FINAL REPORT

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Wyoming Department of Transportation, State of Wyoming

MANAGING PAVEMENT FRICTION OF WYOMING'S ROADS CONSIDERING SAFETY

By:

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16. Abstract: This research addressed the management of pavement friction in Wyoming, focusing on its impact on road safety. The primary objective was to investigate the relationship between pavement surface friction and friction-related traffic crashes. Comprehensive data collection and advanced statistical methods, such as Bayesian analysis, were employed to analyze the relationship between pavement surface friction and traffic crashes, particularly at intersections. The investigation revealed that improved pavement friction is particularly beneficial in high-traffic and geometrically complex road sections, significantly reducing crash frequencies. The study indicates that lower pavement friction correlates with higher crash frequencies, underscoring the need for effective friction management strategies.

The effectiveness of different surface treatments was assessed, with results showing that treatments like chip seals and microsurfacing not only extend pavement life but also improve friction, thereby decreasing friction-related crashes. The research also integrated pavement friction management into Pavement Asset Management Systems (PAMS) across state Departments of Transportation, highlighting variability in implementation practices and calling for standardized protocols.

This study provides practical recommendations for implementing a robust friction management system. Emphasizing continuous monitoring and proactive maintenance.

17. Key Words

Pavement Friction, Road Safety, Traffic Crashes, Friction Management, Bayesian Analysis, Pavement Treatments.

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		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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LIST OF ABBREVIATIONS

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BMP	Beginning Mile Post
BPT	British Pendulum Tester
CARE	Critical Analysis Reporting Environment
CPFM	Continuous Pavement Friction Measurement
CST	California Skid Tester
DOT	Department of Transportation
EMP	Ending Mile Post
EPDO	Equivalent Property Damage Only
ESAL	Equivalent Single Axle Load
FHWA	Federal Highway Administration
FN	Friction Number
HFS	High Friction Surfacing
HFST	High Friction Surface Treatments
HMA	Hot-Mix Asphalt
HSIP	Highway Safety Improvement Program
IRI	International Roughness Index
LSD	Least Significant Difference
LTPP	Long-Term Pavement Performance
MAD	Mean Absolute Deviation
MTTF	Median Time To Failure
NB	Negative Binomial
NHS	National Highway System
NHTSA	National Highway Traffic Safety Administration
OGFC	Open Graded Friction Course
PCI	Pavement Condition Index
PDO	Property Damage Only
PFM	Pavement Friction Management
PMS	Pavement Management System
PSI	Pavement Serviceability Index
SCRIM	Sideway Force Coefficient Routine Investigation Machine
SN	Skid Number
SPF	Safety Performance Function
UTBWC	Ultra-Thin Bonding Wearing Course
VIF	Variance Inflation Factor
VPD	Vehicle Per Day
WYDOT	Wyoming Department of Transportation

CHAPTER 1: INTRODUCTION

Pavement surface friction, also known as skid resistance, is a surface characteristic that enables the driver to maneuver the vehicle (McCarthy et al., 2016). Pavement friction results from a complex interplay between two principal frictional force components: adhesion and hysteresis (Kouchaki et al., 2018). Adhesion is the friction resulting from the small-scale bonding of the vehicle's tires and the pavement surface, while the hysteresis component of the frictional forces results from the energy loss created within the tire as it responds to texture (Kouchaki et al., 2018). Achieving adequate levels of pavement friction enhances road safety in terms of reducing proportions of certain crash types. Although pavement friction is considered in managing maintenance plans of roadways, most state Departments of Transportation (DOTs) consider simple friction criteria, such as the Friction Number (FN), for selecting treatments. The Wyoming Department of Transportation (WYDOT) categorizes its road network in excellent condition (greater than 55 FN), good condition (greater than 40 FN but less than or equal to 55 FN), fair condition (greater than 35 FN but less than or equal to 40 FN), and poor condition (less than or equal to 35 FN). The FN values aid in the determination of construction and maintenance treatment activities on a contract level and internal WYDOT crew level. As a result, the impact of various conditions on pavement friction and the relationship between skid resistance and traffic safety are not well investigated.

1.1. Problem Statement

Wyoming experienced 14,900 crashes in 2019, of which 120 (0.8 percent) were fatal and, 2,580 (17.3 percent) were injury crashes. These crashes have a significant impact on the state's economy and the well-being of its residents. Wyoming is characterized by a high percentage of truck traffic along its highways. Some of the high traffic volumes are due to industrial activities in the state. The Wyoming I-80 corridor serves an average annual daily traffic (AADT) volume ranging from 12,000 to 17,000 vehicles per day (vpd) with a percentage of trucks estimated at up to 51 percent. A considerable proportion of the Wyoming statewide crashes occurred on non-dry road surfaces (e.g., wet, icy, snowy or slushy surfaces). With all these facts, certain crash types such as lane departure and rear-end crashes are expected to be strongly influenced by pavement friction levels in Wyoming. Other factors may have the potential to impact the occurrences of skid related crashes including vertical profile, horizontal profile, operating speeds, surface type (e.g., asphalt or concrete), and road functional classification. Pavement friction is currently treated in Wyoming using thin layers of bonded aggregates. Yet, the effectiveness of each of the different treatments is not covered. These challenges require additional research needs to interpret the association between traffic safety and skid resistance properties to arrive at better informed decisions regarding pavement maintenance.

In terms of traffic safety, drivers' ability to accelerate, brake, and steer the vehicle is significantly affected by pavement friction and skid resistance (McCarthy et al., 2016). The friction properties of the pavement play a key role in the skid resistance across the pavement surface. Vehicles tend to have different friction demands, which are levels of skid resistance needed to execute safe driving maneuvers (Najafi et al., 2017). The highway engineering literature shows that there are different factors affecting friction demands including roadway geometries, operating speeds, weather conditions, traffic volumes and vehicle mix compositions, among other factors. Higher friction values are commonly required at horizontal curves, steep grades and areas in which vehicles are required to stop or slow down (e.g. intersections and roundabouts). Friction demands could be more important on roads encountering higher rates of precipitation. A research study conducted by the National Transportation Safety Board shows that improving pavement friction can mitigate wet road crashes by 70 percent (McGovern et al., 2011). According to the National Highway Traffic Safety Administration (NHTSA), more than 19,000 fatalities resulted from roadway departure crashes from 2016 to 2018 (FHWA, 2020). The road departure crashes represent 51 percent of the nationwide fatality toll. Pavement friction can contribute to lane departure crashes in areas where friction demands are high.

This study identified the relationship between pavement performance in terms of skid resistance and the probability of skid-related crashes. The study also expanded these relationships to manage the pavement maintenance plans considering the long-term friction performance of surface treatments, costs, and safety performance targets.

1.2. Objectives

The main goal of this study was to enhance road safety in Wyoming by integrating a crash risk mitigation approach into the pavement friction management program. This goal was accomplished by performing the following tasks:

- Investigate the relationship between pavement surface friction and friction-related crashes in Wyoming.
- Define the best practices of maintaining pavement friction levels using bonded aggregates and surface treatments.
- Implement a data-driven approach to select friction related maintenance strategies.
- Estimate the potential reduction in friction related crashes due to the enhanced maintenance activities, which consider the restoration of adequate pavement friction levels.
- Develop a detailed methodological framework for implementing pavement friction treatments for WYDOT considering safety implications.
- Determine the cost-effectiveness of the proposed pavement friction management plans in terms of crash reduction benefits and associated maintenance costs.

- Propose an enhanced pavement management policy for WYDOT considering friction treatment plans to ensure safe traffic operations.

1.3. Report Organization

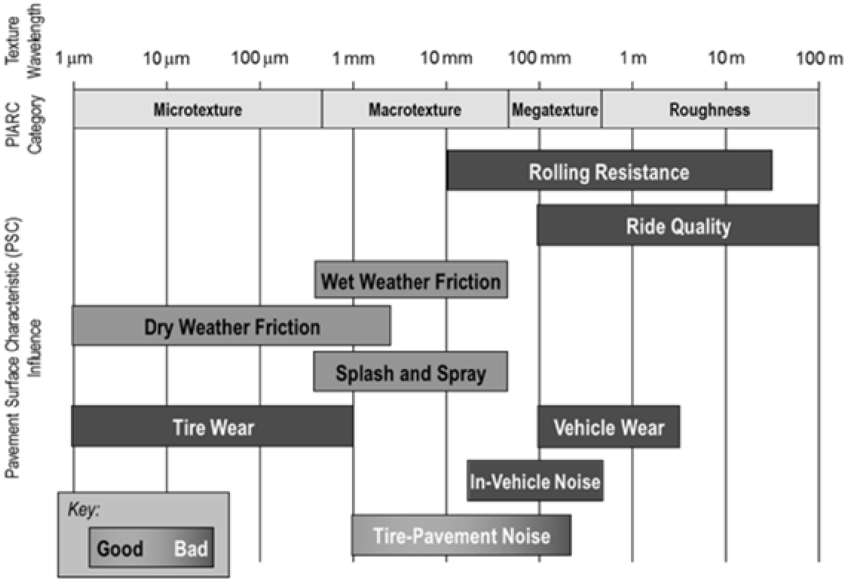
This report is organized into six chapters. Chapter 2 comprises background information and a review of previous studies related to this project. The subsequent chapter, Chapter 3, entails the summarized results of the relationship between pavement surface friction and friction-related crashes in Wyoming. Chapter 4 presents discussions of incorporating pavement friction management into pavement asset management systems while focusing on state DOT’s experience. Chapter 5 demonstrates the evaluation of the effectiveness of surface treatments on pavement friction performance using deterministic historical data and survival analysis. Finally, Chapter 5 is composed of the conclusions of this research and recommendations for future work.

CHAPTER 2: LITERATURE REVIEW

2.1. Pavement Friction Characteristics

Pavement friction is an important resisting force that eliminates the relative motion between the vehicle tires and the pavement surface (Hall et al. 2009a). The frictional force between the tires and the surface is generated in two main directions, namely the longitudinal and lateral directions. These forces are greatly affected by the pavement texture which can be classified according to the texture's wavelength (Henry, 2000). As shown in Figure 1, the microtexture and the macrotexture are two critical characteristics affecting the skid resistance of the pavement. The term microtexture refers to the small-scale of the pavement aggregate surfaces and is responsible for achieving adequate adhesion between the tires and the pavement surface in dry conditions. However, this adhesion is reduced when the pavement is wet. On the other hand, the macrotexture is the large-scale texture of the pavement surface due to the aggregate particle arrangement. The higher wavelengths entailed in macrotexture materials are essential to provide paths for water drainage from beneath the tire such that the adhesive component of the friction provided by microtexture is reestablished.

Microtexture is affected by the properties of the surface coarse aggregates used in asphalt pavements while fine aggregates and cement paste provide the required micotexture adhesions for concrete pavements. On the other hand, the pavement-tire friction of macrotexture asphalt surfaces is formed from the size of the aggregate particles, shape of the aggregate particles and porosity of the surfaces. The pavement-tire friction of macrotexture concrete surfaces is shaped by grooving as shown in Figure 2.



Source: The Transtec Group, Inc.

Figure 1. Chart. Effect of pavement texture on road surface friction (Source: Merritt et al., 2015).

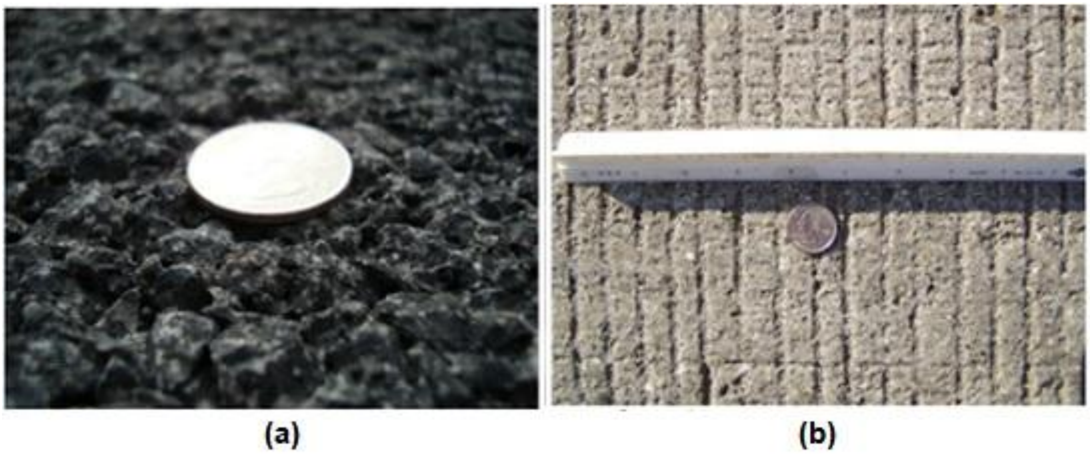


Figure 2. Illustration. Macrotexture of pavement surfaces: (a) asphalt; (b) concrete tining. (Source: Merritt et al., 2015)

2.2. Friction Number

Although the pavement performance is represented by several indices, pavement friction is commonly determined in terms of Friction Number (FN). The locked wheel test measures the steady-state friction force applied on a locked wheel dragged over a wetted pavement surface and under a constant load and constant speed. The full-scale automotive tire can be either ribbed or smooth. The FN, also referred as Skid Number (SN), is simply the ratio of friction lateral force and vertical weight load multiplied by 100, see Equation 1. Typically, FN ranges between 0 and 100, being 100 the complete friction. However, pavement practically exhibits FN values ranging between 20 and 70 depending on the friction performance in addition to the tester speed and type of tires. FN values are generally designed by the testing speed in mile per hour (mph) followed by letter “R” for ribbed or “S” for smoothed.

$$FN = \frac{F}{W} * 100 \tag{1}$$

where,
F is tractive horizontal force applied to the test tire at the tire-pavement contact patch (lbf or N).
W is dynamic vertical load on test wheel (lbf or N).

The current practices of managing pavement friction indicates that some state DOTs consider a minimum FN value for maintenance intervention to enhance the safety performance of pavement friction. In Wyoming, the minimum acceptable friction value is when (FN40R) is 49 and 46 for rural interstate and urban interstate, respectively. No defined criteria are followed for lower road classes, including national highway system (NHS) and non-NHS. Some state DOTs include a predefined values of minimum friction ranging between 20 and 40 (Elkhazindar et al., 2022).

2.3. Importance of Pavement Safety

The importance of maintaining adequate pavement friction cannot be overstressed. The friction resulting from the interaction between the tires and the pavement plays a critical role in highway safety. It inhibits drivers from executing unsafe maneuvers involving veering off their intended travel trajectories. It is also needed for highway geometric design when it comes to determining minimum stopping distances (Hall et al., 2009a). In addition, the pavement friction ought to be adequate for skid resistance purposes when having wet, icy, snowy or slushy road surfaces. At the national level, roughly, 25 percent of total crashes and 13.5 percent of fatal crashes occur on wet roads (Hall et al., 2009a; Kuemmel et al., 2000). The following content is composed of discussions of research studies about the relationship between pavement friction and safety.

Rizenbergs et al. (1972) found that the rates of crashes that occurred on wet road surfaces were higher for conditions in which the SN40R were lower than 40. That was for roads with light and medium traffic volumes. The SN40R is the American Society for Testing and Materials (ASTM) designation for the friction number measured using a test vehicle with grooved tires traveling 40 mph over the pavement under study. The American Association of State Highway and Transportation Officials' (AASHTO's) designation for this measure is FN40R (Hall et al., 2009b). Giles et al. (1962), Cairney (1997) and Gothie (1996) confirmed that FN values under 50 indicated hazardous conditions whereas those higher than 60 indicated a reduced likelihood of pavement friction related crashes. McCullough and Hankins (1966) suggested a friction coefficient that is not less than 0.4. This value was ascertained based on tests of which the test vehicle was driven at 30 mph. Miller and Johnson (1973), Kamel and Gartshore (1982) and Bray (2002) discovered that maintaining the pavement such that its friction is at an appropriate level reduces wet surface related crashes. McLean (1995) inferred that crash rates may rise for rural highway sites that were upgraded to have higher friction numbers. This was possibly because drivers were likely to use lower friction roads and to travel faster.

In a more recent study, Noyce et al. (2007) investigated the association between pavement skid resistance and crash count. The research team did not conclude that a correlation exists between both parameters based on their statistical analyses. However, the data showed that lower friction numbers corresponded to unsafe road surface conditions. Also, it was recommended that the roads be maintained such that their FN40R's do not drop to 35 or lower. Mayora and Piña (2009) also maintained that higher friction numbers translated to safer roads for wet road surface conditions. Note that the authors used skid resistance data collected from the Sideway Force Coefficient Routine Investigation Machine (SCRIM).

Other notable relevant studies are those of the Organization for Economic Cooperation and Development (1984), Wallman and Astrom (2001), Gandhi et al. (1991), Craus et al. (1991), Larson (1999), Xiao et al. (2000) and Schulze et al. (1976). The previously discussed studies show that the likelihood of wet surface related crashes reduce with the enhancement of pavement friction levels. Also, surfaces with friction numbers less than particular values, depending on the site, represent hazardous conditions (Kuttesch, 2004). Yet, the occurrences of wet surface related crashes are not only attributed to the pavement friction but also to other crash contributing factors. Hence, the relationship between the risk of wet surface related crashes and pavement friction, whether linear or not, is dependent on the roadway facility under study (Hall et al., 2009a).

2.4. Friction Management System

As per the Highway Safety Improvement Program (HSIP), each state shall incorporate a process for analyzing traffic safety data that identifies highway safety improvement projects (FHWA, 2019). Hence, state DOTs can prioritize and manage the use of resources to reduce friction-related vehicle crashes using a network-level friction management program. In this program, pavement friction characteristics are periodically collected on road segments to find sections which have intolerable rates of friction-related crashes. Processed pavement friction management data aids DOTs in arriving at better informed decisions to enhance skid resistance at high crash risk locations, or hot-spots, to reduce expected fatalities and injuries in the state. The FHWA issued guidelines for the implementation of Pavement Friction Management (PFM) programs which cover several topics including (FHWA, 2017):

- Measuring pavement friction,
- Identifying and classifying road network hot-spots,
- Prioritizing projects for improving pavement friction levels, and
- Determining the effectiveness of developed friction management programs.

Due to the federal policies embedded in both the Moving Ahead for Progress in the 21st Century (MAP-21) Act (MAP-21, 2022) and the Highway Safety Improvement Program (HSIP) (HSIP, 2022), the PFM has been increasingly recommended to promote safety by reducing the number of friction-related crashes and enhancing the efficiency of pavements (Friction Management, 2022). Consequently, various forms of friction guidance and organizations have been developed to help transportation agencies cover the technical aspects of pavement friction, including the FHWA Technical Advisories on pavement friction management and the AASHTO Guides, Manuals, and Guide Specifications for geometric design (Guide for Pavement Friction, 2008; Pavement Friction Management, 2021). In addition, pavement industry groups and international agencies have been involved in developing bulletins, guides, and manuals for friction testing, design, and safety management (Shaffer et al., 2006; Highways England, 2022; Austroads, 2011). The initial concern of pavement friction and safety performance was raised only on roads during wet weather conditions, but recent studies have found that friction should be addressed to include all pavement surface conditions (e.g., wet and dry surfaces) (McCarthy et al., 2021a). Several studies assess the friction demands on roads considering investigatory and intervention levels (Hall et al., 2009; McCarthy et al., 2021b). Other studies link between the friction demands and road geometric characteristics, and the lowest friction levels were found on high-speed roads, curves, and approaches to intersections (de León Izeppi et al., 2019). This emphasizes on addressing the specific friction demands on transportation facilities where vehicles are required to frequently stop and slow down. As a consequence, a continuous pavement friction measurement (CPFM) was evolved to measure pavement friction continuously through tangents, curves, and intersections. The FHWA encourages the use of CPFM to provide a comprehensive pavement friction data (CPFM, 2022). As far as pavement friction enhancements, several surface treatments were evaluated on the expected performance of skid resistance, including chip seal, fog seal, miscrosurfacing, ultra-thin bonding wearing course (UBWC), among other treatments (Li et al., 2011). Moreover, higher quality materials were used in the innovative High Friction Surface Treatments (HFST) which demonstrated nationally and internationally significant increases in friction for spot applications (HFST, 2022).

There has been an interest in assessing the agency's procedures and practices of managing the pavement friction. Henry (2000) conducted a survey for identifying friction and texture measurements in addition to the requirements among state agencies who responded in 1999. Another study was conducted by Shaffer et al. (2006) which was limited to the low number of participation (i.e., only nine states participated in the interview survey). Although much information and guidance related to pavement friction is available, some studies mention that such recommendations are not integrated into a comprehensive administrative policy and design tool for addressing friction issues (Hall et al., 2009a). Based on a literature search and brainstorming meetings, Speir et al., (2009) indicated that few state DOTs adopted practices of skid accident reduction programs and/or PFM systems.

