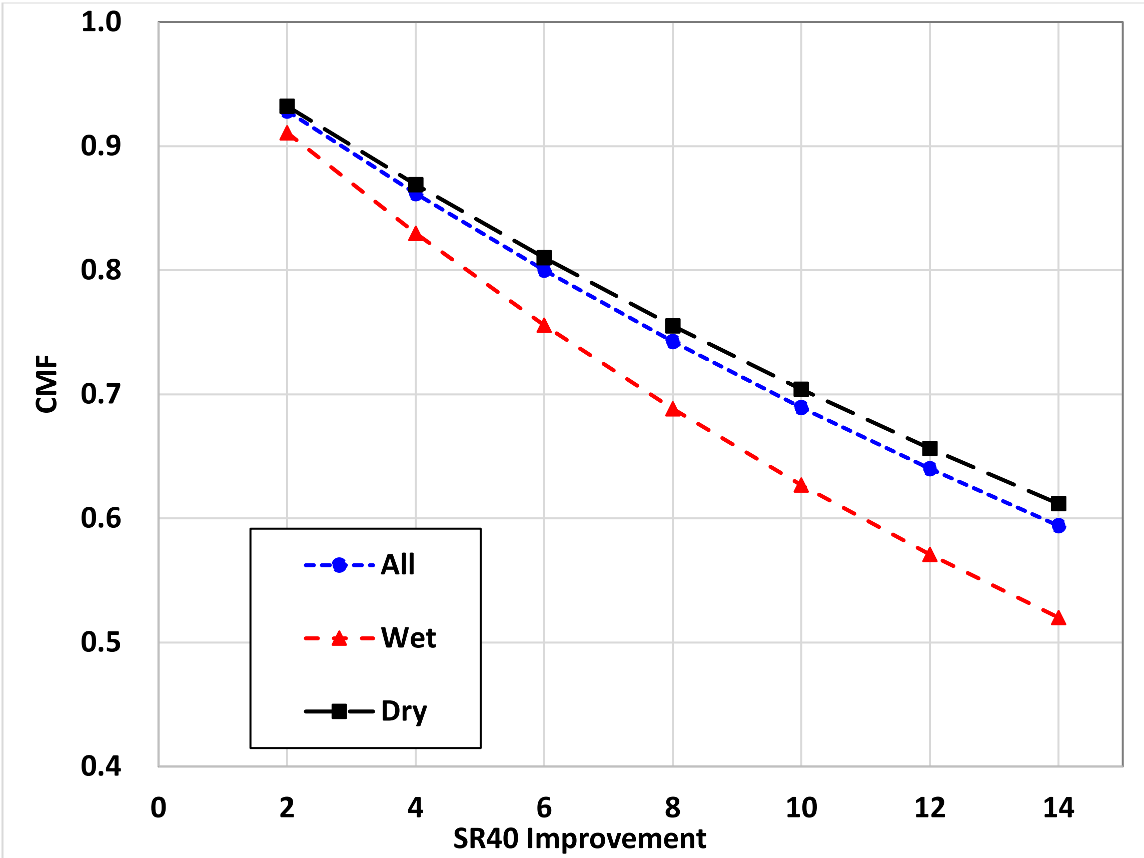


Figure 7. Graph. CMFx for friction on rural two-lane, two-way road segments by surface condition (Source: FHWA).

4.2.2 CMFs for Macrotexture Improvements

Table 12 presents the macrotexture improvement CMFx regression coefficient (β_1) in terms of MPD for each roadway facility and site type in which macrotexture has a statistically significant effect on crashes. It lists the corresponding CMFs for a 0.5-mm increase in macrotexture (MPD) using equation (8) and the predicted percent crash reduction in each case.

$$CMF=\exp(\beta_1 \Delta MPD) \qquad (8)$$

Table 12. CMFx and percent crash reduction for a 0.5-mm increase in MPD.[1]

Roadway Facility	Site Type	CMFx regression coefficient (β_1)	CMF for 0.5-mm Increase in MPD (1)	Standard Error (CMF)	% Crash Reduction
All Road Facilities	All Site Types	-0.2400	0.89	0.0064	11.3
Freeways	All Site Types	0.1175	0.94	0.0141	5.7
	Tangent Segments	-0.0982	0.95	0.0159	4.8
	Ramp Access Points	-0.2159	0.90	0.0317	10.2
	Curves	N/A			
Urban Arterials	All Site Types	-0.2363	0.89	0.0164	11.1
	Divided Tangent Segments	-0.2608	0.88	0.0299	12.2
	Undivided Tangent Segments	N/A			
	Intersections	-0.2207	0.90	0.0214	10.4
	Curves	N/A			
Rural Multilane Highways	All Site Types	-0.1645	0.92	0.0352	7.9
	Divided Tangent Segments	N/A			
	Undivided Tangent Segments	N/A			
	Intersections	-0.2885	0.87	0.0533	13.4
	Curves	N/A			
Rural 2-lane, 2-way Road	All Site Types	N/A			
	Tangent Segments	N/A			
	Intersections	N/A			
	Curves	N/A			

[1] *The CMF values were obtained using equation (8), with the corresponding regression coefficients for β_1 provided in this table, and assuming a 0.5-mm increase in MPD value.*

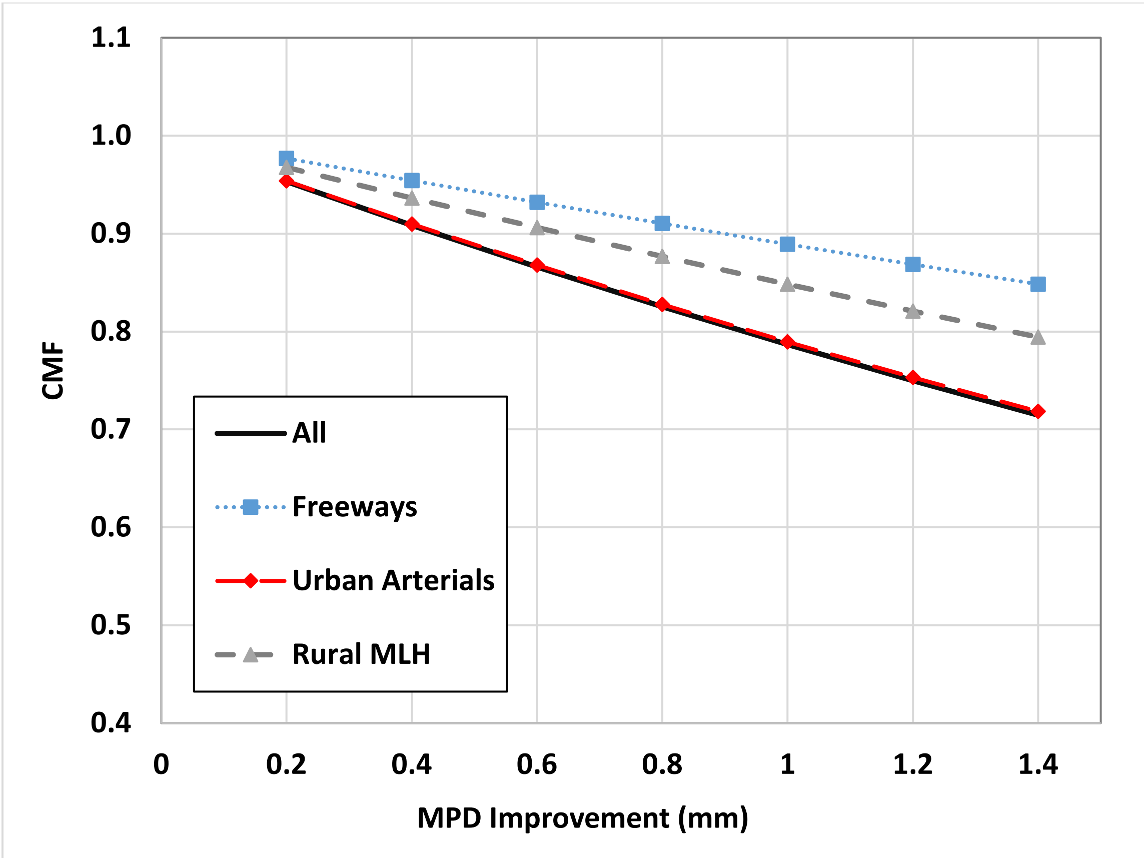


Figure 8. Graph. Comparison of CMFx for macrotexture on different roadway facility types (Source: FHWA).

4.2.3 Interaction Between Friction and Macrotexture

Pavement friction is measured as the combination of two main components: microtexture and macrotexture. In this report, microtexture is represented by AASHTO TP 143 sideway-force friction (SFN40), and macrotexture is characterized by the mean profile depth, or "MPD."

The values of SFN40 generally vary from 10 to 90 and are affected by the polishing caused by the tires of the vehicles traveling on the individual aggregate particles in the pavement surface. The MPD values of the macrotexture are reported in millimeters and generally vary between 0.1 and 3 mm. MPD values are representative of the level of openness in the pavement surface that allows water to travel out of the path of a tire. Pavement surface friction characteristics (i.e., microtexture and macrotexture) need to meet the friction demand for the given pavement section. Friction demand is the level of friction needed to safely perform braking, steering, and acceleration maneuvers. Friction demand varies with location and time due to changing geometrics, site and environmental conditions, traffic characteristics, and driver/vehicle characteristics. The interplay between microtexture and macrotexture to develop the needed friction forces to meet the friction demand is complex and varies. For example, macrotexture becomes more critical for meeting the friction demand as speed increases. Thus, the interaction of the two must be kept in mind when using the CMFs presented in the previous section. Research on pavement surface characteristics to develop a single parameter to describe friction has not yet succeeded. Several indices have been proposed, like the International Friction Index (IFI) and other variants, but they consistently have been proven unreliable in resolving this problem (Jackson, 2008).

4.3 Friction Investigatory Thresholds

As previously discussed, the research team employed two approaches to identify the investigatory level, including the model-based method, and a more practical, graphical assessment using observed crash rates per 100 MVMT for different friction levels. The investigatory levels presented in this report reflect the graphical assessment of the dataset investigated. It is expected that larger datasets will improve the basis of investigatory thresholds.

Figure 9 presents the investigatory threshold results for freeways. In general, for freeway tangent segments there is a trend of higher crash rates at lower friction values; however, the crash risk clearly increases when the friction value is lower than 36–38. Specifically, the difference in average crash rate is maximized when the friction threshold is set to that level. Therefore, in this example, the friction investigatory level would be between 36 and 38 SFN40, which corresponds to an approximate average risk of 80 crashes per 100 MVMT. The distribution of friction values for this roadway category is superimposed on the plot to provide an indication of what percentage of sections would fall below the investigatory level.

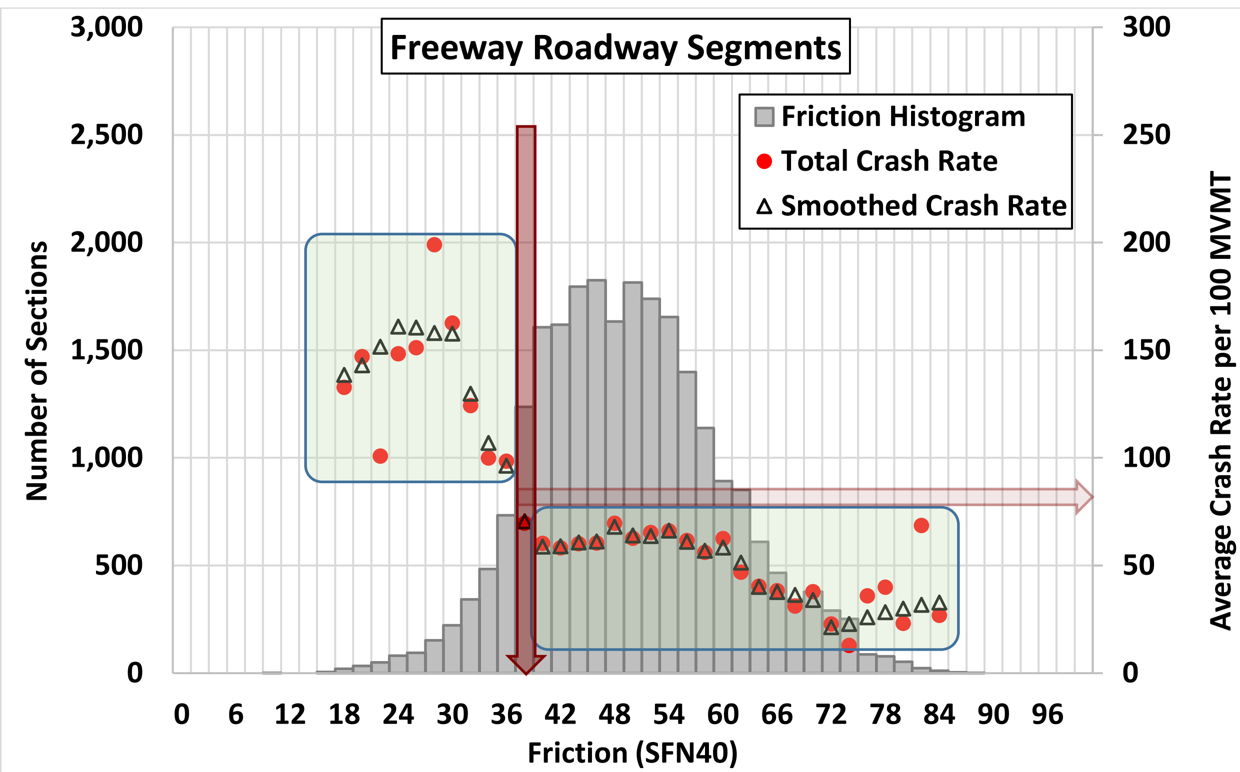


Figure 9. Chart. Friction distribution, crash rates, and estimated thresholds for freeway tangent segments (Source: FHWA).