2.5. Pavement Friction Treatments

Most surface treatments are responsible for improving the micro- and macrotexture of pavement surfaces which increase the skid resistance. Several treatments are used throughout the U.S. to enhance pavement friction as listed in Table 1 (Merritt et al., 2015). According to the current practices of managing pavement friction among state DOTs, the most applied surface treatments for asphalt skid resistance are chip seal, microsurfacing, thin overlay, and open graded friction course (Elkhazindar et al., 2022). This is due to the fact that these surface treatments are relatively less expensive and have a significant enhancement in the friction properties. In addition, these treatments are common among the pavement preservation strategies for addressing pavement cracking and minor defects.

The following subsections describe the three most common surface treatments used for pavement friction.

Table 1. Common surface treatments to increase skid resistance.

Asphalt Pavement	Concrete Pavement
Chip Seal	Grooving
Micro-Milling	Diamond Grinding
Thin Hot-Mix Asphalt (HMA) Overlay	Thin HMA Overlay
Open Graded Friction Course (OGFC)	Open Graded Friction Course (OGFC)
Ultra-Thin Bonded Wearing Course (UTBWC)	Ultra-Thin Bonded Wearing Course (UTBWC)
Microsurfacing	Microsurfacing
Texturing: Shot Blasting /Abrading	Texturing: Shot Blasting /Abrading
High Friction Surfacing (HFS)	High Friction Surfacing (HFS)
Cape Seal	Epoxy Overlay (Bridge Deck)
Scrub Seal	
Slurry Seal	

2.5.1. Chip Seal

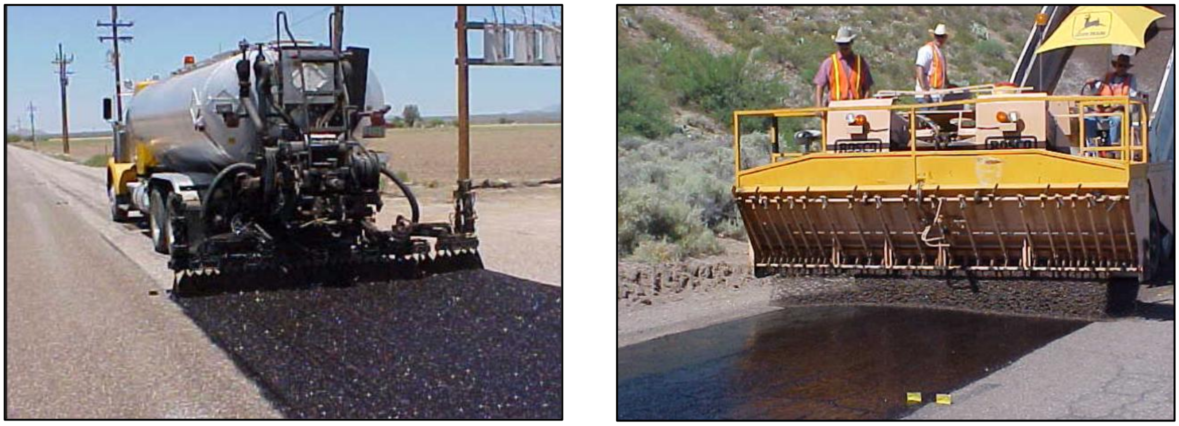
Chip seal is one of the most common types of surface treatments and preventive maintenance among agencies. As shown in Figure 3, a chip seal is constructed by applying a layer of asphalt binder on the surface. Then a layer of single-sized aggregate is distributed with only limited compaction efforts. The aggregate of chip seal can be applied as a single or multiple layers. Some agencies use double chip seals when a harder wearing and longer lasting surface treatment is needed.

2.5.2. Microsurfacing

Microsurfacing consists of small-size-aggregate asphalt mixtures that can enhance the micro-texture properties of pavement friction. Microsurfacing is similar to slurry seal; however, its mixture can include polymer modified emulsion, water, and additives. Also, microsurfacing doesn’t need regular curing via evaporation since it contains chemicals and can break and set up quickly regardless of the weather conditions. The previous experience showed that microsurfacing can enhance the skid resistance of pavement. Figure 4 shows an application of microsurfacing on asphalt pavement.

2.5.3. Thin Overlay

Thin and ultra-thin overlays are used as a preventive maintenance to retard future deteriorations. Compared to chip seal and microsurfacing, thin overlays can add structural value and improve ride quality. Furthermore, thin overlays seal cracks, enhance skid resistance, and improve drainage by repairing slopes. Generally, thin overlays are applied with a thickness of 1.5 inches. They can also be placed very thin, close to about 0.5-inch thick.



a) Binder Application

b) Spreading of Aggregate

c) Rolling

d) Sweeping

Figure 3. Photos. Construction process for chip seals (Caltrans, 2007).

Figure 4. Photo. Application of microsurfacing (Cleaver, 2016).

Highway agencies are recommended to include informed decisions of maintenance considering the effectiveness of treatments and quantifiable friction measurements. The most common friction index used by state highway agencies is the FN (Elkhazindar et al., 2022). FN is determined on the road using locked-wheel friction testers (ASTM, 2016), and these values mainly depend on the velocity and type of the test tire.

Wang and Wang (2013) evaluated the effectiveness of four pavement preservations treatments on friction performance using pairwise Fisher's Least Significant Difference (LSD) tests of the friction numbers. Then, a multiple regression analysis was conducted to consider the effect of traffic, climate, and material factors on friction numbers. Although the study addressed the variation of friction for the pavement preservation strategies, the benefits of the added friction values with respect to the post-treatment performance life are not covered. Lu and Steven (2006) tested the friction of pavement using California Skid Tester (CST), the British Pendulum Tester (BPT), and other devices to evaluate the change in friction caused by fog seals. The study considered correlation techniques for friction measurements within a short timeframe to be just before placement of the fog seal and soon after. In the state of Indiana, Li et al. (2011) evaluated the effectiveness of pavement preservation strategies followed by Indiana DOT using state road test sections. The results showed that the age of chip seals varied from 12 months to 42 months with friction numbers ranging from 50 to 70. A failed chip seal treatment tended to reduce the friction number significantly within the first 12 months. In addition, applying a fog seal on top of a chip seal led to reduce the friction number by 20-30 percent. Li et al. (2017) applied a panel data analysis to identify the affecting factors of friction for chip seals, slurry seals, thin overlay, and crack seals using the Long-Term Pavement Performance (LTPP) dataset.

Similar to the previous studies, this research addressed the affecting factors on the improvements in friction numbers without addressing the additional benefits obtained from the area under the curve of the pavement friction performance models.

Two major issues are identified form the literature review on evaluating pavement friction treatments. The first issue relates to the lack of long-term assessment of pavement friction. The literature shows that most studies focused on the affecting factors on the immediate improvement in friction. However, pavement friction tends to deteriorate with different rates which provide different benefit-cost impacts on the pavement life cycle. In addition, the results obtained from the previous studies limit the affecting conditions to be within the local conditions. The results are not supported with probabilistic techniques to account for the large variability of pavement performance and the uncertainty of unknown affecting factors. This study contributes to the effectiveness of pavement surface treatments on skid resistance performance by classifying the treatments on the long- and short-term basis followed by a probabilistic analysis to determine the survival probability of each treatment along a five-year time period.

CHAPTER 3: INVESTIGATING THE RELATIONSHIP BETWEEN PAVEMENT SURFACE FRICTION AND FRICTION-RELATED CRASHES IN WYOMING

3.1 Effects of Pavement Friction and Geometry on Traffic Crash Frequencies: A Case Study in Wyoming

3.1.1 Background

Pavement friction is affected by three main factors: pavement surface-related factors such as texture, grading curve, aggregates nature, size and shape, surface age, etc.; vehicle and tire-related factors such as vehicle speed, tire operating conditions, tire characteristics; environmental-related factors such as water film thickness, surface contamination, long-term and short term temperature effects, and road geometry (D'Apuzzo et al., 2020). Pavement friction supply diminishes over time because of the wearing of the surface attributed to the traffic loads, water, contaminants, or other factors (McCarthy et al., 2016). This loss of skid resistance inhibits the driver's ability to efficiently control the vehicle leading to a rise in crash counts. Many studies identified the association between low friction numbers and higher crash frequencies (McCarthy et al., 2016; Hall et al., 2009a; Cafiso et al., 2021; Lyon and Persaud, 2008). Therefore, managing the pavement to ensure adequate friction is essential from a safety point of view.

Roadway engineers typically keep track of their pavement friction levels as a component of their roadway maintenance strategies (Najafi et al., 2014). In addition, transportation agencies can include friction into network-level pavement management systems (PMSs) because of the development of high-speed friction measurement tools (Justo-Silva and Ferreira, 2018). Therefore, incorporating safety concerns is one of the urgent needs of the PMSs to optimize the management of resources and to reduce road fatalities (Justo-Silva and Ferreira, 2018). Skid resistance is considered one of the most important characteristic of crashes and has a serious effect on crash occurrence, especially in wet surface conditions (Mataei et al., 2016). The number of wet-pavement crashes can be greatly reduced by conducting frequent skid measurements, which will ensure an adequate level of skid resistance of pavements (Chowdhury et al., 2017). The importance of managing roadways to ensure the pavement surface is performing well, in terms of supplying sufficient friction for the vehicle tires, cannot be overemphasized. The required friction supply levels vary by roadway functional classification (McCarthy et al., 2021b). WYDOT rates its roadway surfaces as either excellent, good, fair, or poor depending on the FNs. They are $FN > 55$, $40 < FN \leq 55$, $35 < FN \leq 40$ and $FN \leq 35$ respectively. WYDOT maintains its roadway surfaces based on their friction numbers. Further research is required to examine the relationship between skid resistance and safety to posit sound strategies to manage roadway surfaces, which is addressed by this study.

The study's objective was to develop crash frequency prediction models, also known as safety performance functions (SPFs) for predicting the frequencies and severities of crashes. The FHWA suggests applying SPFs to predict average crash counts of any roadway segment as a function of the AADT and other crash precursors (Srinivasan and Bauer, 2013). Ample crash data, roadway geometric design data, traffic data, and roadway functional classification data were incorporated into the development of this study's SPFs. The SPFs were developed for total crashes and equivalent PDO (EPDO) crashes, which are crash counts magnified by the costs incurred to communities. SPFs may be implemented to screen roadway networks to identify the locations associated with abnormal counts of crashes. Therefore, this study laid the foundation for this endeavor.

3.1.2 Research Methodology

The research methodology involved developing SPFs for different functional classifications of urban and rural roadways in Wyoming. SPFs are NB models. Since the Poisson model's assumptions are quite restrictive in that, the mean of the crash frequencies is equivalent to the variance of the crash frequencies, overdispersion is not permitted. Overdispersion is when the variance of the crash frequencies is greater than the mean of the crash frequencies. The NB model, which is a modification of the Poisson model that permits overdispersion (Xu and Huang, 2015), was employed. Under the NB model, the risk, P_i, of experiencing y_i crashes on a specific segment, i, is computed as follows (Farid et al., 2018):

$$P_i(y_i) = \frac{\Gamma\left(y_i + \frac{1}{k_i}\right)}{y_i! * \Gamma\left(\frac{1}{k_i}\right)} \times \left(\frac{\frac{1}{k_i}}{\frac{1}{k_i} + \lambda_i}\right)^{\frac{1}{k_i}} \times \left(\frac{\lambda_i}{\frac{1}{k_i} + \lambda_i}\right)^{y_i} \tag{2}$$

In the formula, λ_i, k_i and $\Gamma(.)$ are the mean crash frequency, dispersion parameter and gamma function. Dispersion parameters measure how much a sample fluctuates around a mean value. The Gamma function is a commonly used extension of the factorial function to complex numbers.

The NB model's variance function is expressed as (Farid et al., 2018):

$$\mathrm{Var}(y_i) = \lambda_i(1 + \lambda_i k_i) \tag{3}$$

Variance measures variability from the mean. It is described as the squared average distance from the mean.

The mean crash frequency is obtained using the following expression (Kuttesch, 2004):

$$\lambda_i = \exp(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_p X_p + \theta_i) \quad (4)$$

The X's are the crash precursors while the β's are the coefficients obtained using maximum likelihood estimation. The variable, θ_i, is a stochastic term such that $\exp(\theta_i) \sim \Gamma(1, k_i)$ as per Xu and Huang (2015).

The mean is the SPF's crash count prediction, $N_{SPF\,i}$. It is formulated as follows (Farid et al., 2018; AASHTO, 2010):

$$N_{SPF\,i} = \exp\left[\beta_0 + \beta_1 \times \ln(AADT_i) + \left(\sum_{j=1}^{J} \beta_j X_{ji}\right) + \ln(L_i)\right] \quad (5)$$

The parameters incorporated are the average annual daily traffic ($AADT_i$) volume, the segment length, L_i, and others, X_{ji}'s. The dispersion parameter is computed using the following formula (AASHTO, 2010):

$$k_i = \frac{1}{\exp[\beta_{j+1} + \ln(L_i)]} \quad (6)$$

The overdispersion k_i describes the variance of crash counts and is used in the computation of the log-likelihood function (Farid et al., 2018).

In order to develop SPFs, both crash counts and EPDO crashes were considered. Crash frequency alone cannot accurately reflect the magnitude of traffic risk since crashes range widely in terms of their severity levels (Ma et al., 2016). Therefore, crash severity is an important consideration while conducting safety evaluations. Also, most safety improvement programs are focused on preventing fatal and severe injury crashes (Afghari et al., 2020). Hence, a criterion capable of comprehensively integrating the probability of crash occurrence and the likely severity is necessary (Ma et al., 2016). EPDO is considered an important approach for combining the information on crash severity with the crash count. Hence, both total and EPDO crashes were considered in order to develop SPFs in this study.

Since the SPFs were developed for both total crashes and EPDO crashes, the computation of EPDO crashes witnessed ought to be described. First, the comprehensive crash costs (property damage costs, legal costs, medical costs, etc.) are obtained as follows according to WYDOT:

- \$2,839,000 for a fatal or an incapacitating injury crash
- \$108,000 for a non-incapacitating injury or possible injury crash
- \$45,000 for a PDO crash or one with a severity that is unknown.

The EPDO crash frequencies are obtained by taking the ratio of the crash cost to that of a PDO crash as the following:

- 63.1 (\$2,839,000/\$45,000) for a fatal or an incapacitating injury crash
- 2.4 (\$108,000/\$45,000) for a non-incapacitating injury or possible injury crash
- 1 (\$45,000/\$45,000) for a PDO crash or a crash with a severity level that is designated as unknown

The goodness of fit measures that are used to assess the SPFs' performances are the log-likelihood, LL, expressed as -2LL, Mean Absolute Deviation (MAD) and mean squared prediction error, MSPE (Farid, 2015). The MAD and MSPE are computed using the following formulas:

$$MAD = \sum_{i=1}^{N} \frac{|N_{obs\,i} - N_{SPF\,i}|}{N} \tag{7}$$

$$MSPE = \sum_{i=1}^{N} \frac{(N_{obs\,i} - N_{SPF\,i})^2}{N} \tag{8}$$

Here, N is the sample size of segments, $N_{obs\,i}$ is the observed crash frequency for segment i, and $N_{SPF\,i}$ is the predicted crash frequency for segment i.

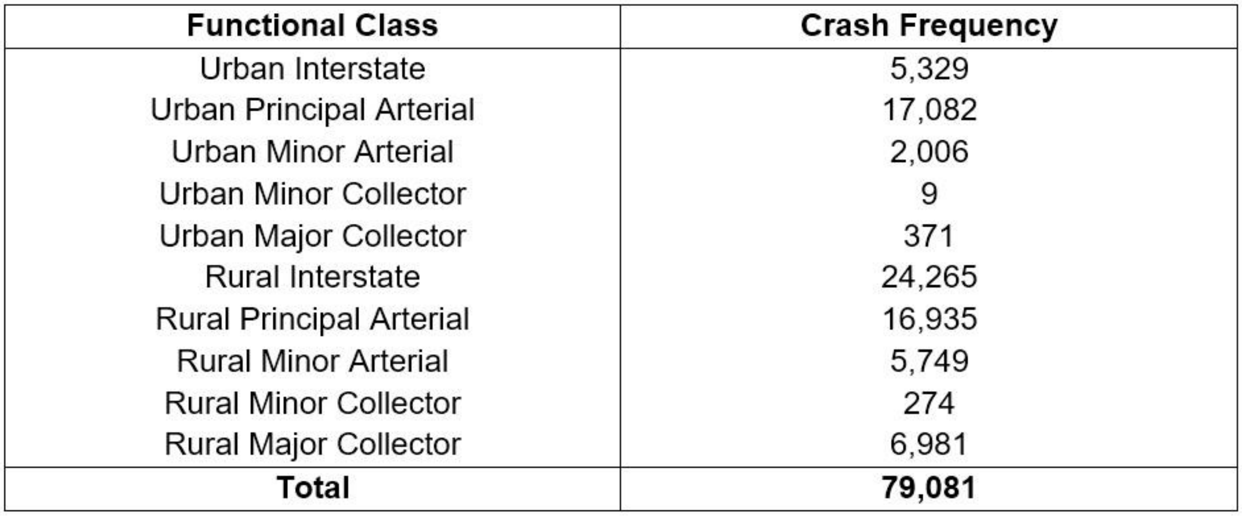
Before fitting the model, it was necessary to assess if there is any multicollinearity among explanatory variables. This study applies a correlation test, tolerance, and Variance Inflation Factor (VIF) to check multicollinearity (Dissanssayake and Roy, 2014). Absolute correlation coefficients near 1 represents strong correlation between explanatory variables. Also, tolerance levels less than 0.1 and VIF greater than 10 indicate the presence of multicollinearity. Explanatory variables identified multicollinear by the criteria mentioned above were removed from the model.

3.1.3 Data Preparation

Data used in this research are traffic volumes, geometric design characteristics, road surface conditions, functional classifications of roads, and friction data from Wyoming. Data from WYDOT was collected in four separate excel files which were crash data, geometric roadway design, pavement surface friction, and roadway functional classification data files. Crash data and roadway geometric data obtained from WYDOT belonged from 2010 to 2019. Speed data used in this study was obtained from crash data. 10 years' (2010-2019) of crash data collected from WYDOT have information about speed and other variables. Both posted speed limit and estimated speed of vehicle during the crash was reported at the crash report. Hence, the data collected from WYDOT has information about both posted speed and estimated speed of the vehicle during the crash.

Friction data from the same period was integrated with the crash and geometric data. The first step was to match the friction numbers with the corresponding crash locations by comparing route and milepost information. It is important to note that friction data was not collected for each segment or year. Therefore average friction numbers were obtained for each milepost. Roadway functional classification data was obtained via a separate excel file which also included route and milepost information. They were integrated with crash data, geometric data, and friction data. Each row corresponded to a particular route, the beginning milepost of the segment, the ending milepost of the segment, roadway functional classification, traffic information, geometric design information, total crash count, EPDO crash count, and friction number. Segment length was obtained by deducting beginning milepost from ending milepost of the segment. WYDOT keeps track of segment based on homogeneous geometric characteristics of the roadway such as horizontal alignment, grade, number of lanes, presence of shoulder, etc. The final dataset had 79,081 unique crash records. Table 2 presents a summary of the data.

Table 2. Summary Statistics of Wyoming's Skid Resistance Related Crashes.



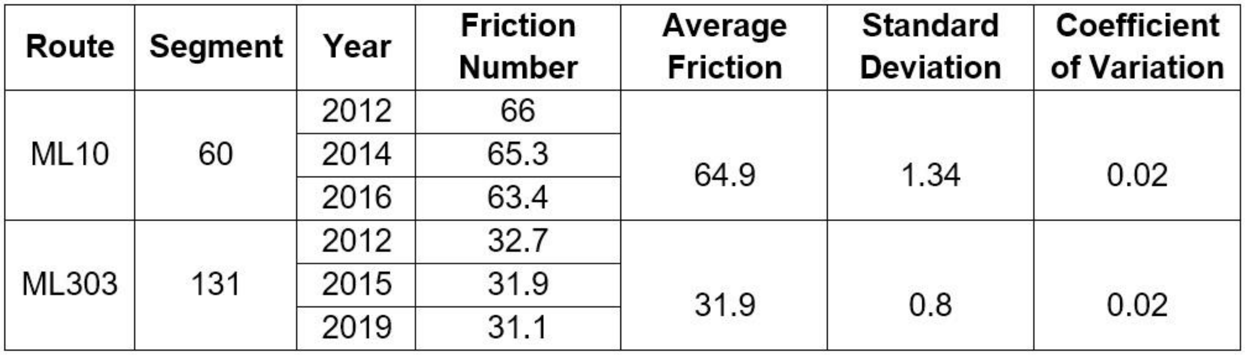
Functional Class	Crash Frequency
Urban Interstate	5,329
Urban Principal Arterial	17,082
Urban Minor Arterial	2,006
Urban Minor Collector	9
Urban Major Collector	371
Rural Interstate	24,265
Rural Principal Arterial	16,935
Rural Minor Arterial	5,749
Rural Minor Collector	274
Rural Major Collector	6,981
Total	**79,081**

3.1.4 Measurement of Friction Data

Friction data used in this study was collected using the locked-wheel technique. Locked-wheel technique is the most common method in the USA for collecting friction data and is used by most state highway agencies (Aldagari et al., 2020). This method uses a locked wheel skidding along the test surface to measure friction. The locked-wheel equipment consists of a trailer with two wheels with full-size tires. One or both of them are used to test longitudinal friction. The locked-wheel device measures friction by completely locking up the test wheels, recording the average sliding force for a period of 3-seconds, and reporting a 1-second average after reaching the fully locked state (de León Izeppi, 2019). The full-lock requirement means that measurements can be recorded periodically over short time intervals (de León Izeppi, 2019). Friction data used in this study is actual field data collected with equipment and calibrated by WYDOT at the regional calibration center.

The average friction number was used in this study since the friction number was not measured each year due to the minimal changes over time. Table 3 shows the friction number collected for a particular segment during the study period (2010-2019). For ML10 - segment 60 and ML 303 - segment 131, friction data was collected three times. The average friction number, standard deviation, and coefficient of variation were shown in the table for those two segments. The low standard deviation and coefficient of variation for each segment demonstrate that there was no significant change in friction over the years.

Table 3. Friction numbers and their average and standard deviation for various segments.



Route	Segment	Year	Friction Number	Average Friction	Standard Deviation	Coefficient of Variation
ML10	60	2012	66	64.9	1.34	0.02
		2014	65.3			
		2016	63.4			
ML303	131	2012	32.7	31.9	0.8	0.02
		2015	31.9			
		2019	31.1			

3.1.5 Analysis of Results and Discussions

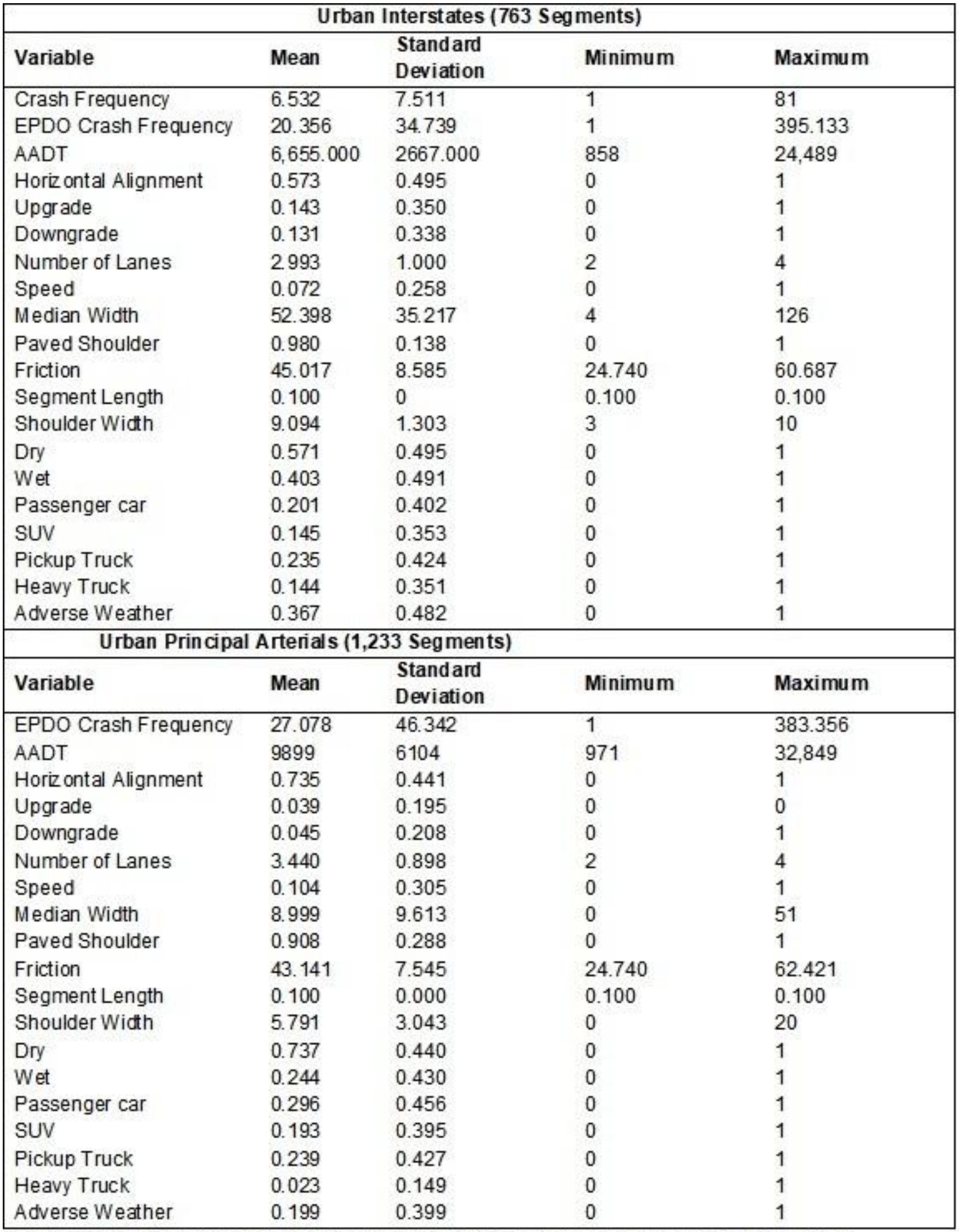
SPFs were developed for urban interstates, urban principal arterials, rural interstates, rural principal arterials, rural minor arterials, and rural major collectors. Since urban minor collectors, urban minor arterials, urban major collectors, and rural minor collectors had exceedingly low crash frequencies; they were not considered for further analysis. In addition to friction, road surface conditions, weather conditions, vehicle types, several geometric characteristics of roadways, and the AADT were considered for the development of the SPFs. The descriptions of the variables, considered in this study, are presented in Table 4. The descriptive statistics of the variables, used for the development of the SPFs, are listed in Tables 5 and 6.

When it comes to SPF development, backward elimination was implemented to exclude statistically insignificant parameters at the 95th percentile confidence interval. The dispersion parameters represented the SPFs' overdispersions and were retained irrespective of their statistical significance. In total, 12 SPFs were developed for the different roadway functional classifications. They were estimated using the NLMIXED procedure of the SAS software package (SAS Institute, 2015). The results of the SPFs of total crashes and EPDO crashes are presented in Tables 7 and 8, respectively. Adverse weather was highly correlated with the wet road surface and hence was not considered in the model. In the discussion that follows the tables, each parameter's results were interpreted assuming all else was controlled.

Table 4. Data Variable's Descriptions.

Variables	Description
EPDO	Frequency of equivalent property-damage-only crashes
AADT	Average annual daily traffic volume (veh/d)
Horizontal Alignment	1 if straight segment; 0 otherwise
Upgrade	1 if grade is uphill; 0 otherwise
Downgrade	1 if grade is downhill, 0 otherwise
Number of Lanes	Number of lanes
Speed	1 if the estimated speed is greater than the posted speed, 0 otherwise
Median Width	Width of the median (ft)
Friction	Average friction number
Paved Shoulder	1 if shoulder is paved; 0 otherwise (unpaved)
Shoulder Width	Width of the shoulder (ft)
Dry	1 if the road surface is dry, 0 otherwise
Wet	1 if the road surface is wet, snowy, or icy, 0 otherwise
Passenger car	1 if the vehicle type is passenger car, 0 otherwise
SUV	1 if the vehicle type is SUV, 0 otherwise
Pickup Truck	1 if the vehicle type is Pickup Truck, 0 otherwise
Heavy Truck	1 if the vehicle type is Heavy Truck, 0 otherwise
Adverse Weather	1 if the weather is not clear, 0 otherwise
Segment Length	Length of the segment (mi)

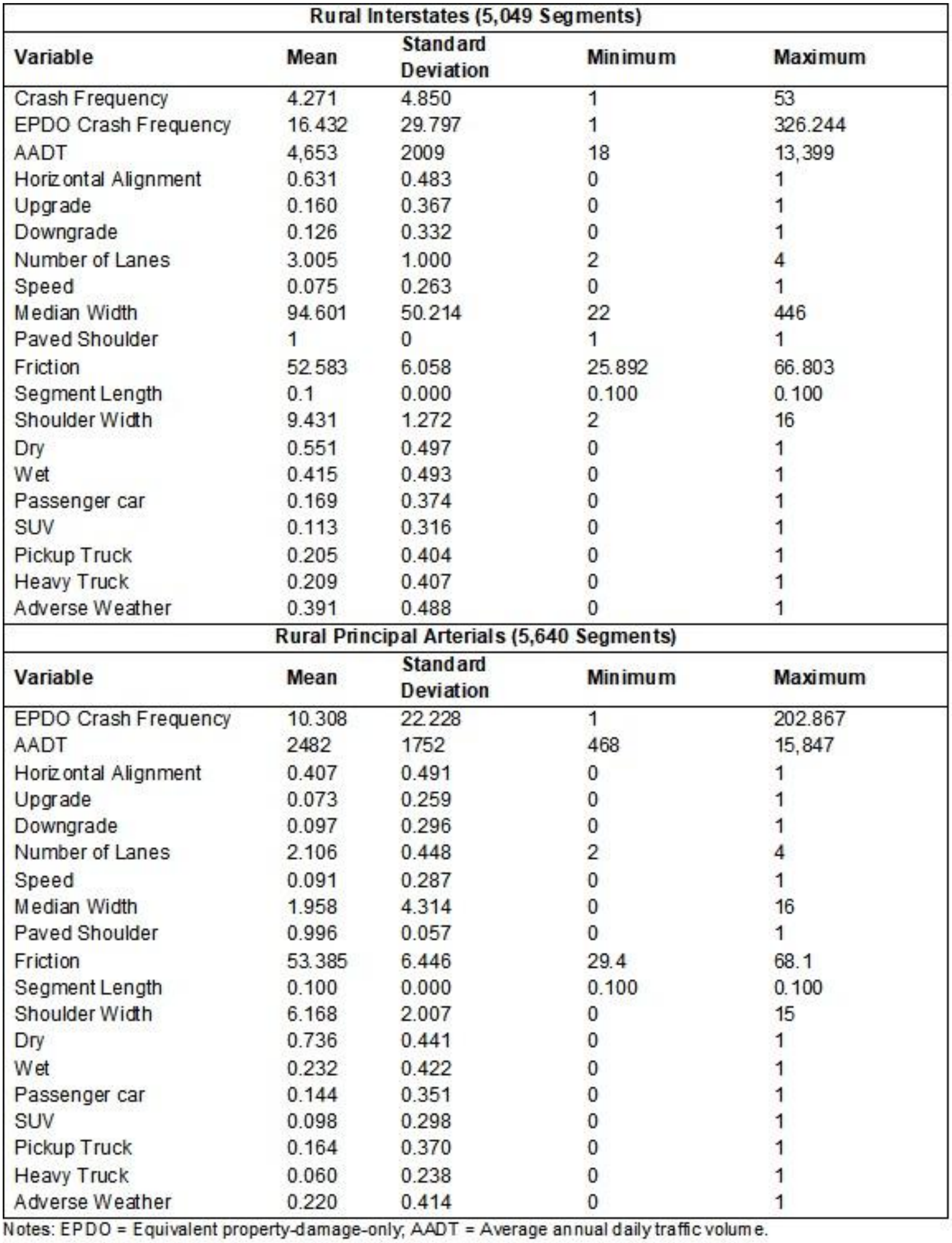
Table 5. Data's Descriptive Statistics for Urban Interstates and Urban Principal Arterials.



Urban Interstates (763 Segments)				
Variable	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
Crash Frequency	6.532	7.511	1	81
EPDO Crash Frequency	20.356	34.739	1	395.133
AADT	6,655.000	2667.000	858	24,489
Horizontal Alignment	0.573	0.495	0	1
Upgrade	0.143	0.350	0	1
Downgrade	0.131	0.338	0	1
Number of Lanes	2.993	1.000	2	4
Speed	0.072	0.258	0	1
Median Width	52.398	35.217	4	126
Paved Shoulder	0.980	0.138	0	1
Friction	45.017	8.585	24.740	60.687
Segment Length	0.100	0	0.100	0.100
Shoulder Width	9.094	1.303	3	10
Dry	0.571	0.495	0	1
Wet	0.403	0.491	0	1
Passenger car	0.201	0.402	0	1
SUV	0.145	0.353	0	1
Pickup Truck	0.235	0.424	0	1
Heavy Truck	0.144	0.351	0	1
Adverse Weather	0.367	0.482	0	1
Urban Principal Arterials (1,233 Segments)				
Variable	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
EPDO Crash Frequency	27.078	46.342	1	383.356
AADT	9899	6104	971	32,849
Horizontal Alignment	0.735	0.441	0	1
Upgrade	0.039	0.195	0	0
Downgrade	0.045	0.208	0	1
Number of Lanes	3.440	0.898	2	4
Speed	0.104	0.305	0	1
Median Width	8.999	9.613	0	51
Paved Shoulder	0.908	0.288	0	1
Friction	43.141	7.545	24.740	62.421
Segment Length	0.100	0.000	0.100	0.100
Shoulder Width	5.791	3.043	0	20
Dry	0.737	0.440	0	1
Wet	0.244	0.430	0	1
Passenger car	0.296	0.456	0	1
SUV	0.193	0.395	0	1
Pickup Truck	0.239	0.427	0	1
Heavy Truck	0.023	0.149	0	1
Adverse Weather	0.199	0.399	0	1

Notes: EPDO = Equivalent property-damage-only; AADT = Average annual daily traffic volume.

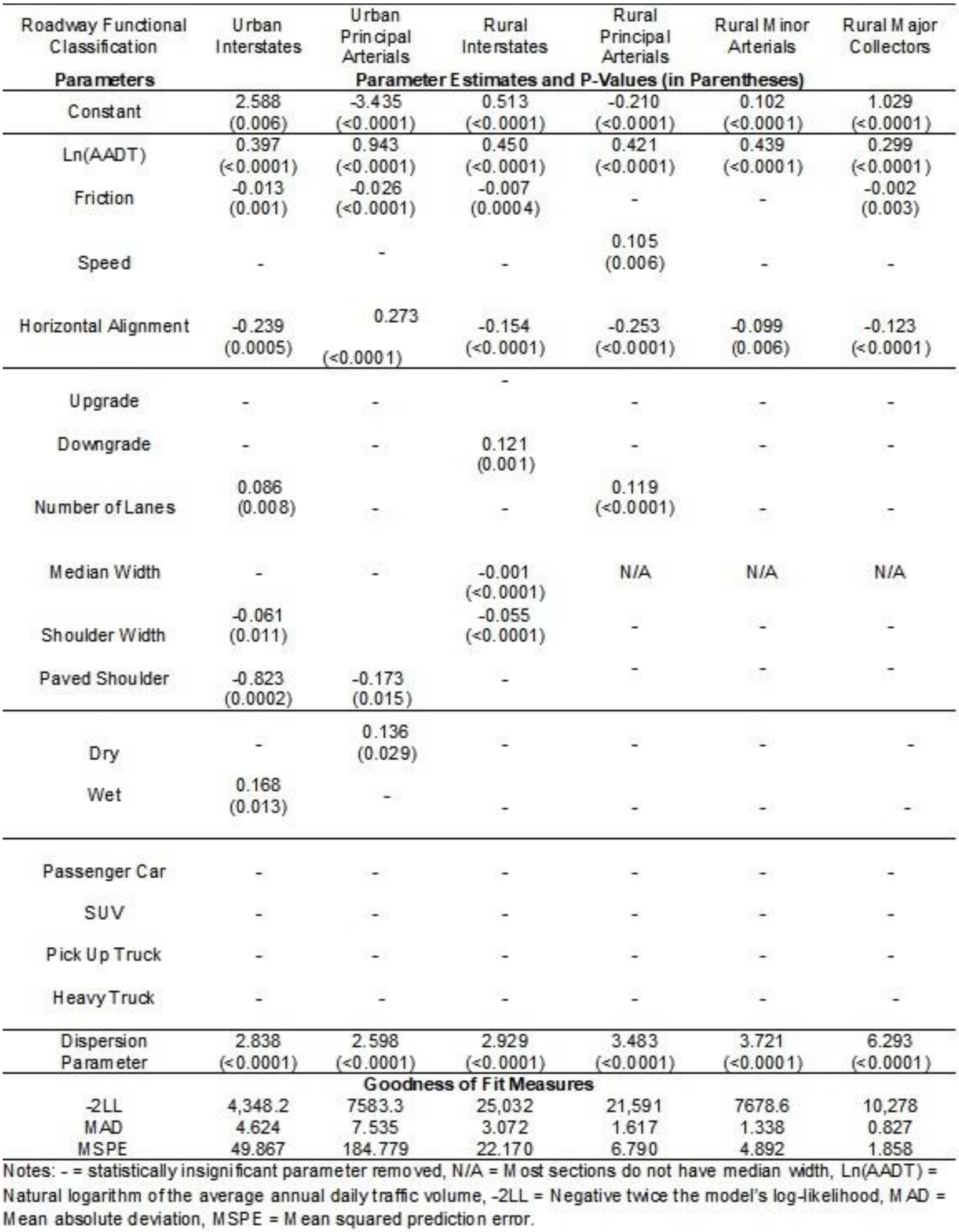
Table 6. Data's Descriptive Statistics for Rural Interstates and Rural Principal Arterials.



Rural Interstates (5,049 Segments)				
Variable	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
Crash Frequency	4.271	4.850	1	53
EPDO Crash Frequency	16.432	29.797	1	326.244
AADT	4,653	2009	18	13,399
Horizontal Alignment	0.631	0.483	0	1
Upgrade	0.160	0.367	0	1
Downgrade	0.126	0.332	0	1
Number of Lanes	3.005	1.000	2	4
Speed	0.075	0.263	0	1
Median Width	94.601	50.214	22	446
Paved Shoulder	1	0	1	1
Friction	52.583	6.058	25.892	66.803
Segment Length	0.1	0.000	0.100	0.100
Shoulder Width	9.431	1.272	2	16
Dry	0.551	0.497	0	1
Wet	0.415	0.493	0	1
Passenger car	0.169	0.374	0	1
SUV	0.113	0.316	0	1
Pickup Truck	0.205	0.404	0	1
Heavy Truck	0.209	0.407	0	1
Adverse Weather	0.391	0.488	0	1
Rural Principal Arterials (5,640 Segments)				
Variable	**Mean**	**Standard Deviation**	**Minimum**	**Maximum**
EPDO Crash Frequency	10.308	22.228	1	202.867
AADT	2482	1752	468	15,847
Horizontal Alignment	0.407	0.491	0	1
Upgrade	0.073	0.259	0	1
Downgrade	0.097	0.296	0	1
Number of Lanes	2.106	0.448	2	4
Speed	0.091	0.287	0	1
Median Width	1.958	4.314	0	16
Paved Shoulder	0.996	0.057	0	1
Friction	53.385	6.446	29.4	68.1
Segment Length	0.100	0.000	0.100	0.100
Shoulder Width	6.168	2.007	0	15
Dry	0.736	0.441	0	1
Wet	0.232	0.422	0	1
Passenger car	0.144	0.351	0	1
SUV	0.098	0.298	0	1
Pickup Truck	0.164	0.370	0	1
Heavy Truck	0.060	0.238	0	1
Adverse Weather	0.220	0.414	0	1

Notes: EPDO = Equivalent property-damage-only; AADT = Average annual daily traffic volume.