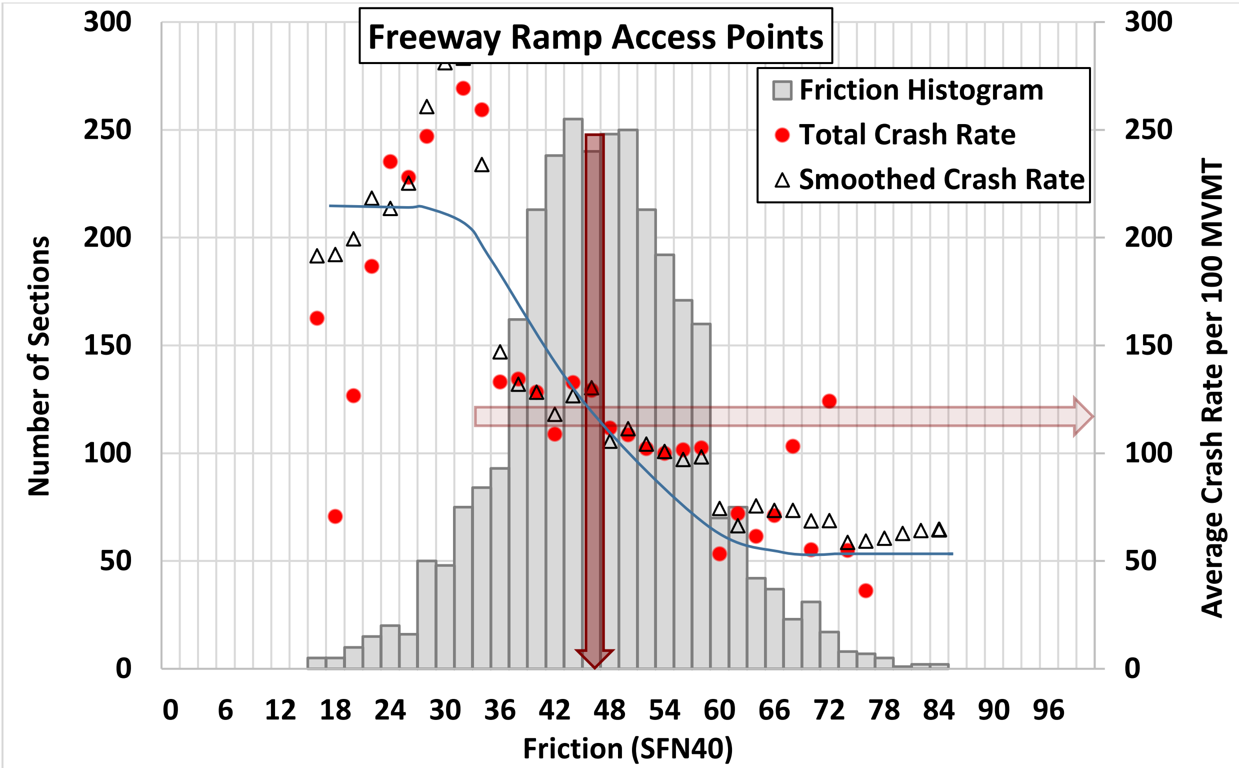
Figure 10 through Figure 16 present the graphical assessment results for investigatory threshold levels for the other roadway facility types. For these plots, the crash rates were calculated using the smoothing methodology from McCarthy et al. (2021a). Where n is the number of roadway segments, the smoothing methodology uses an adjusted, sliding window with $(n \div 4) - 1$ raw data points to flatten the curve produced using the observed crash counts. Using a smoothed curve, an inflection point, also the investigatory level, is easier to identify.

Figure 10 shows that freeway ramp access points and horizontal curves present slightly higher thresholds than tangent segments (SFN40 of 42–44 and 44–46, respectively). Furthermore, the distribution of friction values shows a higher percentage of segments with friction lower than the thresholds, possibly due to the additional surface wear on these high demand friction areas.

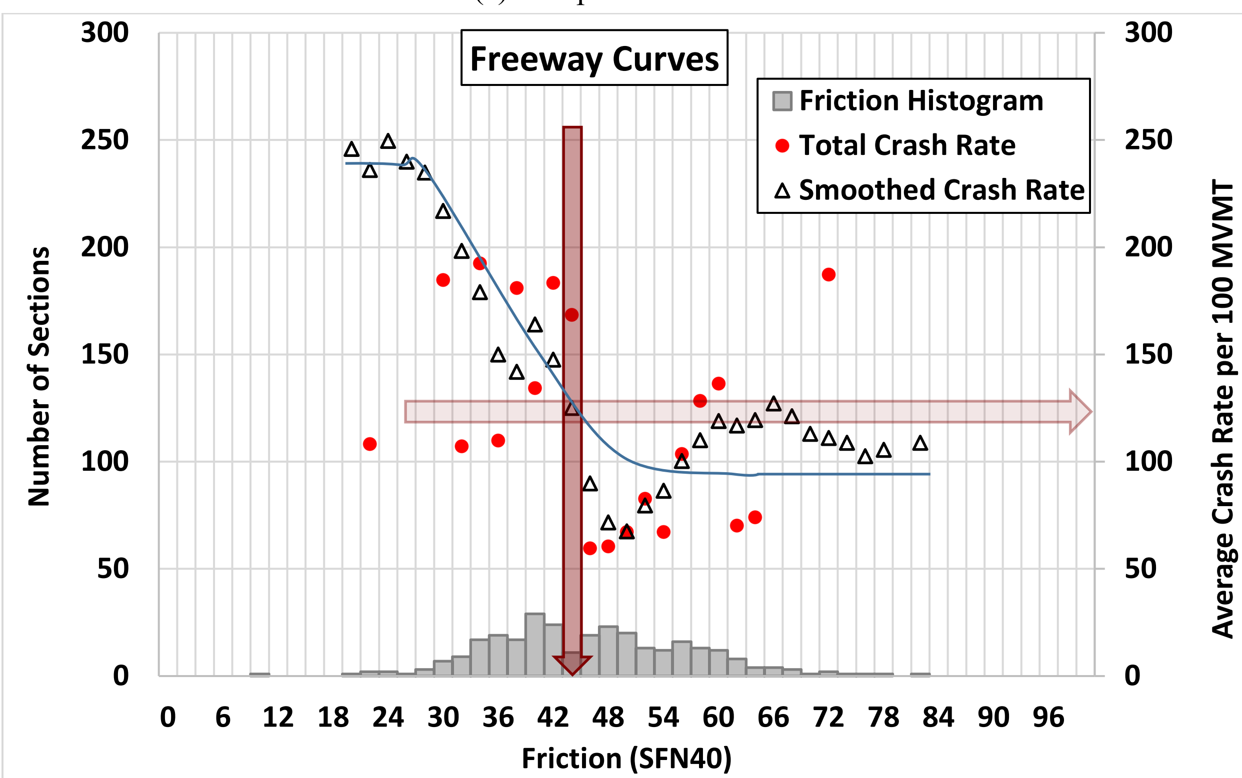
Figure 11 for urban and suburban arterial divided and undivided tangents and Figure 12 for urban and suburban arterial segments with intersections/ramp access points and horizontal curves have higher thresholds than other facility and site types, possibly due to factors other than friction. A friction level of 48–50 SFN40 corresponds to a transition in the crash rate curve for both divided and undivided, tangent segments thus adopted as the investigatory level range for the tangent segments. These values correspond to a risk of approximately 80–120 total crashes per 100 MVMT. A similar value also seems to be applicable to curves, although the sample size was small in this case. Finally, the last plot of the figure shows that crash rates are significantly higher for intersections (note the different scale) and a higher threshold of 54–58 seems to be appropriate.

Figure 13 shows that for rural multilane roadway divided and undivided tangents, the crash rates increase as friction decreases, but the threshold determination is not as clear as in the case of freeway tangents. The figure also shows that a threshold range as high as 64–66 may be selected. However, given the distribution of friction values, a threshold of 48–50, which corresponds to an approximate average risk of 60 crashes per 100 MVMT in both divided and undivided rural multilane roadways, seems more appropriate. An interesting find for this example is that the friction investigatory level for this type of facility is higher than for freeways, possibly due to more potential vehicle maneuvers and conflicts. Although they show more variability, the plots for high demand segments (curves and intersections) in this type of facility indicate that higher thresholds (54–56 SFN40) may be appropriate in these locations.

Figure 15 shows the results for rural 2-lane, 2-way tangent segments, and Figure 16 presents the results for rural 2-lane, 2-way with intersections or curves. In this case, the trend seems to suggest that a threshold range as high as 68–78 SFN40 may be appropriate for tangent segments; however, a lower range is recommended (54–56 SFN40) based on the distribution of friction values measured. As in the previous case, the plots for high demand segments (curves and intersections) in this type of facility indicate that higher thresholds may be appropriate for these locations.