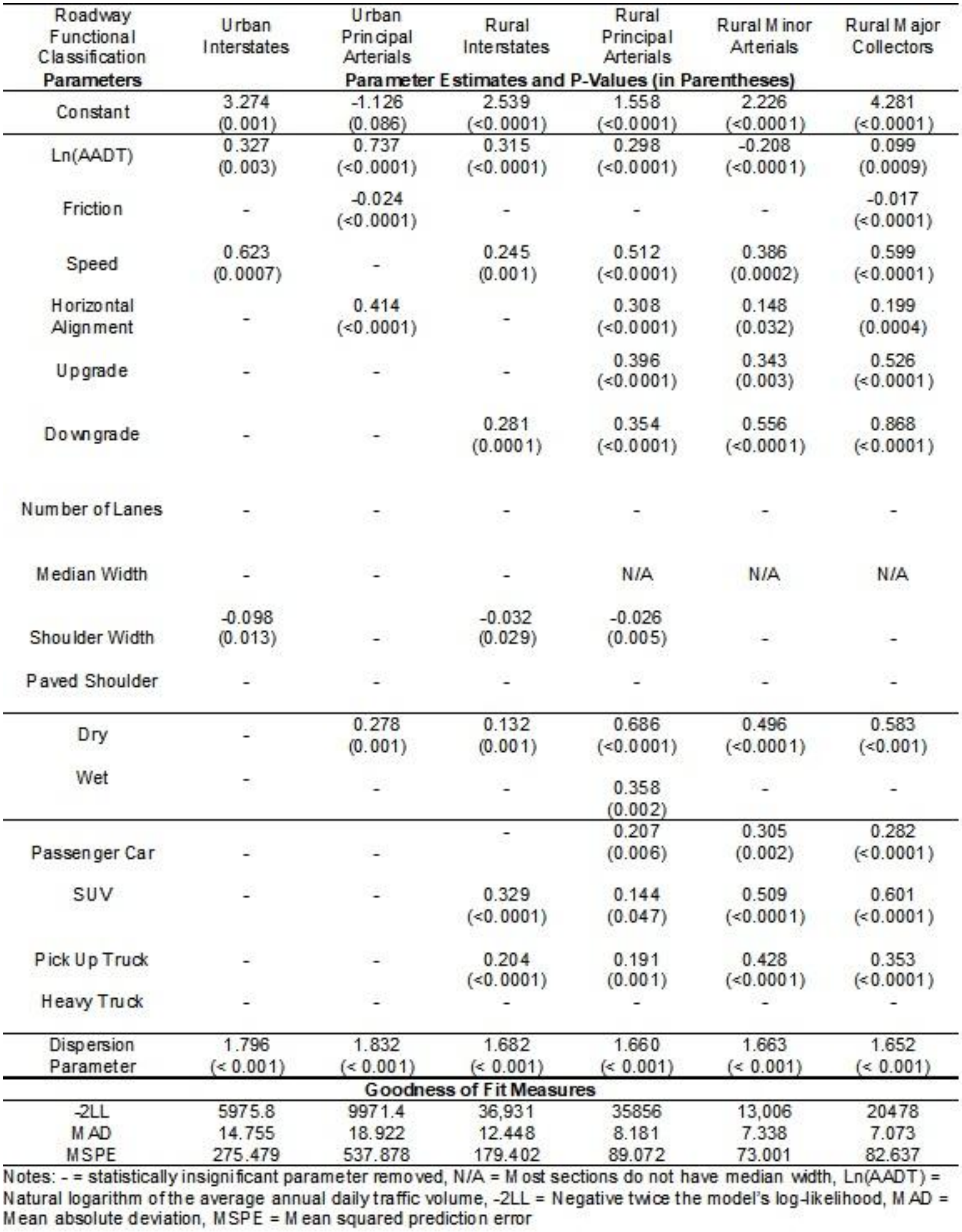
Table 7. Safety Performance Functions of Total Crashes - Empirical Results.



Roadway Functional Classification	Urban Interstates	Urban Principal Arterials	Rural Interstates	Rural Principal Arterials	Rural Minor Arterials	Rural Major Collectors
Parameters	**Parameter Estimates and P-Values (in Parentheses)**					
Constant	2.588 (0.006)	-3.435 (<0.0001)	0.513 (<0.0001)	-0.210 (<0.0001)	0.102 (<0.0001)	1.029 (<0.0001)
Ln(AADT)	0.397 (<0.0001)	0.943 (<0.0001)	0.450 (<0.0001)	0.421 (<0.0001)	0.439 (<0.0001)	0.299 (<0.0001)
Friction	-0.013 (0.001)	-0.026 (<0.0001)	-0.007 (0.0004)	-	-	-0.002 (0.003)
Speed	-	-	-	0.105 (0.006)	-	-
Horizontal Alignment	-0.239 (0.0005)	0.273 (<0.0001)	-0.154 (<0.0001)	-0.253 (<0.0001)	-0.099 (0.006)	-0.123 (<0.0001)
Upgrade	-	-	-	-	-	-
Downgrade	-	-	0.121 (0.001)	-	-	-
Number of Lanes	0.086 (0.008)	-	-	0.119 (<0.0001)	-	-
Median Width	-	-	-0.001 (<0.0001)	N/A	N/A	N/A
Shoulder Width	-0.061 (0.011)		-0.055 (<0.0001)	-	-	-
Paved Shoulder	-0.823 (0.0002)	-0.173 (0.015)	-	-	-	-
Dry	-	0.136 (0.029)	-	-	-	-
Wet	0.168 (0.013)	-	-	-	-	-
Passenger Car	-	-	-	-	-	-
SUV	-	-	-	-	-	-
Pick Up Truck	-	-	-	-	-	-
Heavy Truck	-	-	-	-	-	-
Dispersion Parameter	2.838 (<0.0001)	2.598 (<0.0001)	2.929 (<0.0001)	3.483 (<0.0001)	3.721 (<0.0001)	6.293 (<0.0001)
Goodness of Fit Measures						
-2LL	4,348.2	7583.3	25,032	21,591	7678.6	10,278
MAD	4.624	7.535	3.072	1.617	1.338	0.827
MSPE	49.867	184.779	22.170	6.790	4.892	1.858

Notes: - = statistically insignificant parameter removed, N/A = Most sections do not have median width, Ln(AADT) = Natural logarithm of the average annual daily traffic volume, -2LL = Negative twice the model's log-likelihood, MAD = Mean absolute deviation, MSPE = Mean squared prediction error.

Table 8. Safety Performance Functions of Equivalent PDO Crashes - Empirical Results.



Roadway Functional Classification	Urban Interstates	Urban Principal Arterials	Rural Interstates	Rural Principal Arterials	Rural Minor Arterials	Rural Major Collectors
Parameters	**Parameter Estimates and P-Values (in Parentheses)**					
Constant	3.274 (0.001)	-1.126 (0.086)	2.539 (<0.0001)	1.558 (<0.0001)	2.226 (<0.0001)	4.281 (<0.0001)
Ln(AADT)	0.327 (0.003)	0.737 (<0.0001)	0.315 (<0.0001)	0.298 (<0.0001)	-0.208 (<0.0001)	0.099 (0.0009)
Friction	-	-0.024 (<0.0001)	-	-	-	-0.017 (<0.0001)
Speed	0.623 (0.0007)	-	0.245 (0.001)	0.512 (<0.0001)	0.386 (0.0002)	0.599 (<0.0001)
Horizontal Alignment	-	0.414 (<0.0001)	-	0.308 (<0.0001)	0.148 (0.032)	0.199 (0.0004)
Upgrade	-	-	-	0.396 (<0.0001)	0.343 (0.003)	0.526 (<0.0001)
Downgrade	-	-	0.281 (0.0001)	0.354 (<0.0001)	0.556 (<0.0001)	0.868 (<0.0001)
Number of Lanes	-	-	-	-	-	-
Median Width	-	-	-	N/A	N/A	N/A
Shoulder Width	-0.098 (0.013)	-	-0.032 (0.029)	-0.026 (0.005)	-	-
Paved Shoulder	-	-	-	-	-	-
Dry	-	0.278 (0.001)	0.132 (0.001)	0.686 (<0.0001)	0.496 (<0.0001)	0.583 (<0.001)
Wet	-	-	-	0.358 (0.002)	-	-
Passenger Car	-	-	-	0.207 (0.006)	0.305 (0.002)	0.282 (<0.0001)
SUV	-	-	0.329 (<0.0001)	0.144 (0.047)	0.509 (<0.0001)	0.601 (<0.0001)
Pick Up Truck	-	-	0.204 (<0.0001)	0.191 (0.001)	0.428 (<0.0001)	0.353 (<0.0001)
Heavy Truck	-	-	-	-	-	-
Dispersion Parameter	1.796 (< 0.001)	1.832 (< 0.001)	1.682 (< 0.001)	1.660 (< 0.001)	1.663 (< 0.001)	1.652 (< 0.001)
Goodness of Fit Measures						
-2LL	5975.8	9971.4	36,931	35856	13,006	20478
MAD	14.755	18.922	12.448	8.181	7.338	7.073
MSPE	275.479	537.878	179.402	89.072	73.001	82.637

Notes: - = statistically insignificant parameter removed, N/A = Most sections do not have median width, Ln(AADT) = Natural logarithm of the average annual daily traffic volume, -2LL = Negative twice the model's log-likelihood, MAD = Mean absolute deviation, MSPE = Mean squared prediction error

In all SPFs of total crashes, the pavement surface friction parameter was statistically significant except for rural principal arterials and rural minor arterials. Pavement friction was also found to be inversely proportional to total crashes indicating that higher friction levels are associated with fewer crashes. This suggested that pavement friction was an important parameter affecting traffic crashes, and maintaining adequate friction level is important to reduce traffic crashes.

Likewise, the SPFs of EPDO crash results demonstrated that higher friction levels were associated with fewer EPDO crashes on urban principal arterials and rural major collectors. The friction parameter was insignificant for rural principal arterials, rural interstates, rural minor arterials and urban interstates, indicating that the surface friction did not influence EPDO crash frequencies. The results of the SPFs relating to total crashes and EPDO crashes showed that pavement friction was a critical factor associated with traffic crashes. Hence, it could be interpreted that maintaining the pavement to ensure adequate surface friction levels reduce overall crash counts and those of severe crashes.

The AADT, which is the exposure, was directly proportional to the occurrences of total crashes for all facilities. This indicated that as the traffic volume increase, the crash frequency will also increase.

The exposure was also found to increase EPDO crash frequencies on all facilities. Plausibly, on all those facilities, the traffic speeds would become sufficiently large such that an increase in traffic volume would lead to a rise in the count of injury crashes.

Among the geometric variables which were considered in this study, it was found that, for the SPFs of total crashes, the upgrade and downgrade parameters were not statistically significant for any facility, except for rural interstates where downgrade was significant. The parameters' results could be interpreted as that upgrades and downgrades are not associated with the count of total crashes. However, a downgrade would lead to a rise in total crashes on rural interstates.

Also, interesting findings were obtained regarding EPDO crashes. Upgrades would lead to a rise in EPDO crashes along rural principal arterials, rural minor arterials, and rural major collectors. Downgrades also increased EPDO crash frequencies on rural interstates, rural principal arterials, rural minor arterials, and rural major collectors. Such findings indicated that crashes would be severe on non-level grades.

From the SPF results of total crashes, it was inferred that the horizontal alignment was associated with the occurrences of crashes for all facilities. The result showed that tangent segments would experience fewer crashes than curved segments for urban interstates, rural interstates, rural principal arterials, rural minor arterials, and rural major collectors. However, in urban principal arterials, it was found that tangent segments would lead to higher crashes, likely due to the proportion of tangent segments in urban principal arterials is higher than curved segments.

Other than the case of total crashes, the results demonstrated that the horizontal alignment was positively associated with EPDO crash frequencies for urban principal arterials, rural principal arterials, rural minor arterials, and rural major collectors. This indicated that tangent segments were associated with higher EPDO crash frequencies than curved segments. Possibly, drivers traveled cautiously when navigating curves (Milton and Mannering, 1998; Amarasingha and Dissanayake, 2013) and hence reduced their risk of being involved in severe crashes.

The number of lanes was directly proportional to the frequency of total crashes on urban interstates, and rural principal arterials. As the number of lanes increases, the chances of conflicts also increase because of lane-change maneuvers, increasing the number of crashes (Amarasingha and Dissanayake, 2013). The SPFs of total crashes indicated that the number of lanes was not associated with the frequencies of total crashes for all other roadway classes.

The SPFs of EPDO crashes showed that the number of lanes was not associated with the frequencies of EPDO crashes on any facility. This finding indicated that the number of lanes is not a significant parameter associated with EPDO crashes.

The presence of paved shoulder in the results of the SPFs belonging to total crashes on urban interstates and urban principal arterials demonstrated that paved shoulders would observe fewer crashes than unpaved shoulders. For the other roadway functional classifications, the SPF results of total crashes showed that the shoulder’s pavement type had no effect on crash occurrence.

The SPFs of EPDO crashes indicated that the presence of paved shoulders was not significant for any facility. This finding indicated that the shoulder’s pavement type had no effect on EPDO crash frequencies.

According to the results of the SPFs of total crashes, wider medians and wider shoulders would reduce the counts of total crashes on rural interstates. Wider shoulders were also found to reduce crashes on urban interstates. For the other roadway facilities, the median width and shoulder width were not associated with the count of total crashes. For rural principal arterials, rural minor arterials and rural major collectors, it was found that most segments did not have medians, hence it was not applicable to include median width while developing SPFs for those facilities.

Regarding EPDO crashes, the results of the SPFs of EPDO crashes indicated that widening the shoulder would contribute to fewer EPDO crashes on urban interstates, rural interstates, and rural principal arterials. For all other functional classes, shoulder width were not found to influence the occurrences of EPDO crashes. Median width, on the other hand, was found to not be associated with EPDO crash frequencies for all functional classes of roadways.

When the estimated speed of the vehicle was higher than the posted speed limit, it was found that the frequency of total crashes would increase in rural principal arterials. For all other roadway facilities, speed was not found to be significant.

When it comes to EPDO crashes, it was inferred that when the estimated speed of the vehicle was higher than the posted speed limit, it would result in severe crashes in urban interstates, rural interstates, rural principal arterials, rural minor arterials, and rural major collectors. This suggests that speed is an important parameter influencing EPDO crashes.

From the SPFs of total crashes, it was found that dry road surfaces would lead to a rise in total crashes in urban principal arterials. This was probably because drivers tend to increase their speed, which leads to more crashes on dry road surfaces. Also, total crashes would increase in urban interstates when the road surfaces were wet. Friction is an issue, especially on wet road surfaces. The number of wet pavement crashes can be greatly reduced with adequate friction demand.

When the results of SPF of EPDO crashes were considered, it was found that dry road surfaces would lead to severe crashes in urban principal arterials, rural interstates, rural principal arterials, rural minor arterials, and rural major collectors. Also, wet road surfaces would lead to a rise in EPDO crashes in rural principal arterials. The SPFs of total and EPDO crash demonstrated that road surface condition is an important factor influencing crashes. Maintaining an adequate friction level is important on both dry and wet road surfaces.

When vehicle type was considered, it was found from the results of SPFs of total crashes that vehicle body type is not an important parameter influencing total crashes. No vehicle type was found significant in any roadway functional classes when SPFs were developed for total crashes.

Regarding EPDO crashes, the results of SPFs revealed that EPDO crashes would increase in rural interstates, rural principal arterials, rural minor arterials, and major rural collectors when SUVs and Pickup trucks were involved. Also, there would be a rise in severe crashes in rural principal arterials, rural minor arterials, and rural major collectors when passenger cars were involved. This suggests that vehicle type is an important parameter influencing EPDO crashes.

Summary:

Table 9 Comparative Matrix Table provides a comparative analysis of safety parameters across various functional classes of roadways to present a clear and concise overview of how different parameters impact total crashes and EPDO crashes. The table details at-a-glance which safety parameters, such as pavement friction, AADT, horizontal alignment, and others, influence crash rates and severity. This comprehensive layout helps identify where safety improvements can be effectively targeted by focusing efforts on specific parameters, enhancing road safety, and reducing crash incidences.

Table 9 Comparative Matrix Table

Functional Class	Safety Parameters	Impact on Total Crashes	Impact on EPDO Crashes	Safety Improvement Focus
Urban Interstates	Pavement Friction	Higher friction levels reduce crashes.	Not significant	Focus on improving and maintaining adequate pavement friction.
	AADT	Increased traffic volume leads to more crashes.	Increased traffic volume leads to more crashes.	Monitor and manage traffic volumes.
	Horizontal Alignment	Tangent segments have fewer crashes.	Not significant	Enhance curvature design.
	Number of Lanes	More lanes increase crashes.	Not significant	Optimize lane management and configurations.
	Paved Shoulder	Paved shoulders reduce crashes.	Not significant	Maintain and improve shoulder paving.
	Shoulder Width	Wider shoulders reduce crashes.	Wider shoulders reduce severe crashes.	Increase shoulder width.
	Speed	Not significant	Higher speeds lead to more severe crashes.	Enforce speed limits and consider traffic calming measures.
	Road Surface Condition	Wet road surfaces increase crashes.	Not significant	Improve drainage and friction on wet surfaces.
Urban Principal Arterials	Pavement Friction	Higher friction levels reduce crashes.	Higher friction levels reduce severe crashes.	Focus on improving pavement friction.
	AADT	Increased traffic volume leads to more crashes.	Increased traffic volume leads to more crashes.	Monitor and manage traffic volumes.
	Horizontal Alignment	Tangent segments have more crashes.	Tangent segments have more severe crashes.	Redesign tangent segments and improve driver awareness.
	Paved Shoulder	Paved shoulders reduce crashes.	Not significant	Maintain and improve shoulder paving.
	Road Surface Condition	Dry road surfaces experienced more crashes.	Dry road surfaces experienced more crashes.	Improve pavement friction on dry surfaces.

Functional Class	Safety Parameters	Impact on Total Crashes	Impact on EPDO Crashes	Safety Improvement Focus
Rural Interstates	Pavement Friction	Higher friction levels reduce crashes.	Not significant	Focus on improving pavement friction.
	AADT	Increased traffic volume leads to more crashes.	Increased traffic volume leads to more crashes.	Monitor and manage traffic volumes.
	Horizontal Alignment	Tangent segments have fewer crashes.	Not significant	Improve curve design and driver awareness on curves.
	Median Width	Wider medians reduce crashes.	Not significant	Increase median width.
	Shoulder Width	Wider shoulders reduce crashes.	Wider shoulders reduce crashes.	Increase shoulder width.
	Speed	Not significant	Higher speeds lead to more severe crashes.	Enforce speed limits and consider traffic calming measures.
	Road Surface Condition	Not significant	Dry road surfaces experienced more crashes.	Improve pavement friction on dry surfaces.
	Slope (Downgrade)	A steep slope leads to more crashes.	A steep slope leads to more crashes.	Special cautions need to be implemented at downgrade slopes.
Rural Principal Arterials	AADT	Increased traffic volume leads to more crashes.	Increased traffic volume leads to more crashes.	Monitor and manage traffic volumes.
	Horizontal Alignment	Tangent segments have fewer crashes.	Tangent segments have more severe crashes.	Improve curve design and driver awareness on curves.
	Number of Lanes	More lanes increase crashes.	Not significant	Optimize lane management and configurations.
	Shoulder Width	Not significant	Wider shoulders reduce severe crashes.	Increase shoulder width.
	Speed	Higher speeds lead to more crashes.	Higher speeds lead to more severe crashes.	Enforce speed limits and consider traffic calming measures.
	Road Surface Condition	Not significant	Dry and wet road surfaces experienced significant crashes.	Improve drainage and friction on wet surfaces.
	Slope (Downgrade and Upgrade)	Not significant	A steep slope leads to more crashes.	Special cautions need to be implemented at steep slopes.
Rural Minor Arterials	AADT	Increased traffic volume leads to more crashes.	Increased traffic volume does not lead to more crashes.	Monitor and manage traffic volumes.

Functional Class	Safety Parameters	Impact on Total Crashes	Impact on EPDO Crashes	Safety Improvement Focus
	Horizontal Alignment	Tangent segments have fewer crashes.	Tangent segments have more crashes.	Improve curve design and driver awareness on curves.
	Speed	Not significant	Higher speeds lead to more severe crashes.	Enforce speed limits and consider traffic calming measures.
	Road Surface Condition	Not significant	Dry road surfaces increase crashes.	Improve pavement friction on dry surfaces.
	Slope (Downgrade and Upgrade)	Not significant	A steep slope leads to more crashes.	Special cautions need to be implemented at steep slopes.
Rural Major Collectors	Pavement Friction	Higher friction levels reduce crashes.	Higher friction levels reduce severe crashes.	Focus on improving pavement friction.
	AADT	Increased traffic volume leads to more crashes.	Increased traffic volume leads to more crashes.	Monitor and manage traffic volumes.
	Horizontal Alignment	Tangent segments have fewer crashes.	Tangent segments have more PDO crashes.	Improve curve design and driver awareness on curves.
	Speed	Not significant	Higher speeds lead to more severe crashes.	Enforce speed limits and consider traffic calming measures.
	Road Surface Condition	Not significant	Dry road surfaces increase crashes.	Improve pavement friction on dry surfaces.
	Slope (Downgrade and Upgrade)	Not significant	A steep slope leads to more crashes.	Special cautions need to be implemented at steep slopes.