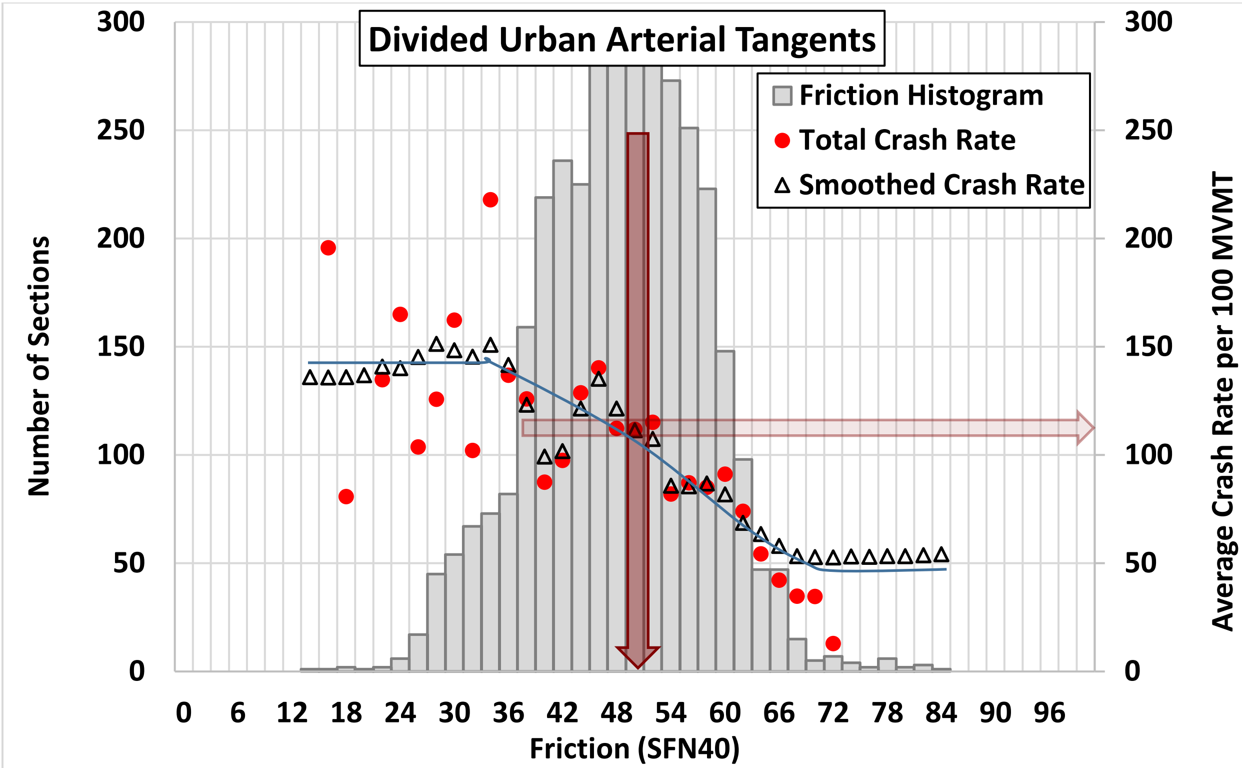


(a) Ramp Access Points

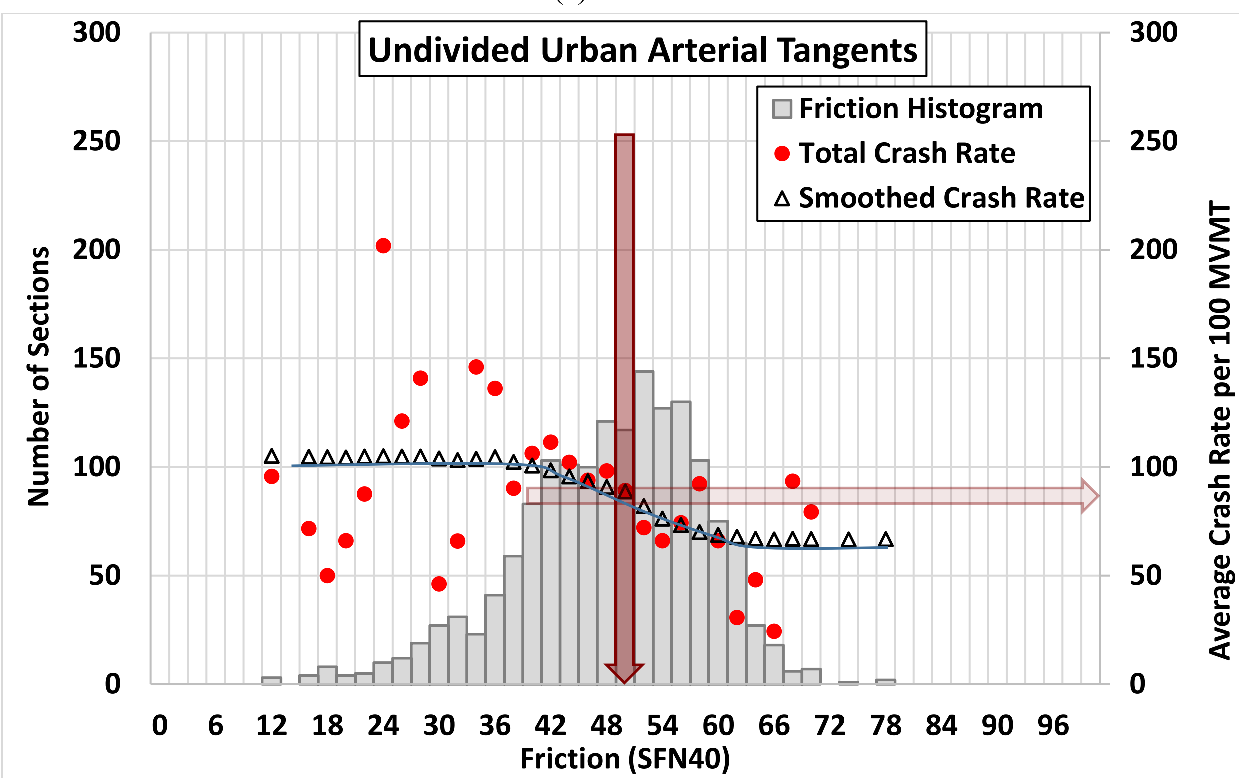


(b) Freeway Curves

Figure 10. Graph. Friction distribution, crash rates, and estimated thresholds for freeway curves and ramp access points (Source: FHWA).

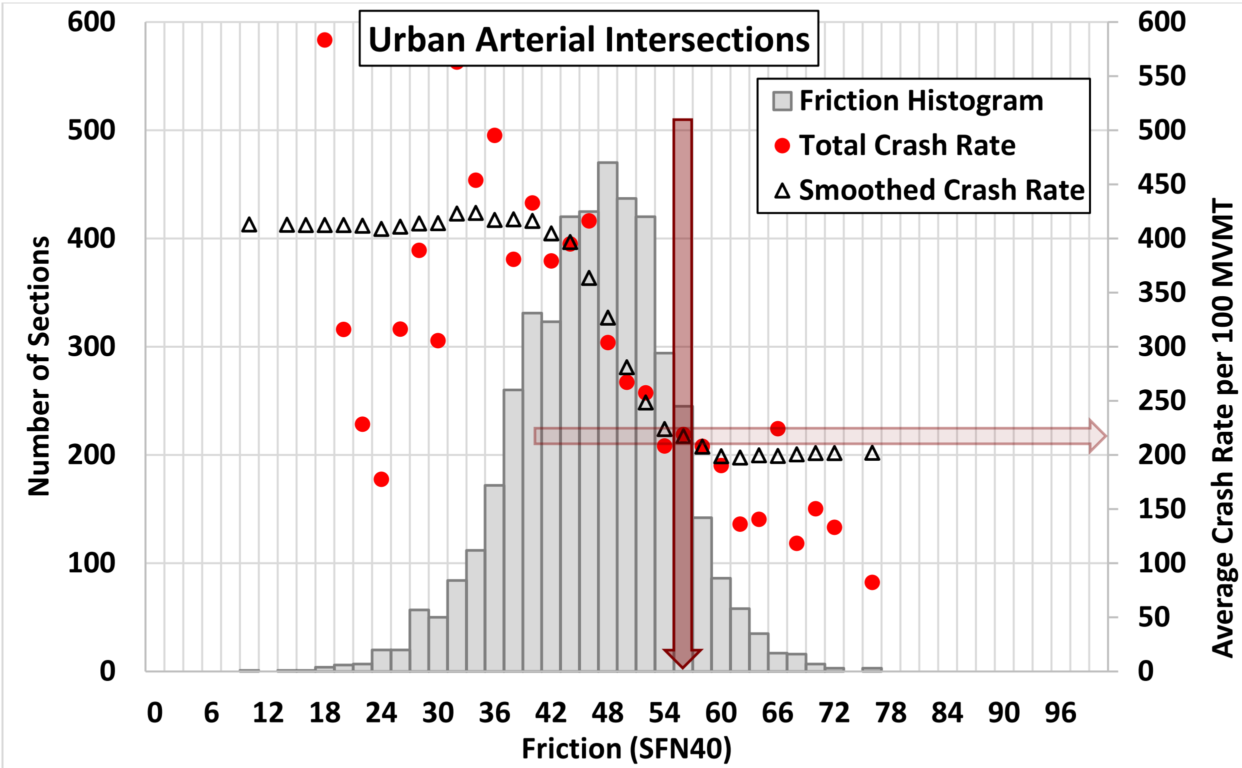


(a) Divided

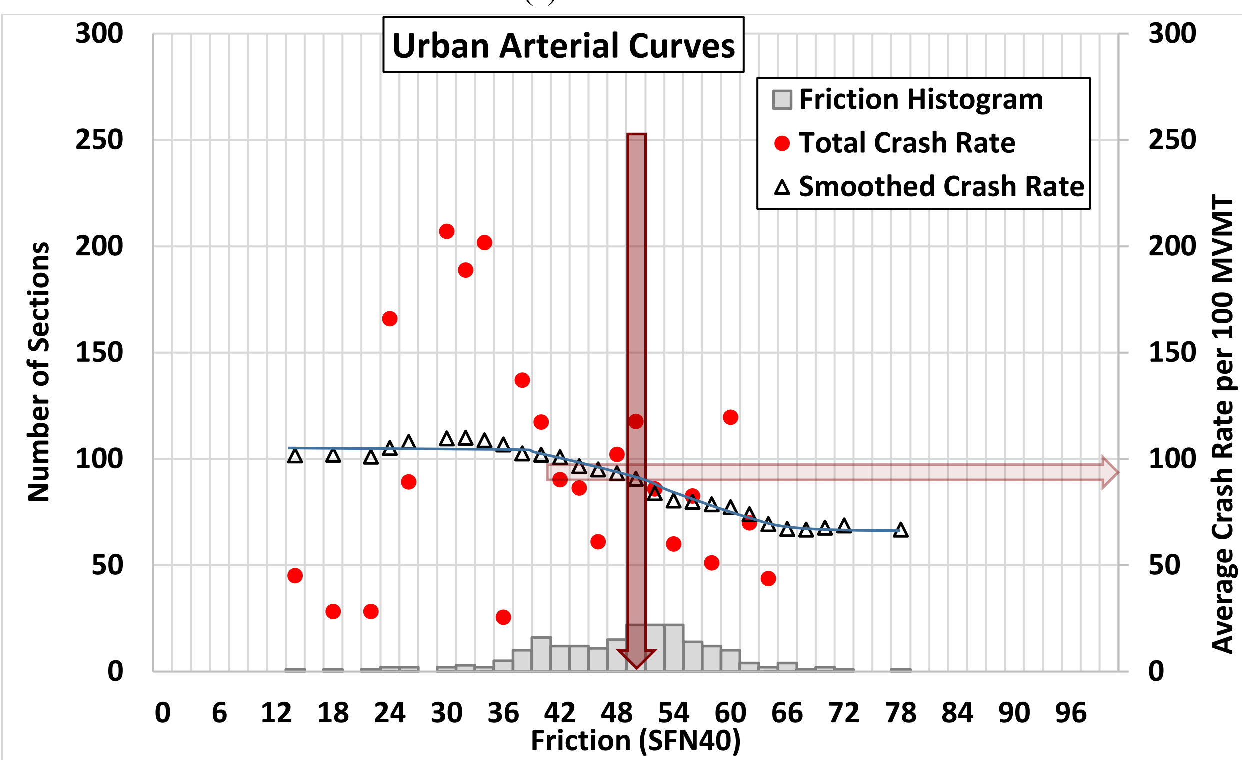


(b) Undivided

Figure 11. Graph. Friction distribution, crash rates, and estimated thresholds for urban and suburban arterial highway tangents (Source: FHWA).