3.2 A Bayesian Approach to Examine the Impact of Pavement Friction on Intersection Safety

3.2.1 Background

Signalized intersections are responsible for 61 percent of pedestrian crashes which emphasizes the importance of proper signal operation, traffic control and the consideration of other risk factors to ensure the safety of pedestrians and other road users (Cvijovic et al., 2022; Arafat et al., 2020). Furthermore, new challenges are being faced when it comes to the safety of intersections with the increasing traffic volumes and emerging technologies. Traffic control and safety at intersections can be even more challenging with multimodal operations (Cvijovic et al., 2021; Stevanovic et al., 2019). Therefore, improving intersection safety is one of the priorities of the WYDOT.

Broadly speaking, excessive speed and drivers' inattention often create an environment where friction demand is higher than that supplied by standard pavement surfaces resulting in a loss of control (Alrejjal and Ksaibati, 2021). Therefore, achieving adequate levels of pavement friction enhances road safety in terms of reducing the severity of certain crash types. Pavement friction is a crucial resisting force that eliminates the relative motion between the vehicle tires and the pavement surface (Hall et al., 2009a). Equipped with more knowledge about pavement conditions and performance especially pavement friction, transportation engineers can devise fundamentally safer intersections for roadway users (Abdalla et al., 2021).

Generally, the friction levels decrease with time due to traffic volumes that polish the texture of aggregates in the pavement surface layer. As a result, it is strongly recommended that state DOTs and transportation agencies monitor the friction levels regularly. In terms of friction levels and intersection safety, the application of pavement surface treatments plays a critical role in the potential hazards of skid-related (also known as friction-related) crashes. Pavement surface treatments include chip seals, micro-milling, thin Hot-Mix Asphalt (HMA) overlay, Open-Graded Friction Course (OGFC), cape seals, scrub seals, and slurry seals, among others. Some of these treatments may be used as spot applications to increase the intersection friction levels where higher friction demands are required to reduce skid-related crashes. As a result, the impact of various roadway conditions and the relationship between skid resistance and traffic safety are not well investigated (Roadway Departure Safety, 2021).

The objective of this study was to identify crash severity risk as a function of pavement friction, crash characteristics, driver characteristics, environmental characteristics, and other factors. First, the critical parameters was identified using the variable importance charts of the random forest technique. Afterward, a Bayesian ordinal probit model was developed to achieve the objective. That is because Bayesian models mitigate the negative consequences of processing limit data.

3.2.2 Research Methodology

Two methods were employed to analyze the intersection safety data of this study. First, a preliminary analysis was conducted using the random forest machine learning technique to identify the critical independent explanatory variables influencing crash injury severity risk. Second, a Bayesian ordinal probit model was applied to gain insights into the relationships between crash injury severity risk and the crash contributing factors. The advantage of Bayesian modeling structures is that they are appropriate for conducting analyses on limited data (Lord and Miranda-Moreno, 2008; Miranda-Moreno et al., 2013; Asanya et al., 2021).

The random forest technique is an extension of the decision tree machine learning technique (James et al., 2021). It involves fitting a decision tree to bootstrapped datasets. A bootstrapped set consists of multiple data points sampled from the original data with replacement. The size of the bootstrapped set is equivalent to that of the original dataset. The mean of the results of the predictions outputted by each tree is the reported predictions of the random forest model. Yet, when developing each tree, the technique specifies that the tree branches are bifurcated by performing computations on data of a select subset of the total set of explanatory variables. The variables of the subset are randomly selected, and the count of those variables is equal to the square root of the total number of variables in the original dataset rounded to the nearest integer. Furthermore, the random forest technique may be used to identify the critical variables and interpret the relative importance of each variable in terms of its influence on the model's predictive power. The reader is referred to James et al. (2021) for details on decision tree methods and their variants.

Other than the random forest machine learning method that would be applied for gauging the variables' importance measures, a Bayesian ordinal probit model would be developed to interpret the influence of the crash contributing factors on crash severity. Under the ordinal probit structure, a latent propensity, y^*, is defined for each crash record, i, as follows (Eluru et al., 2008):

$$y_i^* = \beta_1 X_{1i} + \beta_2 X_{2i} + \cdots + \beta_p X_{pi} + \varepsilon_i \tag{9}$$

The X's are the crash contributing factors and the β's denote their respective regression coefficients. The variable, ε_i, is the error term, which is assumed to follow the normal distribution with a mean of 0 and a standard deviation of 1, also known as the standard normal distribution. The outcome, y_i, is defined as (Eluru et al., 2008):

$$y_i = \begin{cases} O, & y_i^* < \psi_1 \\ C, & \psi_1 < y_i^* < \psi_2 \\ KAB, & y_i^* > \psi_2 \end{cases} \tag{10}$$

The variables, ψ's, are thresholds that demarcate the boundaries among injury severity categories. Note that the constant term in Equation (9), β_0, is omitted and, instead, the first threshold, ψ_1, is computed. Alternatively, β_0 may be retained and the threshold, ψ_1, is set as 0. Either formulation is equivalent to the other. The injury severity risks, $P(.)$'s, are computed using the following formulas where $F(.)$ represents the function that is used to obtain the cumulative standard normal distribution (Fountas et al., 2018):

$$P(y_i = O) = F\left(\psi_1 - \sum_{j=1}^{J} \beta_j X_{ji}\right) \tag{11}$$

$$P(y_i = C) = F\left(\psi_2 - \sum_{j=1}^{J} \beta_j X_{ji}\right) - F\left(\psi_1 - \sum_{j=1}^{J} \beta_j X_{ji}\right) \tag{12}$$

$$P(y_i = KAB) = 1 - F\left(\psi_2 - \sum_{j=1}^{J} \beta_j X_{ji}\right) \quad (13)$$

In the frequentist approach, the model's variable coefficients are obtained using the maximum likelihood estimation (MLE) method. On the other hand, in the Bayesian approach, posterior distributions of the coefficients are obtained using prior information about the current data, also known as prior distributions, or simply priors, and the crash injury severity likelihoods, estimated from the data. Under Bayes' theorem, the posterior distributions of the variables' coefficients, β's, are proportional to the products of the coefficients' prior distributions and the crash injury severity likelihoods as per the data (Cowles, 2013). The posterior distributions of the parameter coefficients cannot be directly computed since high dimensional integrands are involved. Instead, Markov Chain Monte Carlo (MCMC) simulation methods, including the Gibbs sampler and the Metropolis-Hastings method, are appropriate means of obtaining the coefficients' posterior distributions (Cowles, 2013; Heydari et al., 2014). In this study, the brms package of R software was implemented to develop the model (Bürkner, 2017). The package employs the Stan programming language to run Hamiltonian Monte Carlo simulations. Also, weakly informative priors were assigned to each independent variable. That is, each variable's prior was assumed to follow the standard normal distribution (*N*[0, 1]) as suggested by Lemoine (2019). Weakly informative priors compensate for the data's low sample size (Asanya et al., 2021). A Bayesian credible interval (CI) is typically established to assess the explanatory variables' distributions. It is interpreted as the probability that a variable's coefficient lies within the interval. On the other hand, in the frequentist approach, inferences are drawn from the confidence interval such that the explanatory variable's coefficient lies within the interval had the data collection and processing procedure been conducted repeatedly (Lu, 2021).

When it comes to the goodness of fit (GOF) evaluation of the Bayesian ordinal probit model, the deviance information criterion (DIC) is a widely used metric that gauges model performance. However, it has been subject to criticism (Bürkner, 2017; van der Linde, 2005; Spiegelhalter, 2002) partly because it is descriptive of a single estimated value. In particular, it is a function of the effective number of parameters and the output deviance computed using the means of the explanatory variables' posterior distributions (Spiegelhalter, 2003). Instead, the Watanabe-Akaike information criterion (WAIC), which is a measure that involves averaging the crash injury severity risks across the explanatory variables' posterior distributions (Gelman et al., 2014), is more appropriate than the DIC (Bürkner, 2017). Another effective measure is the leave-one-out (LOO) cross-validation measure which is used for ascertaining the predictive power of the model. Smaller WAIC and LOO cross-validation values indicate improved model performance (Bürkner, 2017). More information about the WAIC and the LOO cross-validation measures are found in Gelman et al. (2014) and Vehtari et al. (2016), respectively.

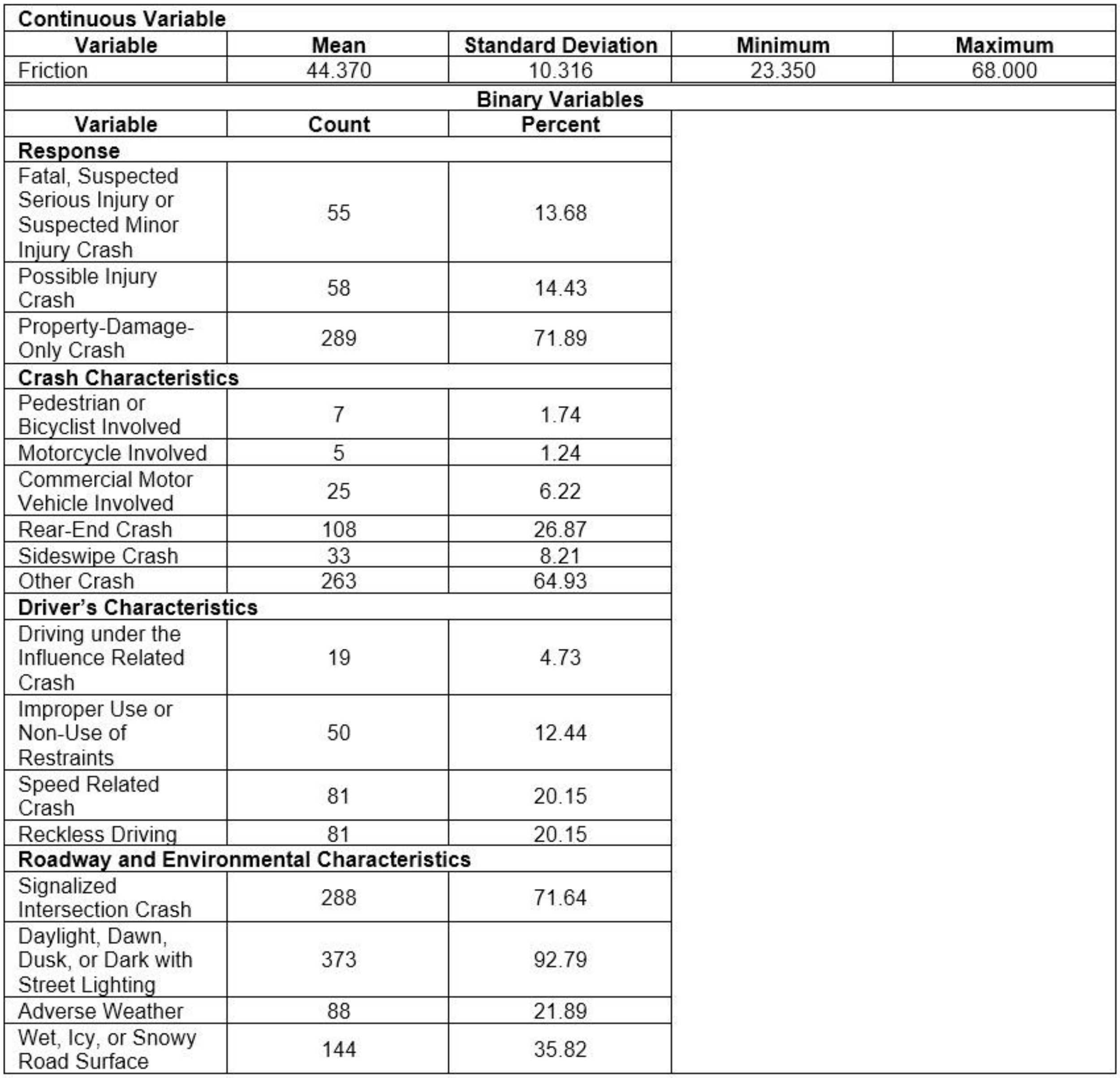
The variables' results are commonly interpreted using marginal effects (Washington et al., 2021). A marginal effect is a change in crash injury severity risks due to a change in the explanatory variable's value (i.e. from 0 to 1). Thus, for each observation, the crash injury severity risks were computed using Equations (11) through (13) once assuming that the variable's value was 0 and once using a value of 1. For both conditions, the values of the other variables were as provided in the data. The variables' coefficients, inputted in the computations, were the means of their output posterior distributions. The marginal effect of the variable was computed for each observation. The average of the marginal effects across all observations was considered as the variable's marginal effect. Similarly, this procedure was repeated for all other explanatory variables.

3.2.3 Data Description

The data comprised records of 402 crashes at 52 intersections from January 2007 through December 2017. Note that data for the years 2010 and 2011 were excluded since friction records were not available for these years. The majority of the data's variables including the crash, driver, and environmental characteristics were obtained from the Critical Analysis Reporting Environment (CARE) package of WYDOT. In this study, the crashes are considered intersection crashes when they are located within 250 feet from the center of the intersection (AASHTO, 2010).

In addition, the roadway surface friction data were collected by WYDOT personnel using the locked-wheel tester. When not available directly, the friction measurement at the intersection is estimated from the friction measurements along the route of the intersection. The friction measurements are linked to the crash data in the whole same year. Table 10 presents summary statistics of this study's data variables.

Table 10. Summary Statistics of Wyoming's Sample Intersection Safety Data.



Continuous Variable				
Variable	Mean	Standard Deviation	Minimum	Maximum
Friction	44.370	10.316	23.350	68.000

Binary Variables		
Variable	Count	Percent
Response		
Fatal, Suspected Serious Injury or Suspected Minor Injury Crash	55	13.68
Possible Injury Crash	58	14.43
Property-Damage-Only Crash	289	71.89
Crash Characteristics		
Pedestrian or Bicyclist Involved	7	1.74
Motorcycle Involved	5	1.24
Commercial Motor Vehicle Involved	25	6.22
Rear-End Crash	108	26.87
Sideswipe Crash	33	8.21
Other Crash	263	64.93
Driver's Characteristics		
Driving under the Influence Related Crash	19	4.73
Improper Use or Non-Use of Restraints	50	12.44
Speed Related Crash	81	20.15
Reckless Driving	81	20.15
Roadway and Environmental Characteristics		
Signalized Intersection Crash	288	71.64
Daylight, Dawn, Dusk, or Dark with Street Lighting	373	92.79
Adverse Weather	88	21.89
Wet, Icy, or Snowy Road Surface	144	35.82

For this study, the response modeled was the crash severity. It was categorized into three classes, namely (i) fatal crashes, suspected serious injury crashes and suspected minor injury crashes, (ii) possible injury crashes, and (iii) property-damage-only crashes. They are denoted as KAB, C, and O as per the Highway Safety Manual (AASHTO, 2010), respectively. Possible injury crashes are those in which drivers complain of pain, which may or may not be a result of the crash. Most crashes were property-damage-only crashes.

When it comes to the crash characteristics, non-motorists and motorcycle involvement each comprised less than 2 percent of the data points. Hence, they were not incorporated as variables in the models. On the other hand, the presence of commercial vehicles variable represented 6 percent of the data's records. Also, a quarter of such intersection crashes were rear-end crashes, while sideswipe crashes comprised lower proportions of the data. All other crashes, such as head-on and left-turn crashes, among others, represented more than half of the total crash records.

Regarding the driver's characteristics, crashes involving improper use or non-use of safety restraints, over-speeding, and reckless driving comprised considerable proportions of the data. On the contrary, crashes involving driving under the influence of drugs or alcohol represented less than 5 percent of the data.

Concerning roadway and environmental characteristics, the friction values ranged from 23 to 68 and the average value was 44. In addition, unsignalized intersection crashes accounted for a minority of the crash records (28 percent). Adverse weather-related crashes and crashes that occurred on non-dry roads constituted 22 percent and 36 percent of the total crashes, respectively. The term, adverse weather, refers to conditions such as raining, snowing, and any other unfavorable conditions.

3.2.4 Empirical Analysis

Preliminary analysis on the intersection safety data was conducted using the random forest machine learning technique and the variable importance charts were obtained. The analysis was conducted using the randomForest package (Breiman et al., 2021) of R software with a preset random seed and 500 bootstrapped datasets. The variable importance charts are presented in Figures 5 and 6. Figure 5 illustrates the variables' importance in terms of the mean decrease in accuracy measure while Figure 6 depicts the variables' importance in terms of the mean reduction in the Gini index averaged across all generated trees in the random forest model. The mean decrease in accuracy is the loss in accuracy that results when removing an explanatory variable, redeveloping the model, and predicting the responses. On the other hand, the Gini index is a measure of tree node purity where a genuinely pure node is one of which all data points belong to one category of the response (James et al., 2021).

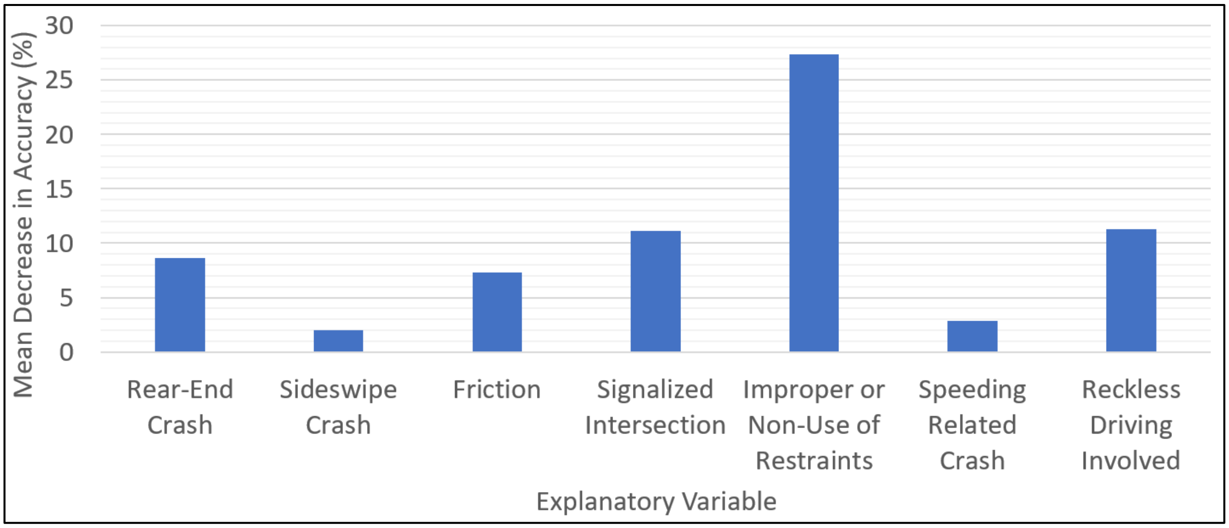


Figure 5. Chart. Variables' importance as per mean decrease in accuracy.