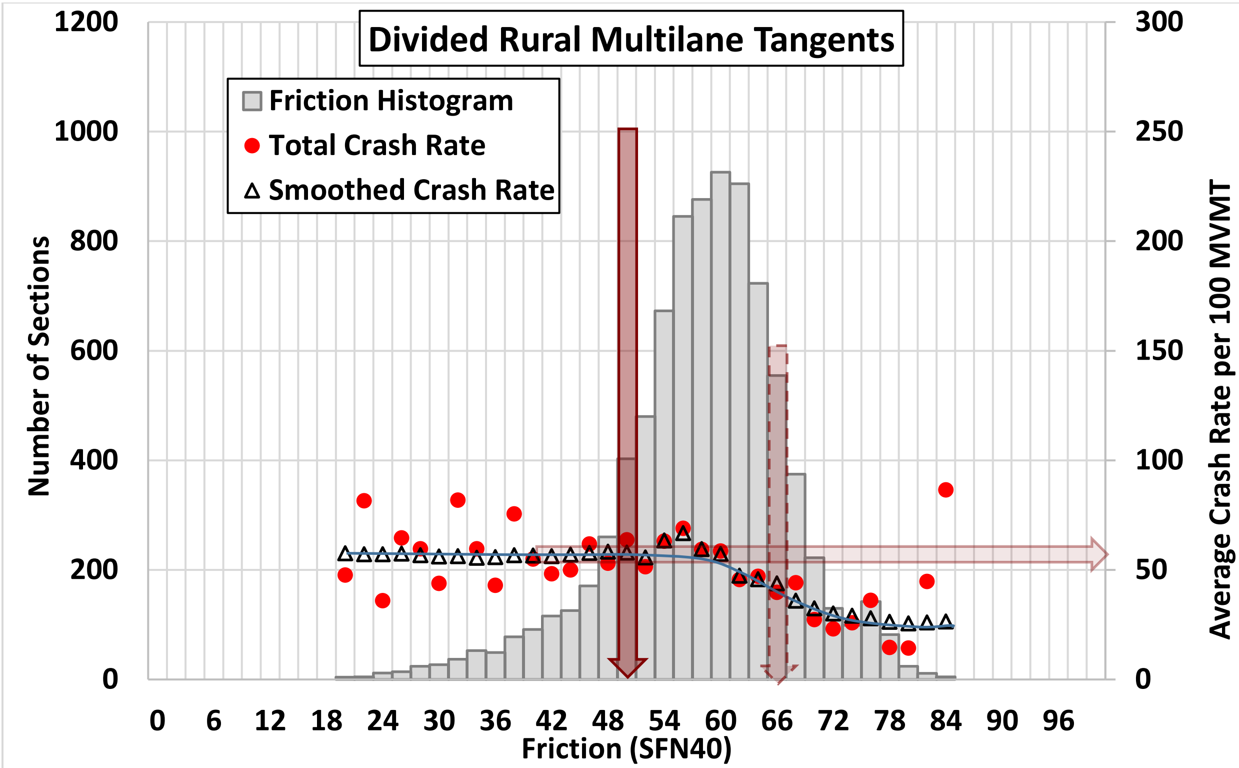


(a) Intersections

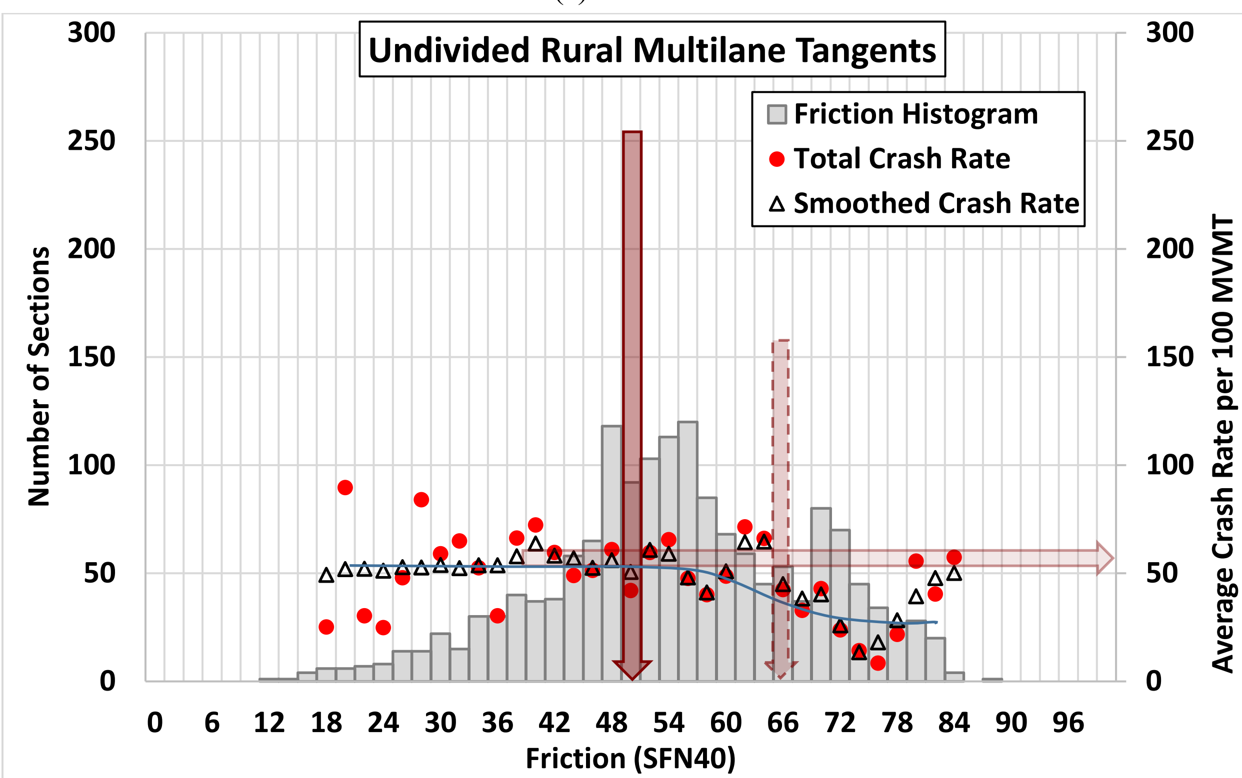


(b) Curves

Figure 12. Graph. Friction distribution, crash rates, and estimated thresholds for urban and suburban arterial highway intersections/ramp access points and horizontal curves (Source: FHWA).

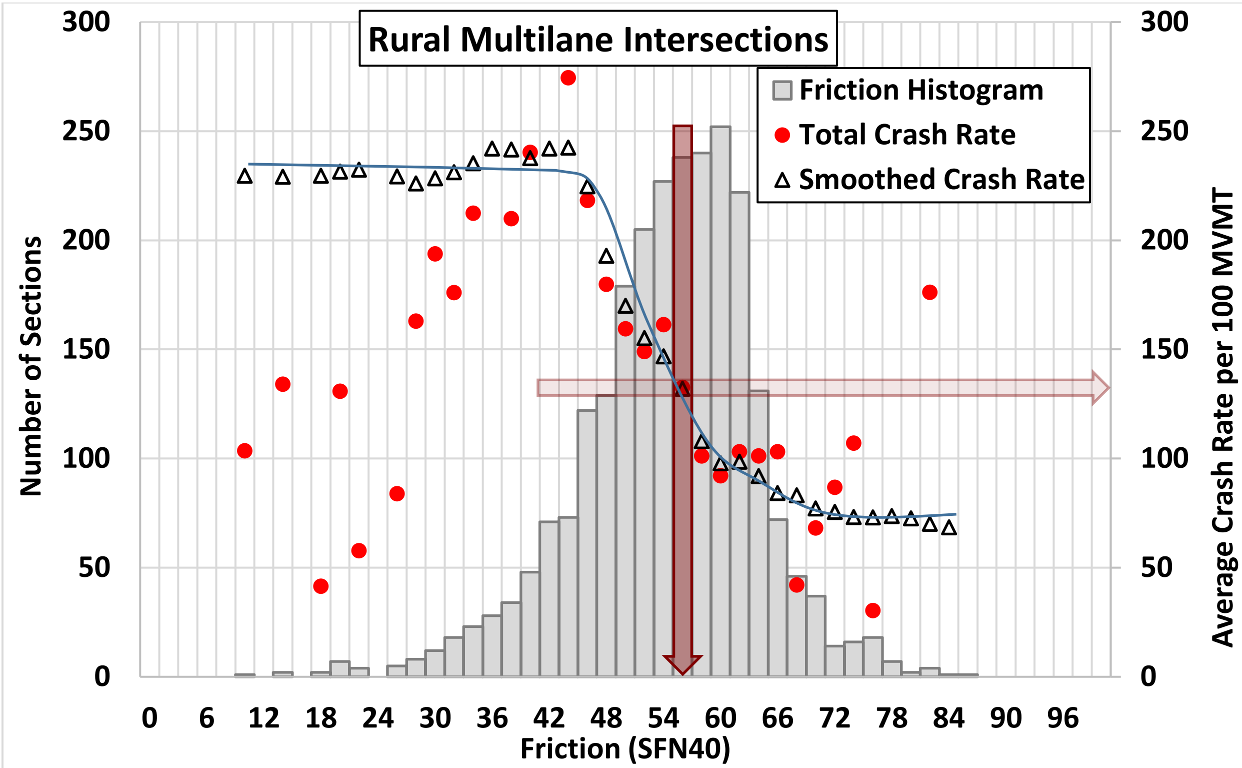


(a) Divided

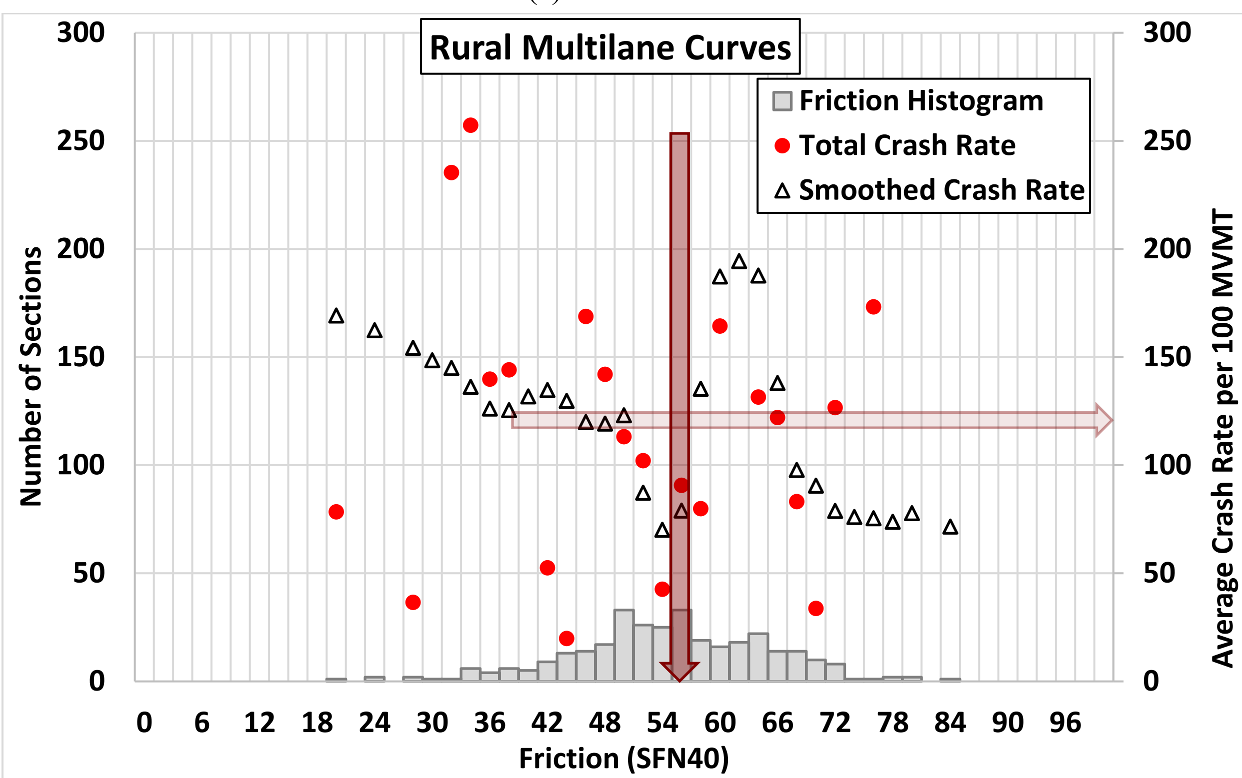


(b) Undivided

Figure 13. Graph. Friction distribution, crash rates, and estimated thresholds for rural multilane road tangent segments (Source: FHWA).



(a) Intersections



(b) Curves

Figure 14. Graph. Friction distribution, crash rates, and estimated thresholds for rural multilane road segments with intersections or horizontal curves (Source: FHWA).

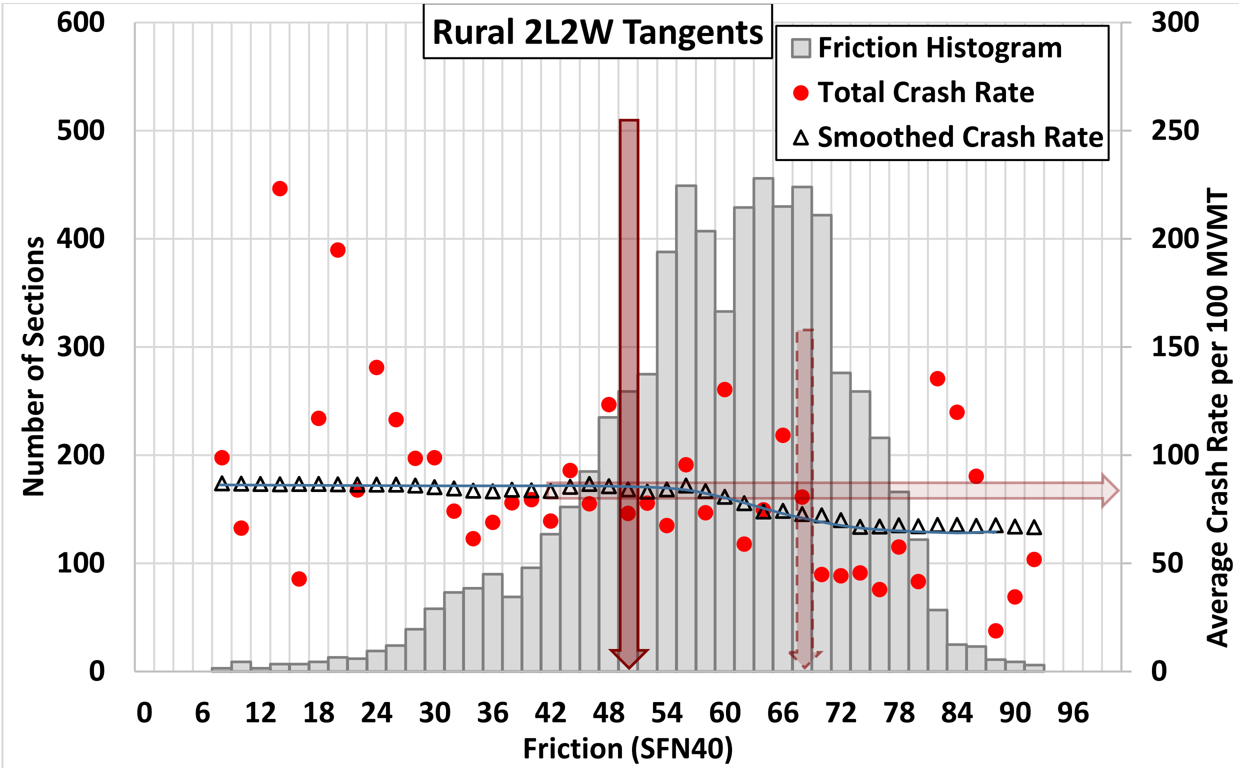
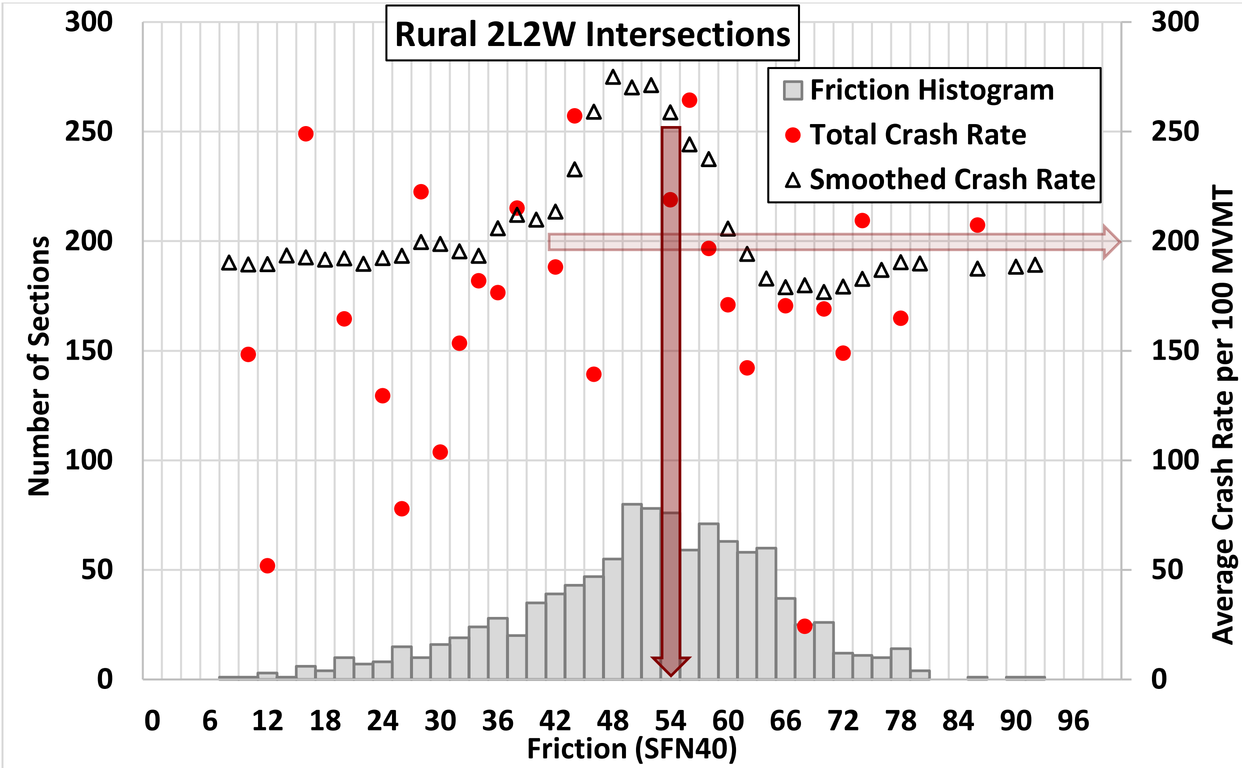
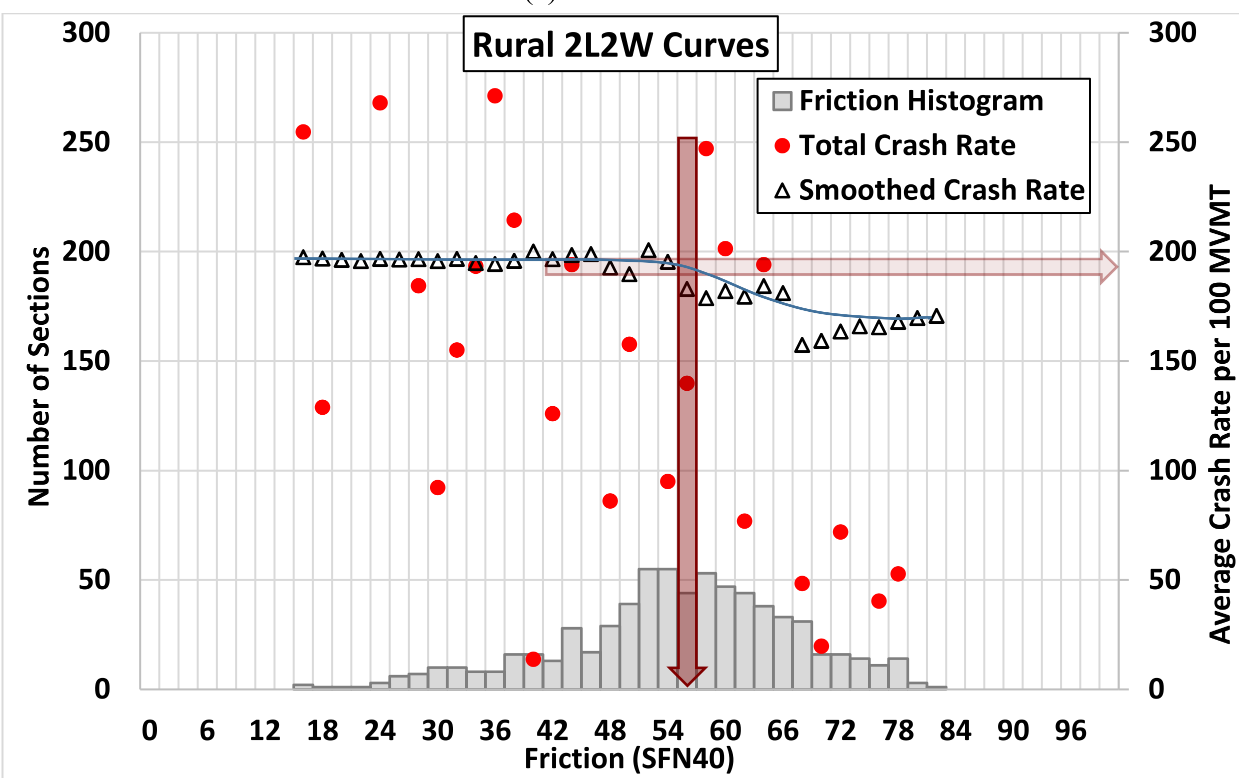