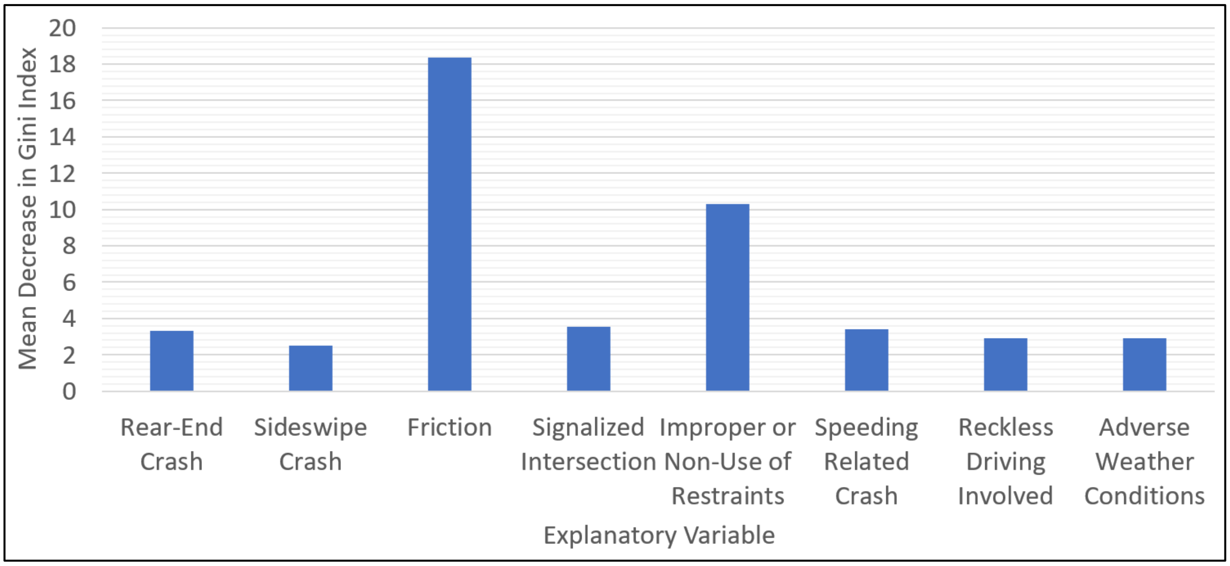
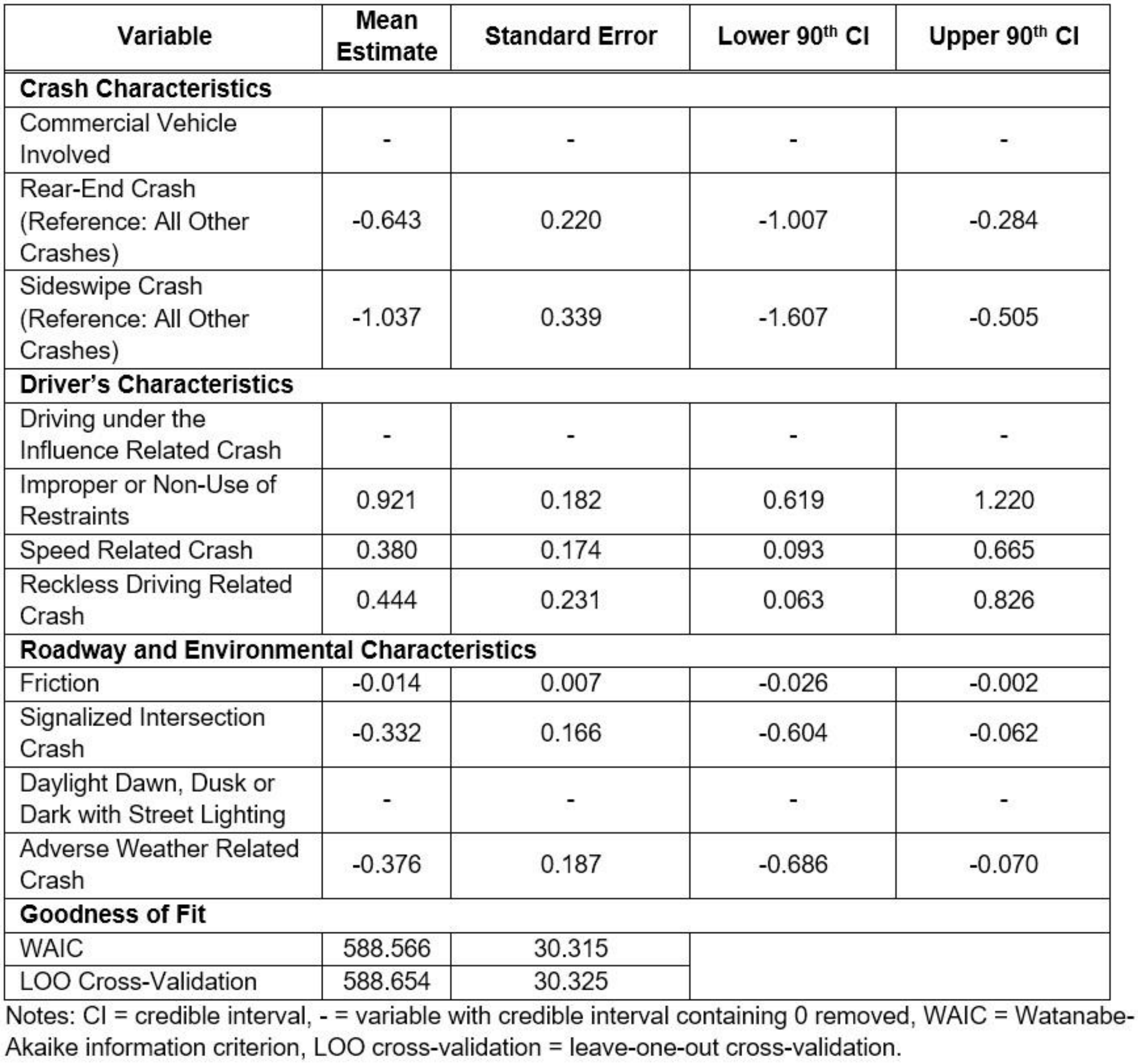


Figure 6. Chart. Variables' importance chart as per mean decrease in the Gini index.

As shown in Figure 5, the top critical explanatory variables, as per the mean decrease in accuracy metric, were the improper use or non-use of safety restraints, reckless driving, and signalized intersections. On the contrary, the pavement surface friction was the top explanatory variable influencing model performance followed by the improper use or non-use of restraints and the signalized intersection variables in terms of average loss in the Gini index. This would emphasize the importance of maintaining the pavement such that its surface friction levels provide adequate skid resistance.

Other than the preliminary analysis, the Bayesian ordinal probit model was developed successfully using the brms package of R. Three chains, each of which entailed 10,000 iterations, were run. Also, the number of burn-in iterations per chain was set as 2,000. Density and trace plots were outputted and, as per inferences drawn from them, the model converged. The model's results are presented in Table 11. Note that, in the table, the standard errors represent estimates of the standard deviations of the variables' posterior distributions. Also, the 90th percentile credible interval was used instead of the 95th credible interval since the sample size was small. The variable marginal effects are presented in Table 12. In Table 12, the Δ*P*(.)'s denote the changes in crash injury severity risks. The subsequent content comprises the discussion of the results. Each variable's effect on the response was inferred assuming all else was controlled.

Table 11. Bayesian Ordinal Probit Model Results.



Variable	Mean Estimate	Standard Error	Lower 90th CI	Upper 90th CI
Crash Characteristics				
Commercial Vehicle Involved	-	-	-	-
Rear-End Crash (Reference: All Other Crashes)	-0.643	0.220	-1.007	-0.284
Sideswipe Crash (Reference: All Other Crashes)	-1.037	0.339	-1.607	-0.505
Driver's Characteristics				
Driving under the Influence Related Crash	-	-	-	-
Improper or Non-Use of Restraints	0.921	0.182	0.619	1.220
Speed Related Crash	0.380	0.174	0.093	0.665
Reckless Driving Related Crash	0.444	0.231	0.063	0.826
Roadway and Environmental Characteristics				
Friction	-0.014	0.007	-0.026	-0.002
Signalized Intersection Crash	-0.332	0.166	-0.604	-0.062
Daylight Dawn, Dusk or Dark with Street Lighting	-	-	-	-
Adverse Weather Related Crash	-0.376	0.187	-0.686	-0.070
Goodness of Fit				
WAIC	588.566	30.315		
LOO Cross-Validation	588.654	30.325		

Notes: CI = credible interval, - = variable with credible interval containing 0 removed, WAIC = Watanabe-Akaike information criterion, LOO cross-validation = leave-one-out cross-validation.

Table 12. Variable Marginal Effects.

Variable	Marginal Effects (%)		
	ΔP(y = O)	ΔP(y = C)	ΔP(y = KAB)
Crash Characteristics			
Rear-End Crash (Reference: All Other Crashes)	17.40	-6.92	-10.48
Sideswipe Crash (Reference: All Other Crashes)	22.58	-10.58	-12.00
Driver's Characteristics			
Improper or Non-Use of Restraints	-31.90	7.98	23.92
Speed Related Crash	-11.76	3.86	7.90
Reckless Driving Related Crash	-13.73	4.29	9.44
Roadway and Environmental Characteristics			
Friction	10.37	-3.38	-6.99
Signalized Intersection Crash	10.25	-3.54	-6.71
Adverse Weather-Related Crash	10.45	-4.10	-6.35

Notes: The friction variable's marginal effects were computed assuming that its value changed from 35 to 55 and that all other variable values were 0, Δ*P*(*y* = O) = change in the likelihood of incurring no injury, Δ*P*(*y* = C) = change in the likelihood of incurring possible injury, Δ*P*(*y* = KAB) = change in the likelihood of incurring fatal, suspected serious injury or suspected minor injury.

As shown in Table 12, rear-end and sideswipe crashes were found to be less severe than all other crashes, such as head-on, left-turn, angle, and fixed-object crashes. It was estimated that, on average, a rear-end crash would have a 10 percent lower chance of resulting in a KAB injury relative to all other crashes except sideswipe crashes. Likewise, as per the estimated results, a sideswipe crash would have a 12 percent lower risk of resulting in a KAB injury relative to all other crashes except rear-end crashes. Abdel-Aty and Keller (2005) inferred that signalized intersection head-on, angle, and left-turn crashes would be severe relative to both sideswipe and rear-end crashes.

Regarding the driver's characteristics, seat belt use habits were found to play a major role in influencing injury severity likelihoods conditional on the occurrences of crashes. Failing to properly buckle up would raise the probability of a severe injury by an estimated 24 percent on average, a finding in-line with Bham et al. (2012). It was also interpreted that speeding would increase the chance of incurring severe injury by 8 percent. Imprialou et al. (2016) concluded that speeding would lead to grievous consequences. Reckless driving was also found to increase the likelihood of KAB injuries (marginal effect = 9 percent), a finding consistent with Weiss et al. (2014). Driving under the influence of intoxicants was not found to have an impact on injury severity risk, a finding that contradicted that of Bham et al. (2012).

When it comes to the roadway and environmental characteristics, it was interpreted that improving pavement surface friction from 35 to 55 would reduce the risk of incurring severe injury and hence increase that of incurring no injury. The average marginal effect for this variable was computed as -7 percent assuming all other variable values were 0. Mayora and Piña (2009) contended that larger friction levels indicated fewer hazards during wet pavement conditions. Signalized intersection crashes were found to be less likely to be severe (marginal effect = -7 percent for KAB injury). Plausibly, signalized intersections are safer than unsignalized intersections (McGee et al., 2003). The model's results also indicated that adverse weather-related crashes would be less likely to result in severe injury possibly because drivers traveled more cautiously during such conditions and would collide at lower speeds. Kelarestaghi et al. (2017) concluded that inclement weather conditions ameliorated crash severity.

3.3 Evaluating appropriate Pavement Friction Levels for different Roadway Scenarios and Estimating the corresponding Crash Reduction Benefits

3.3.1 Introduction

Pavement friction (skid resistance) is an essential aspect of road safety that allows for vehicle acceleration, deceleration, and directional control (Cafiso et al. 2021). Maintaining traction and stopping quickly during an emergency can be challenging without sufficient friction. Hence, preserving an adequate level of pavement friction is key to ensuring a safe and efficient driving experience, as it reduces vehicle sliding and stopping distance, especially in wet conditions (Noyce et al. 2005). Nearly 30 percent of annual highway fatalities are attributed to insufficient pavement conditions (Larson et al. 2008). Insufficient pavement conditions can include factors such as poor surface texture, worn or uneven pavement, or lack of proper drainage, which can lead to reduced skid resistance and increase the risk of crashes. Pavement friction is primarily influenced by three types of variables: Pavement surface, vehicle and tire, and environmental factors. The pavement surface includes the texture, grading curve, type, size, form of the aggregates, etc. Vehicle and tire-related factors include the vehicle speed, tire operating conditions such as wheel slip ratio, slip angle, tire pressure, tire characteristics, and each tire's unique features. Finally, environmental variables like road geometry, surface contamination, water film thickness, temperature, and precipitation all have an impact on pavement friction (Anupam et al. 2013; Bazlamit and Reza 2005; D'Apuzzo et al. 2020). Considering the substantial snowfall rates in

Wyoming, it is not surprising that over 30 percent of crashes in the state happen on wet, icy, snowy, or slushy road surfaces (NHTSA 2022).

Pavement friction decreases over time due to various factors, including the polishing action of traffic, water, contaminants, etc., which can cause the pavement surface to wear down and become smoother, resulting in a decrease in friction or skid resistance (McCarthy et al. 2016). The driver's ability to control the vehicle effectively is impaired by the decrease in pavement friction, which increases the number of crashes. Low friction number contributes up to 35 percent of US wet-weather crashes (Hoerner 2002). In the realm of pavement friction level, FN40R values for road surfaces should be 35 or higher (Noyce et al. 2007). FN40R corresponds to the SN40R metric, as defined by the American Association of State Highway and Transportation Officials (AASHTO) (Hall et al. 2009a). Xiao et al. (2000) found that wet-pavement crashes decreased by almost 60 percent when the skid number (SN) increased from 33.4 to 48. Numerous investigations have investigated the relationship between pavement surface friction level and safety (Kuttesch 2004; Mayora and Piña 2009; Wallman and Astrom 2001). However, the correlation between pavement friction and crash risk is site-specific, influenced by factors beyond pavement friction (Hall et al. 2009b). This emphasizes the imperativeness for a focused analysis of pavement friction, determining the cost-effective friction level especially in the context of Wyoming.

Despite the numerous studies conducted in recent years, there remains significant room for improvement, particularly regarding the crash analysis considering only friction-related crashes (FR crashes). The analysis of total crashes falls short in replicating the complexities of FR crashes in real conditions, potentially resulting in an underestimation of the influence exerted by only FR crashes. A study performed by Kuemmel et al. (2000) reveals that wet road conditions account for 14 percent of fatal crashes and 25 percent of all crashes, and the majority of crash investigations focus solely on incidents that happened on wet pavement surfaces (Hall et al. 2009b; Ivan et al. 2012). However, most of the research conducted on pavement friction analysis has focused on total and wet crashes. In this study, we aimed to analyze the factors affecting only FR crashes, which are primarily associated with wet weather, runoff, and swerving due to slippery conditions. A more comprehensive understanding of the relationship between pavement friction and accident rates can be gained by focusing on these specific types of crashes. As this study aimed to develop a crash prediction model, logistic regression was identified as the most suitable approach to identify the significant factors affecting FR crashes. As the response variable, the FR crash, is dichotomous, the binary regression model was deemed suitable for this research.

The main objective of this study is to improve road safety in Wyoming by implementing a crash risk mitigation approach into the pavement friction management program. To achieve this, several tasks were undertaken. Firstly, Wyoming crash data, roadway geometric design data, traffic data, and weather data were integrated to develop a crash prediction model for both interstate and non-interstate highways. The model focused on FR crashes resulting from wet weather, runoff, and swerve due to slippery conditions. Then, binary logistic regression analysis was considered to identify the significant factors influencing FR crashes in Wyoming. Moreover, the potential reduction in FR crashes resulting from maintenance activities that restore pavement friction levels was estimated. Finally, the proposed pavement friction levels were assessed for their cost-effectiveness by considering the benefits of reducing crashes and associated maintenance costs.

Wyoming Department of Transportation (WYDOT) measures pavement friction using the locked-wheel testing methodology that utilizes a truck (skid truck) with two wheels with full-size tires to drag the skid trailer over the pavement's surface at the desired speed. This method records longitudinal friction by completely locking the test wheels, measuring the average sliding force over 3 seconds, and recording a 1-second average after achieving a fully locked state (de León Izeppi et al. 2019). The friction data utilized in this study was derived from actual field data, collected and calibrated by WYDOT at the regional calibration center. The locked-wheel tester primarily measures the pavement friction as friction number (FN). The friction number (FN), also known as the skid number (SN).

3.3.2 Research Methodology

The research methodology involves three steps. First, a crash dataset was analyzed and categorized to determine how the occurrence of FR crashes varies with different parameters. Second, an appropriate analysis method was selected to identify potential significant factors influencing FR crashes. Finally, the crash reduction benefits associated with an appropriate level of friction were evaluated.

The binary regression model was used to identify the significant factors affecting FR crashes. The response variable FR crash was a binary variable and used as "0" for "non-friction related crash" and "1" for "friction-related crash." The general form of binary logistic regression is given below:

In the binary logistic regression framework, the probability, P_i of encountering occupant injury outcome i is defined as follows:

$$log\left[\frac{P_i}{1-P_i}\right] = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \cdots + \beta_m x_{im} \tag{14}$$

The equation includes m explanatory variables, denoted by x_i in the vector of explanatory variables, with their respective coefficients represented by the β's. The intercept parameter is represented by β_0. This equation of the cumulative probability can be expressed as follows:

$$P_i = \frac{exp(\beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} \dots + \beta_m x_{im})}{1 + exp(\beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} \dots + \beta_m x_{im})} \quad (15)$$

To better understand the effects of changes in the predictor variable on the probability of FR crashes, the marginal effect was calculated in this study. The marginal effect is a statistical measure that indicates how the probability of an event changes due to a change in one or more predictor variables while holding all other variables constant. This effect measures the probability change of FR crashes when the indicator variables shift from zero to one while holding all other covariates constant. Marginal effects can be a more accessible and informative way to interpret and communicate the results of statistical analyses, especially when the practical significance of the effects is of primary interest. Equation 16 was used to calculate the marginal effect.

$$\mathbf{ME_i} = \beta X\mathbf{i} \times \mathbf{P_i}\, (1 - \mathbf{P_i}) \quad (16)$$

where ME_i is the marginal effect of the predictor X_i, βX_i is the parameter coefficient corresponding to X_i, and P_i and (1- P_i) are the probabilities of FR crash outcome and no FR crash outcome, respectively. The models' marginal effect (ME) percent showed how the presence or absence of certain conditions affected the probability of FR crashes. A positive or negative marginal effect indicated that a one-unit increase in the examined variable would increase or decrease the likelihood of FR crashes. A marginal effect of 0 meant that there was no significant effect on FR crashes.

This study utilized correlation testing, tolerance, and variance inflation factor (VIF) to assess for multicollinearity. The outcomes of all three measures were used in this study to validate the absence of multicollinearity among the predictor variables. A 95 percent significance level was used to determine whether any predictor variables were significant or not. For the evaluation of the adequacy of the original model and the best-fit model, several criteria were checked for all the attempted models, such as multicollinearity, standardized residuals, AIC (Akaike information criterion) value, ROC Curve (Receiver Operating Characteristic curve), and goodness of fit test. The association between the predicted and the observed responses can evaluate the model's goodness of fit. Models satisfied with the above criteria and the lowest AIC value and the highest AUC value (i.e., the area under the curve) of the ROC Curve were chosen as the best-fit model.

3.3.3 Data Preparation and Description

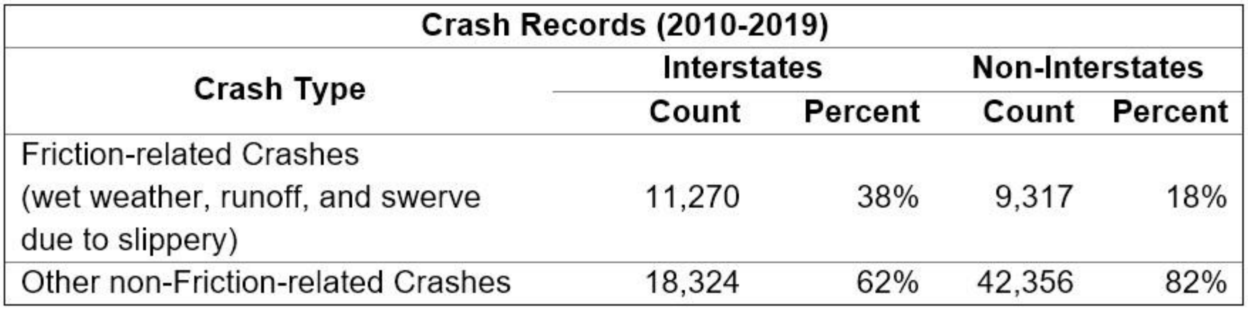
Crash data, traffic volumes, geometric design characteristics, road surface conditions, functional classifications of roads, friction data, and weather data collected from

Wyoming were used in this research. Crash data and roadway geometric data obtained from WYDOT belonged from 2010 to 2019. WYDOT measures friction number every two years. Therefore, the average friction number from the previous and subsequent years was used in this study since the friction number has a minimal change over time.

Crash data were collected from the Critical Analysis Reporting Environment (CARE) package, supported by the WYDOT. The crash records were collected by WYDOT from police crash reports and filed in the database. The data comprised 29594 unique crash records from January 2010 through December 2019. The crashes in wet weather, runoff, and swerve due to slippery are considered FR crashes. The total dataset was split into two groups: Interstate and non-interstate highways. Additionally, various factors such as friction data, road surface, weather conditions, and geometric characteristics of roadways were considered to develop a crash prediction model. The descriptive statistics of variables used in the analysis are presented in Table 13 and Table 14. Among a total of 29,594 crashes on interstate, 38 percent were FR crashes. In the non-interstates, 18 percent were FR crashes, among a total of 51,673 crashes. A total of thirteen binary variables and three continuous variables were included in the analysis, as shown in Table 14.