Figure 15. Graph. Friction distribution, crash rates, and estimated thresholds for rural 2-lane, 2-way road tangents (Source: FHWA).



(a) Intersections



(b) Curves

Figure 16. Graph. Friction distribution, crash rates, and estimated thresholds for rural 2-lane, 2-way (2L2W) road intersections and horizontal curves (Source: FHWA).

Table 13 summarizes the values obtained by the graphical assessment for all roadway site types investigated. The table also includes an approximate conversion to the side-force coefficient of friction measured in the UK at 30 mph (50 km/h), or "UK CSC," and the friction investigatory levels adopted in the UK for similar roadway types with regular or standard risk areas (ST) and lower-risk areas (LR) (CS 228; Highways England, 2019). The UK equivalent is obtained by removing the adjustment that is used in the UK to account for a change in the rubber characteristics of the tire (0.78), adjusting for speed (40 mph versus 30 mph in the UK), and dividing by 100 to convert the friction number to a coefficient of friction. These are provided as baseline references only, but it is interesting to note that the values are relatively consistent. Furthermore, the CS 228 does not include a separate category for urban and suburban arterial roadways.

Table 13. Summary of the threshold analysis

Roadway Facility Type	Site Type	Suggested	Graphic Threshold	Approximate UK CSC Eq.	CS 228 ST	CS 228 LR
Freeways	Tangents	40	36 – 38	0.29 - 0.31	0.35	0.30
	Curves	45	42 – 44	0.34 - 0.36	0.45 - 0.50	
	Ramp Access	45	44 – 46	0.36 - 0.37		
Rural Multilane Roadways	Divided Tangents	50	48 – 50	0.39 - 0.41	0.35 - 0.40	0.30
	Undivided Tangents	50	48 – 50	0.39 - 0.41	0.40 - 0.45	0.35
	Curves	55	54 – 56	0.44 - 0.46	0.45 - 0.50	
	Intersections	55	54 - 56	0.44 - 0.46	0.45 - 0.55	0.40
Rural 2-lane, 2-way Roadways	Tangents	50	48 - 50	0.39 - 0.41	0.40 - 0.45	0.35
	Curves	55	54 - 56	0.44 - 0.46	0.50- 0.55	0.45
	Intersections	60	54 - 56	0.44 - 0.46	0.45 - 0.55	0.40
Urban and Suburban Arterials	Divided Tangents	50	48 - 50	0.39 - 0.41		
	Undivided Tangents	50	48 - 50	0.39 - 0.41		
	Curves	50	48 - 50	0.39 - 0.41		
	Intersections	55	54 - 56	0.44 - 0.46		

CHAPTER 5. Conclusions

The following conclusions can be drawn from the analysis of the relationship between crash rates and frictional properties using the five-State data set described in this report:

- The analysis confirmed a strong statistical association between pavement surface frictional properties (friction and macrotexture) and crash rates. Lower crash rates were observed with higher friction (SFN40) and macrotexture (MPD) on all roadway types.
- The data supported development of SPFs for total crashes on different roadway facility types that included friction and macrotexture measurement using traditional NB models.
    - Friction was found to have a statistically significant effect for predicting total crashes on all the roadway facility types.
    - Macrotexture was found to have a statistically significant effect for predicting total crashes on all roadway facility types except rural two-lane/two-way roads. However, this is likely due to data limitations, and should not be interpreted to mean that macrotexture is not important on these roads.
- These SPFs were then used to develop CMFs and CMFx for relatively straight segments without events (tangents) and with areas of higher friction demand (curves and intersections) on each type of facility.
    - The CMFx and corresponding crash reduction percentages for 10-unit increases in SFN40 are presented in Tables 10 and 12. They are reasonable and generally follow the expected trends.
    - The results in Table 10 indicated potential reductions of up to 30 percent of total crashes can be achieved with a 10-unit increase in SFN40 (on urban arterial intersections).
- Illustrative friction investigatory thresholds were also defined for the various roadway facility and site types. They were developed based mostly on the graphical interpretation of the crash rates for different friction levels. As expected, the investigatory levels are higher for higher friction demand sites, such as curves, ramp access points, and intersections.

The following research is recommended for further improving the models and resulting CMF/CMFx:

- Some categories have a relatively small number of observations and further work should include incorporating data from other States that is becoming available (Kentucky, Illinois, etc.). It would be particularly useful to assemble larger data sets to get more robust results for fatal and serious injuries crash and crash types.
- The interaction between microtexture and macrotexture needs further investigation.
- As the US gains experience with continuous friction measurement data collection, seasonal adjustments can be applied, in accordance with international practice, to enhance the analysis.

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