Roadway surfaces in WYDOT are classified into four categories (excellent, good, fair, or poor) based on their friction numbers (FNs): FN > 55= excellent, 40< FN ≤ 55= good, 35< FN≤ 40=fair, and FN≤35=poor. In order to gain a more comprehensive understanding of the relationship between FR crashes and roadway friction levels, this study examines four specific friction levels: FN(35-40), FN(40-45), FN(45-50), and FN(>50). Each friction level is divided into five intervals, providing a more detailed and nuanced view of the relationship between pavement friction and crash frequency.

Table 13. Crash Records (2010 – 2019).



Crash Records (2010-2019)				
Crash Type	**Interstates**		**Non-Interstates**	
	Count	**Percent**	**Count**	**Percent**
Friction-related Crashes (wet weather, runoff, and swerve due to slippery)	11,270	38%	9,317	18%
Other non-Friction-related Crashes	18,324	62%	42,356	82%

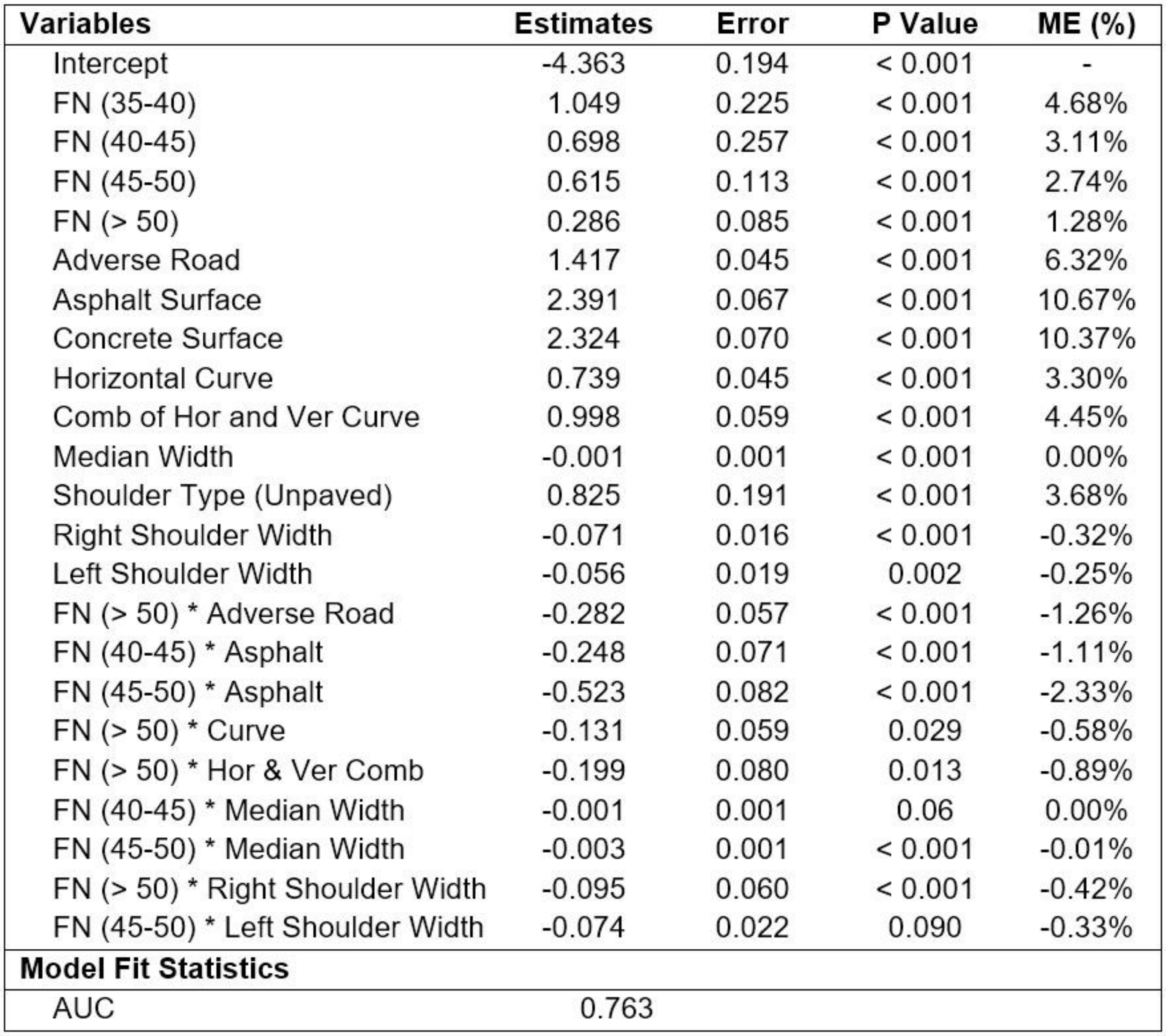
Table 14. Descriptive Statistics

Categorical Variables	Description	Coded Response	Interstates		Non-Interstates	
			Count	Percent	Count	Percent
FN (< 30)	Crashes occurred where friction number is less than 30	0 = No	29,360	99.2%	50,970	98.6%
		1 = Yes	234	0.8%	703	1.4%
FN (30-35)	Crashes occurred where friction number is between 30 and 35	0 = No	28,742	97.1%	47,467	91.9%
		1 = Yes	852	2.9%	4,206	8.1%
FN (35-40)	Crashes occurred where friction number is between 35 and 40	0 = No	26,755	90.4%	46,598	90.2%
		1 = Yes	2,839	9.6%	5,075	9.8%
FN (40-45)	Crashes occurred where friction number is between 40 and 45	0 = No	26,581	89.8%	44,996	87.1%
		1 = Yes	3,013	10.2%	6,677	12.9%
FN (45-50)	Crashes occurred where friction number is between 45 and 50	0 = No	25,211	85.2%	43,435	84.1%
		1 = Yes	4,383	14.8%	8,238	15.9%
FN (> 50)	Crashes occurred where friction number is greater than 50	0 = No	11,321	38.3%	24,899	48.2%
		1 = Yes	18,273	61.7%	26,774	51.8%
Adverse road	The road condition is adverse (e.g., icy, snowy, wet, etc.)	0 = No	15,524	52.5%	38,082	73.7%
		1 = Yes	14,070	47.5%	13,591	26.3%
Inclement weather	The weather condition is inclement (e.g., snow shower, rain, foggy, etc.)	0 = No	17,449	59.0%	40,917	79.2%
		1 = Yes	12,145	41.0%	10,756	20.8%
Asphalt surface	Crashes occurred on asphalt surface	0 = No	12,662	42.8%	23,112	44.7%
		1 = Yes	16,932	57.2%	28,561	55.3%
Concrete surface	Crashes occurred on concrete surface	0 = No	23,504	79.4%	45,520	88.1%
		1 = Yes	6,090	20.6%	6,153	11.9%
Horizontal curve	Presence of horizontal curve segment	0 = No	25,064	84.7%	46,147	89.3%
		1 = Yes	4,530	15.3%	5,526	10.7%
Hor and Ver curve	Combination of horizontal and vertical curve segment	0 = No	18,014	60.9%	48,810	94.5%
		1 = Yes	11,580	39.1%	2,863	5.5%
Shoulder type	When the shoulder type is unpaved	0 = No	29,404	99.4%	48,043	93.0%
		1 = Yes	190	0.6%	3,630	7.0%
Continuous Variables	**Description**		**Interstates**		**Non-Interstates**	
			Mean	**SD**	**Mean**	**SD**
Median width	Median width		86.691	76.389	4.331	8.825
Right shoulder width	Right shoulder width		9.286	1.316	5.378	2.861
Left shoulder width	Left shoulder width		3.694	0.849	5.381	2.859

3.3.4 Analysis of Results and Discussions

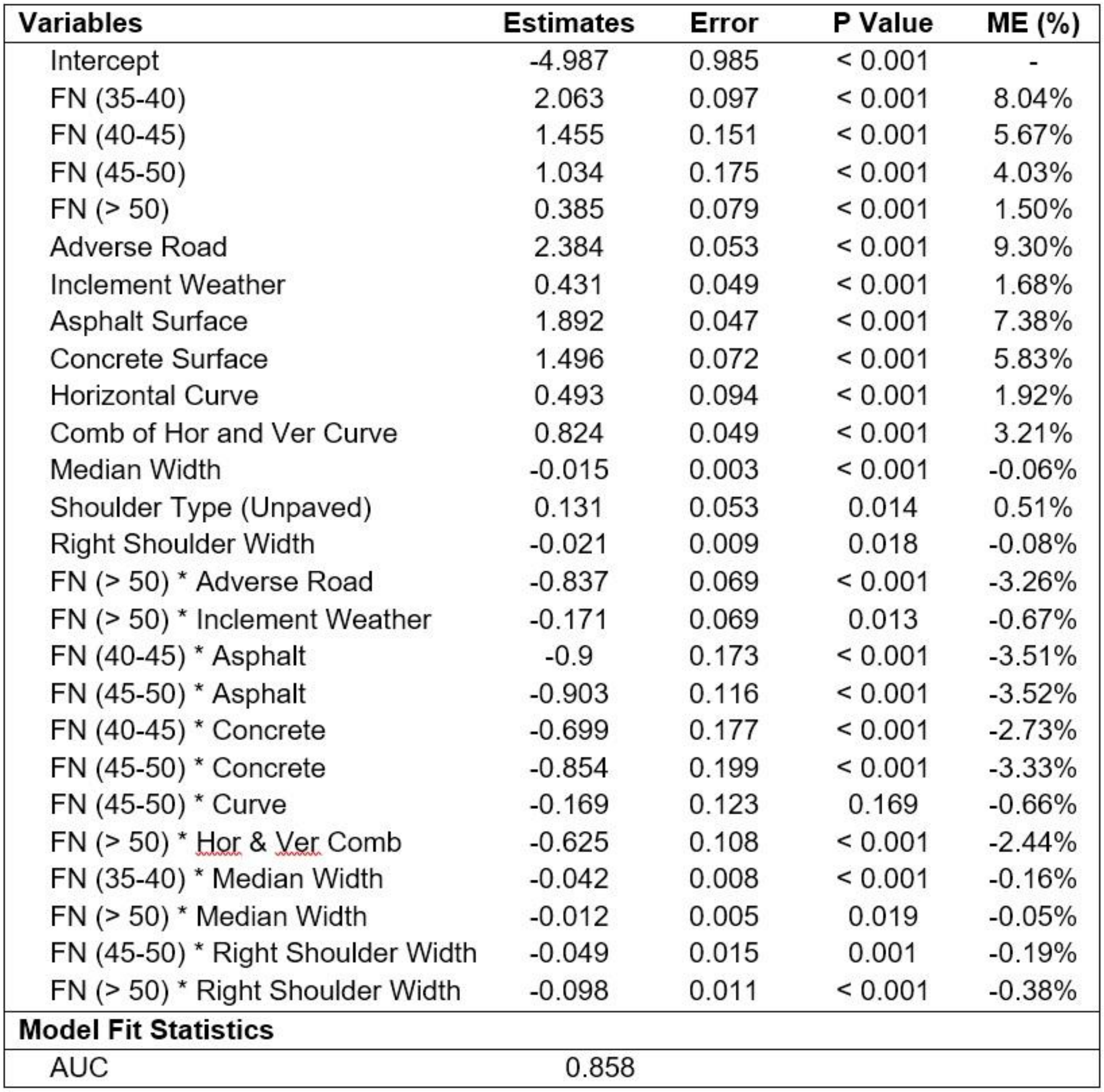
Two models were developed and analyzed by binary logistic regression based on the Interstate and non-interstate datasets to identify the significant factors affecting the FR crash. The results of these analyses are shown in Table 15 and Table 16, and subsequent sections discuss the effects of different variables on the probability of the FR crash. Table 15 and Table 16 display parameter estimates for the best-fit model, with all estimates being significant at the 95th percentile confidence level and the related marginal effects.

Table 15. Interstates Model.



Variables	Estimates	Error	P Value	ME (%)
Intercept	-4.363	0.194	< 0.001	-
FN (35-40)	1.049	0.225	< 0.001	4.68%
FN (40-45)	0.698	0.257	< 0.001	3.11%
FN (45-50)	0.615	0.113	< 0.001	2.74%
FN (> 50)	0.286	0.085	< 0.001	1.28%
Adverse Road	1.417	0.045	< 0.001	6.32%
Asphalt Surface	2.391	0.067	< 0.001	10.67%
Concrete Surface	2.324	0.070	< 0.001	10.37%
Horizontal Curve	0.739	0.045	< 0.001	3.30%
Comb of Hor and Ver Curve	0.998	0.059	< 0.001	4.45%
Median Width	-0.001	0.001	< 0.001	0.00%
Shoulder Type (Unpaved)	0.825	0.191	< 0.001	3.68%
Right Shoulder Width	-0.071	0.016	< 0.001	-0.32%
Left Shoulder Width	-0.056	0.019	0.002	-0.25%
FN (> 50) * Adverse Road	-0.282	0.057	< 0.001	-1.26%
FN (40-45) * Asphalt	-0.248	0.071	< 0.001	-1.11%
FN (45-50) * Asphalt	-0.523	0.082	< 0.001	-2.33%
FN (> 50) * Curve	-0.131	0.059	0.029	-0.58%
FN (> 50) * Hor & Ver Comb	-0.199	0.080	0.013	-0.89%
FN (40-45) * Median Width	-0.001	0.001	0.06	0.00%
FN (45-50) * Median Width	-0.003	0.001	< 0.001	-0.01%
FN (> 50) * Right Shoulder Width	-0.095	0.060	< 0.001	-0.42%
FN (45-50) * Left Shoulder Width	-0.074	0.022	0.090	-0.33%
Model Fit Statistics				
AUC	0.763			

Table 16. Non-Interstates Model



Variables	Estimates	Error	P Value	ME (%)
Intercept	-4.987	0.985	< 0.001	-
FN (35-40)	2.063	0.097	< 0.001	8.04%
FN (40-45)	1.455	0.151	< 0.001	5.67%
FN (45-50)	1.034	0.175	< 0.001	4.03%
FN (> 50)	0.385	0.079	< 0.001	1.50%
Adverse Road	2.384	0.053	< 0.001	9.30%
Inclement Weather	0.431	0.049	< 0.001	1.68%
Asphalt Surface	1.892	0.047	< 0.001	7.38%
Concrete Surface	1.496	0.072	< 0.001	5.83%
Horizontal Curve	0.493	0.094	< 0.001	1.92%
Comb of Hor and Ver Curve	0.824	0.049	< 0.001	3.21%
Median Width	-0.015	0.003	< 0.001	-0.06%
Shoulder Type (Unpaved)	0.131	0.053	0.014	0.51%
Right Shoulder Width	-0.021	0.009	0.018	-0.08%
FN (> 50) * Adverse Road	-0.837	0.069	< 0.001	-3.26%
FN (> 50) * Inclement Weather	-0.171	0.069	0.013	-0.67%
FN (40-45) * Asphalt	-0.9	0.173	< 0.001	-3.51%
FN (45-50) * Asphalt	-0.903	0.116	< 0.001	-3.52%
FN (40-45) * Concrete	-0.699	0.177	< 0.001	-2.73%
FN (45-50) * Concrete	-0.854	0.199	< 0.001	-3.33%
FN (45-50) * Curve	-0.169	0.123	0.169	-0.66%
FN (> 50) * Hor & Ver Comb	-0.625	0.108	< 0.001	-2.44%
FN (35-40) * Median Width	-0.042	0.008	< 0.001	-0.16%
FN (> 50) * Median Width	-0.012	0.005	0.019	-0.05%
FN (45-50) * Right Shoulder Width	-0.049	0.015	0.001	-0.19%
FN (> 50) * Right Shoulder Width	-0.098	0.011	< 0.001	-0.38%
Model Fit Statistics				
AUC	0.858			

Furthermore, marginal effects can be used to estimate the expected change in the FRC for specific values of the independent variables, which can be useful for making predictions and developing interventions. The marginal effect is a statistical measure that indicates how the probability of an event changes due to a change in one or more independent variables while holding all other variables constant.

- Pavement Surface Friction

The pavement surface friction parameters were statistically significant in the interstate and non-interstate models. The results showed that higher friction levels were associated with fewer FR crashes, indicating an inverse relationship between pavement friction and FR crashes (Tables 15 and 16). The marginal effect for the four friction levels, FN(35-40), FN(40-45), FN(45-50), and FN(>50), are 4.68 percent, 3.11 percent, 2.74 percent, and 1.28 percent, respectively (Table 15). Table 15 shows that as the level of friction number increases from FN(35-40) to FN(>50), the marginal effect on the probability of FR crashes decreases from 4.68 percent to 1.28 percent. In other words, higher levels of friction number are associated with a lower probability of FR crashes. Overall, the results suggest that higher levels of friction number can help reduce the probability of FR crashes, and maintaining or improving friction levels on the road surface could effectively prevent these types of crashes.

Likewise, the non-interstate model results demonstrated that higher friction levels were associated with fewer FR crashes (Table 16). The marginal effects for the four levels, FN(35-40), FN(40-45), FN(45-50), and FN(>50), suggest that the probability of FR crashes increases by 8.04 percent, 5.67 percent, 4.03 percent, and 1.50 percent, respectively. The results of both models relating to FR crashes showed that pavement friction was a critical factor associated with traffic crashes. Hence, it could be interpreted that maintaining the pavement to ensure adequate surface friction levels reduces the possibility of FR crashes.

- Horizontal and Vertical Curve

The Interstate and non-interstate model results indicated that the horizontal alignment was associated with FR crash occurrence in all facilities, and the road segments with tangent sections experienced fewer crashes than those with curved segments. Additionally, it was found that the road sections with the combination of horizontal and vertical curves had 4.45 percent and 3.21 percent higher FR crash occurrences for the interstate and non-interstate facilities, respectively (Tables 15 and 16). Such crash impacts are frequently reported in the literature (Alrejjal and Ksaibati 2023; Geedipally et al. 2019a). However, the parameters for vertical curves (upgrade and downgrade) were found to be statistically insignificant for all facilities and thus were removed from both models.

- Shoulder and Median

The analysis result demonstrates that maintaining or improving the quality of shoulders on highways, particularly on interstates, is crucial for reducing the probability FR crashes. Unpaved shoulders were found to be associated with 3.68 percent and 0.51 percent higher FR crash occurrences on interstate and non-interstate facilities, respectively (Tables 15 and 16). The result shows that even a small percentage of unpaved shoulders on interstates (0.6 percent) could lead to a higher probability of FR crashes, indicating the importance of maintaining or improving the pavement quality of shoulders on highways.

It was also found that both right shoulder and median width were statistically significant for FR crashes in interstate and non-interstate models. However, the left shoulder width was only significant in the interstate model and not in the non-interstate model. Table 15 indicated that wider medians and wider right shoulders were associated with reduced crash counts for all highways. Median width had a marginal effect close to 0 percent for both models. A marginal effect close to 0 percent indicates that there is no significant association or effect between the predictor variable and the response variable. Median width indicated a minimal effect on the FR crash, having the marginal effect of -0.01 percent and -0.06 percent. Right shoulder width was associated with reduced FR crashes, with marginal effects of -0.32 percent for the interstate and -0.08 percent for the non-interstate. Similarly, left shoulder width was also associated with reduced FR crashes with a marginal effect of -0.25 percent for the interstate.

- Road Surface Condition

The analysis of both the interstate and non-interstate models of FR crashes revealed that adverse road surface conditions such as ice, snow, and wetness could lead to an increased probability of such crashes. This is mainly because these conditions tend to reduce the friction between the vehicle tires and the road surface, which can cause a loss of control of the vehicle, particularly at high speeds or during sudden braking. Thus, friction is a crucial factor, especially on wet road surfaces. The results in Tables 15 and 16 indicated that the probability of an FR crash increased by 6.32 percent and 9.30 percent for the interstate and non-interstate, respectively, due to adverse pavement surface conditions.

Moreover, the analysis reveals that inclement weather, such as snow showers, rain, and fog, is not statistically associated with FR crashes in the interstate model, but it is significant for the non-interstate model. In non-interstate highways, FR crashes increased by 1.68 percent due to inclement weather. It could be that the higher service level priority in interstates during inclement weather, set by WYDOT, leads to better maintenance and management of the highways, resulting in fewer FR crashes. Furthermore, the analysis showed that the pavement surface type is also a significant predictor of FR crashes. Both asphalt and concrete surfaces were found to have a substantially higher probability of FR crashes compared to the non-asphalt and non-concrete pavement, respectively. Specifically, asphalt surfaces had a 10.67 percent and 7.38 percent higher probability of FR crashes in the interstate and non-interstate, respectively. Concrete surfaces had a 10.37 percent and 5.83 percent higher likelihood of FR crashes in the interstate and non-interstate, respectively, compared to non-concrete pavement.

- Interaction terms with specific pavement friction level

Understanding the interaction effects between pavement friction and different factors can help identify the specific conditions under which FR crashes are more likely to occur. Several interaction terms were explored in this study, including the interactions of pavement friction levels and other factors (i.e., adverse road, inclement weather, asphalt surface, concrete surface, curve, combination of horizontal and vertical curves, median width, right shoulder width, and left shoulder width) and their impact on FR crashes on both interstate and non-interstate highways.

The findings from Tables 15 and 16 demonstrate that adverse road conditions and FN>50 are positively linked with FR crashes. However, when examining the interaction term of FN>50 and adverse road conditions, a negative sign estimate is observed. This implies that if people driving on an adverse road condition with a friction number of FN>50, the likelihood of an FR crash actually decreases by 1.26 percent and 3.26 percent for the interstate and non-interstate highways, respectively, compared to a scenario where there is an adverse road condition without FN>50. These results indicate that maintaining a friction number of FN>50 in adverse weather could significantly lower the incidence of FR crashes on highways. Similarly, in the non-interstate model, the interaction term of FN>50 and inclement weather has a negative sign estimate. It shows that the likelihood of an FR crash decreases by 0.67 percent if the road has a friction number of FN>50 and experiencing inclement weather conditions compared to a scenario where there is no FN>50 in an inclement weather condition. Thus, taking measures to maintain a friction number of FN>50 in inclement weather could also considerably reduce the occurrence of FR crashes on highways.
Asphalt pavement was found to increase FR crashes compared to non-asphalt pavement in both interstate and non-interstate models. However, there are specific friction number ranges for asphalt pavement (FN(40-45) and FN(45-50)) where the interaction term is significant, and the marginal effect of FR crashes decreases for the interstate and non-interstate respectively, compared to asphalt pavement without having those friction levels. This suggests that having those specific friction levels in an asphalt pavement may improve safety in terms of FR crashes.

On the other hand, the interaction term between concrete pavement and friction number was only significant in the non-interstate model. In this case, the presence of specific friction levels in concrete pavement (FN(40-45) and FN(45-50)) was associated with a decrease in FR crashes compared to the absence of those friction levels. In terms of FR crashes, it can be inferred that the presence of specific friction levels in concrete pavement may enhance safety on non-interstate highways.

The modeling results in Tables 15 and 16 indicate that FR crashes are more likely to occur in the horizontal curve section than in the tangent section. Therefore, the study examined the interaction of specific friction levels and curve sections and found it to be significant in decreasing the likelihood of FR crashes. In the case of interstate highways, the curve section with a friction number (FN) greater than 50 reduced the likelihood of FR crashes by a marginal effect of 0.58 percent compared to the curve section with an FN less than 50. Similarly, in non-interstate highways, the curve section with FN (45-50) decreased the likelihood of FR crashes by a marginal effect of 0.66 percent compared to the curve section without the specific friction level of FN(45-50). Although higher FR crashes are more likely in the curve section reported by many researchers, while investigating the combination of horizontal and vertical curves, the marginal effect of FR crash decreased by 0.89 percent and 2.44 percent for the interstate and non-interstate, respectively, due to the presence of FN(>50) compared to the lower friction number FN(<50).

Interaction terms with FN and Median width had a negative FR crash estimate in interstate and non-interstate models. However, Interstate highways with FN(40-45) and FN(45-50) both had marginal effects close to 0 percent, indicating no significant impact on those interaction terms on FR crash on the interstate. Similarly, non- interstate highway with the predicted probability of a FR crash occurring decreases by 0.16 percent and 0.05 percent for every one-unit increase in median width when the FN is in the range of (35-40) and (>50), respectively, compared to a scenario where the FN is not within that range.

In both interstate and non-interstate model, the interaction term with FN and right shoulder width decreased the FR crash by 0.42 percent and 0.38 percent, respectively, for every one-unit increase in right shoulder width when the FN is in the range of (>50) and compared to a scenario where the FN is <50. Similarly, in non-interstate, interaction term with FN and right shoulder width decreased the FR crash by 0.19 percent for every one-unit increase in right shoulder width when the FN is in the range of (45-50) and compared to a scenario where friction number is not within the range. So, it is warranted to maintain FN>50 due to having less probability of FR crash involved due to the right shoulder width.

In the interstate, an increase of one unit in left shoulder width decreased the likelihood of FR crash by 0.33 percent when the pavement has an FN of 45-50 compared to when it does not have this specific friction number.

Overall, this study emphasizes the importance of maintaining adequate pavement friction levels, especially in adverse weather and geometric conditions to reduce FR crashes. It also highlights the need to consider the interaction effects of various factors while formulating safety measures to improve road safety.

3.3.5 Conformance and Verification of the Mode

One way to evaluate the effectiveness of a model is to compare its predicted probabilities with the actual outcomes. The area under the curve (AUC) is commonly used to assess the model's performance. The AUC score ranges from 0 to 1, with a higher score indicating a better fit of the model. The analysis results reveal that the model performed well, with an AUC score of 76.3 percent and 85.8 percent, indicating that 76.3 percent and 85.8 percent of the observed outcomes were predicted accurately for the interstate and non-interstate models. The receiver operating characteristics (ROC) curves with the corresponding AUCs are shown in Figure 8.

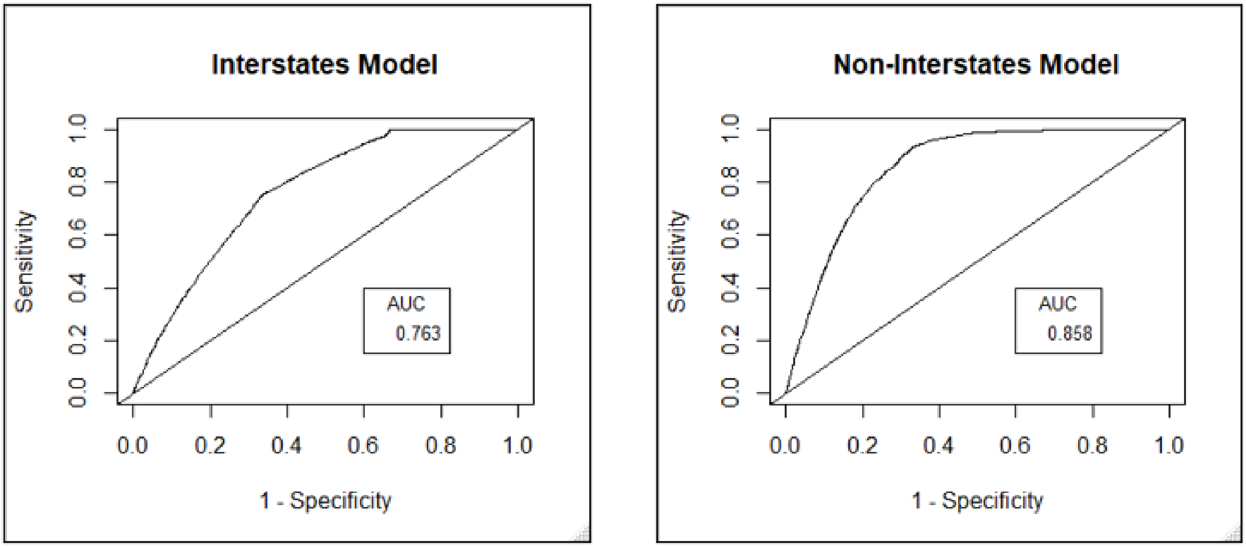
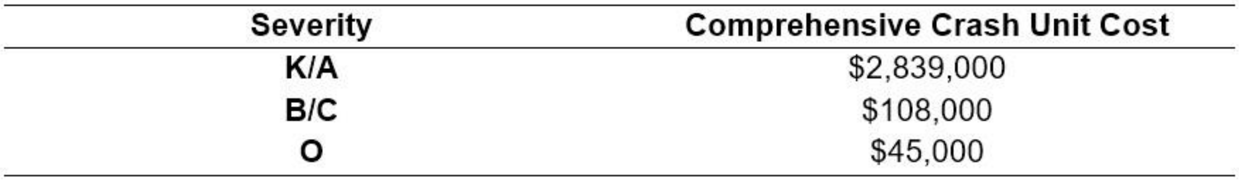


Figure 7. Chart. ROC Curve for Interstates and Non-Interstates Models.

3.3.6 Crash Reduction and Pavement Friction (Benefits)

The “KABCO” injury scale, developed by the National Safety Council (NSC), is widely used to determine crash severity. It categorizes injuries as follows: K – Fatal, A – Incapacitating injury, B – Nonincapacitating injury, C – Possible injury, and O – No injury. WYDOT uses the KABCO injury scale and USDOT fatal injury cost as a base value and then applies weighting factors to create severity-weighted crash unit cost values, including comprehensive crash costs (property damage costs, legal costs, medical costs, etc.), as shown in Table 17.

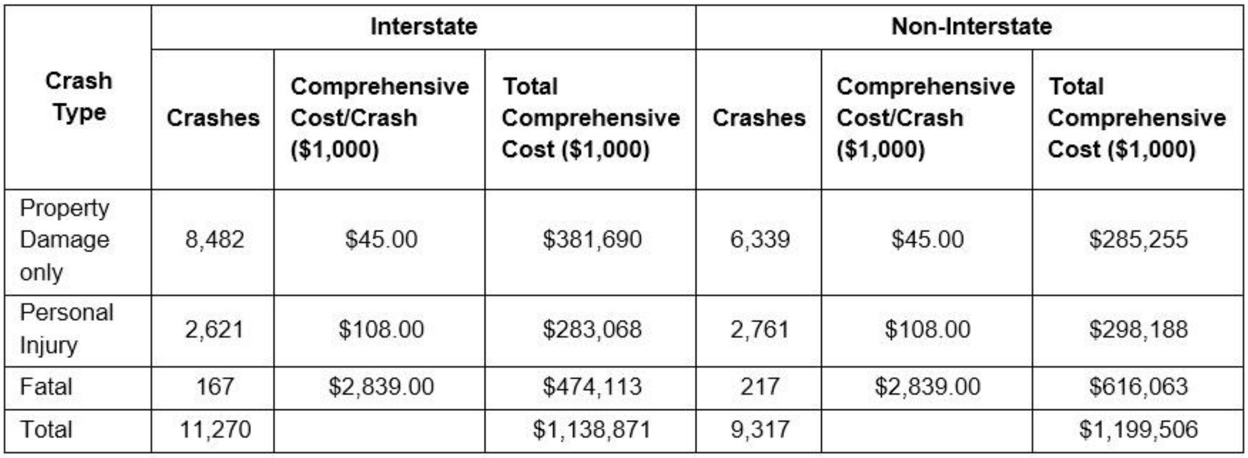
Table 17. Wyoming DOT comprehensive crash unit costs (2022 dollars).



Severity	Comprehensive Crash Unit Cost
K/A	$2,839,000
B/C	$108,000
O	$45,000

The total cost of FR crashes in Wyoming was obtained using these three average unit costs for fatal, injury, and property damage only. Then, an average cost per crash was derived to be used in the benefit calculation. Table 18 summarizes the comprehensive cost of FR crashes in Wyoming.

Table 18. Comprehensive Costs of Friction-related Crashes 2010-2019 in Wyoming



Crash Type	Interstate			Non-Interstate		
	Crashes	Comprehensive Cost/Crash ($1,000)	Total Comprehensive Cost ($1,000)	Crashes	Comprehensive Cost/Crash ($1,000)	Total Comprehensive Cost ($1,000)
Property Damage only	8,482	$45.00	$381,690	6,339	$45.00	$285,255
Personal Injury	2,621	$108.00	$283,068	2,761	$108.00	$298,188
Fatal	167	$2,839.00	$474,113	217	$2,839.00	$616,063
Total	11,270		$1,138,871	9,317		$1,199,506

The average comprehensive costs are estimated at $101,053/crash ($1,138,871,000/11,270) for the interstate and $128,743/crash ($1,199,506,000/9,317) for the non-interstate highways. This average cost per crash was used for further calculation.

3.3.7 Advantages of Reducing Crashes: Exploring the Benefits

The reduction in the number of crashes quantifies the safety benefits. The potential crash reduction is calculated from the marginal effects of expected crashes. This reduction will then be multiplied by the average cost per crash to acquire the benefit of the crash reduction. According to Table 15, for the interstate model, an increase in the level of friction number from FN(35-40) to FN(>50) results in a decrease in the marginal effect on the probability of FR crashes from 4.68 percent to 1.28 percent. If the friction number level is kept at FN(>50), the probability of reducing FR crashes is 3.4 percent, resulting in a cost savings of $40.8 million. Similarly, for the non-interstate model, an increase in the level of friction number from FN(35-40) to FN(>50) leads to a decrease in the marginal effect on the probability of FR crashes from 8.04 percent to 1.50 percent. Maintaining the friction number level at FN(>50) can reduce FR crashes by 6.54 percent and save $74.5 million.

Factors such as adverse road conditions, inclement weather, pavement surface, horizontal curves, and a combination of horizontal and vertical curves increase the likelihood of FR crashes. However, when these factors are used as an interaction term multiplied by specific friction number levels, the crash probability decreases significantly, as discussed in the previous section. Therefore, the crash reduction benefits for the interaction terms are shown in the following tables.

Table 19. Crash reduction benefit in the Interstate Model

Variables	Marginal Effect	Number of Crash reduction	Total Comprehensive Cost of the reduced crash ($1,000,000)
FN (> 50) * Adverse Road	-1.26%	117	15.09
FN (40-45) * Asphalt	-1.11%	103	13.27
FN (45-50) * Asphalt	-2.33%	217	27.99
FN (> 50) * Curve	-0.58%	54	7.01
FN (> 50) * Hor & Ver Comb	-0.89%	83	10.65
FN (40-45) * Median Width	-0.004%	0.4	0.05
FN (45-50) * Median Width	-0.01%	1	0.16
FN (> 50) * Right Shoulder Width	-0.42%	39	5.08
FN (45-50) * Left Shoulder Width	-0.33%	31	3.96

Table 20. Crash reduction benefit in the non-Interstate model

Variables	Marginal Effect	Number of Crash reduction	Total Comprehensive Cost of the reduced crash ($1,000,000)
FN (> 50) * Adverse Road	-3.26%	368	37.17
FN (> 50) * Inclement Weather	-0.67%	75	7.59
FN (40-45) * Asphalt	-3.51%	396	39.97
FN (45-50) * Asphalt	-3.52%	397	40.10
FN (40-45) * Concrete	-2.73%	307	31.04
FN (45-50) * Concrete	-3.33%	375	37.93
FN (45-50) * Curve	-0.66%	74	7.51
FN (> 50) * Hor & Ver Comb	-2.44%	275	27.76
FN (35-40) * Median Width	-0.16%	18	1.87
FN (> 50) * Median Width	-0.05%	5	0.53
FN (45-50) * Right Shoulder Width	-0.19%	22	2.18
FN (> 50) * Right Shoulder Width	-0.38%	43	4.35

From Tables 19 and 20, maintaining pavement friction FN>50 on adverse roads would decrease the cost by $15.09 million and $37.17 million by reducing FR crashes for the interstate and non-interstate. Similarly, maintaining FN>50 in inclement weather would decrease the FR crash cost by 7.59 million. The total cost savings in pavement friction FN(45-50) of asphalt pavement is higher than the FN(40-45). Similarly, in every case, cost savings are higher for the higher level of pavement friction. The only exception is on the non-interstate highway, which has FN(35-50) and FN(>50). Wider medians provide better safety performance by reducing the risk of head-on collisions and allowing more room for errant vehicles to maneuver. Therefore, it is possible that the non-interstate highway with FN(35-50) and FN(>50) has a wider median width, which could have contributed to lower crash costs even at lower levels of pavement friction. It may be possible that the lower cost savings observed for the FN(35-50) range in the non-interstate highway are due to the lower traffic volumes and lower speeds on this type of road, which may result in a lower overall crash cost reduction compared to the higher friction level.

Based on the findings discussed in the previous sections, it is recommended to maintain pavement friction levels at FN(>50) to reduce the probability of FR crashes, particularly in adverse weather and geometric conditions.

3.3.8 Treatment Costs

Improving the surface texture of pavement is critical to enhancing its friction capabilities, and there are various treatments available for this purpose depending on the type of pavement - whether it is asphalt or concrete. High friction surface treatments (HFST), Thin Hot Mix Asphalt (HMA) overlay, Open-graded friction course, Ultra-thin bonded wearing course, Chip seal (seal coat), Slurry seal, micro surfacing, Diamond grinding, Grooving, Micro-milling, Short blasting/abrading, Cape seal, and Scrub seal are some of the treatments available to improve pavement friction (FHWA 2022).

Among these treatments, HFST is commonly used among state DOTs, with 21 adopting it as a major treatment for asphalt pavement, and diamond grinding has also been extensively used and demonstrated to improve the macrotexture properties of concrete pavement (Correa and Wong 2001; Elkhazindar et al. 2022). HFST reduces crashes, injuries, and fatalities associated with friction demand issues, such as during wet conditions and roadway geometrics. According to FHWA, HFST is estimated to reduce wet crashes by 83 percent and total crashes by 57 percent (FHWA 2022). Although the cost of HFST is relatively high - ranging from $22 to $35 per square yard - its durability makes up for the initial high cost since the treatments have at least a 10-year life cycle. A recent report shows that the average cost for HFST treatments is \$27/yd^2, and the average cost of an HMA overlay for a longer section is \$10/yd^2 (Sprinkel et al. 2015).

Diamond grinding, on the other hand, has a unit cost ranging from $1.50 to $5.00 per sq. yd, with an average cost of $2.75 per sq. yd reported by the Pennsylvania Department of Transportation in Kentucky over a 5-year period. Therefore, for 0.1 miles of road (528 ft) with two 12-ft lanes, the cost for an HFST treatment, HMA overlay, and diamond grinding would be $38,016, $14,080, and $3,872, respectively, considering the unit cost of \$27/yd^2, \$10/yd^2, and \$2.75/yd^2.

3.3.9 Benefit to Cost Ratios

Benefit-Cost Ratio evaluates a project's economic advantages and disadvantages by quantifying its benefits and costs in monetary terms to determine the net welfare change, including cost savings and increases in welfare disbenefits and welfare reductions for affected groups. When assessing the benefits from prevented crashes as predicted using the developed models, it becomes clear that regardless of the treatment selected ($14,080, $38,016, or $3,872 per 0.1-mile section), increasing the friction has a net positive economic effect.

Chapter Summary

Crash prediction models, also known as safety performance functions (SPFs), were developed in this study for different functional classes of roadways. SPFs were developed for total crashes and equivalent property-damage-only (EPDO) crashes to investigate the effects of pavement friction, roadway geometry, road surface conditions, and vehicle body types on traffic crash frequencies. Crash data, roadway geometric design data, and friction data obtained from the Wyoming Department of Transportation (WYDOT) were processed to develop the SPFs. The results of the SPFs revealed that lower friction numbers not only increased the occurrences of total crashes but also increased the occurrences of EPDO crashes. This suggests that maintaining adequate friction levels reduce both total and EPDO crashes. Several geometric characteristics of roadways were found to be significant from the results of the SPFs. Upgrades and downgrades were found to increase EPDO crashes in most facilities. Tangent segments were found to reduce total crashes but increase EPDO crashes. When road surface condition was considered, it was found that dry and wet road surfaces were positively associated with both total and EPDO crashes. The average annual daily traffic (AADT) volume, an exposure measure, was positively associated with the frequencies of total crashes and EPDO crashes, assuming that all else was unchanged. The results from the SPFs would be beneficial in identify locations that are at risk of experiencing crashes because of low pavement friction numbers.

The safety of intersections has been the focus of many studies since intersections are considered hazardous zones of road networks. Identifying the main contributing factors of severe traffic crashes at intersections is crucial to implementing appropriate countermeasures. We investigated the major contributing factors to crash injury severity at intersections, particularly pavement surface friction. Nine years of Intersection crash data in Wyoming has been analyzed for this study. The random forest technique was employed to identify the critical variables influencing crash injury severity risk. Also, a Bayesian ordinal probit model was developed to explore the relationships between such risk and the crash contributing factors. As per the random forest model's results, pavement friction has a strong impact on crash injury severity risk along with using safety restraints, intersection type, signalized or unsignalized, reckless driving, and crash type. The results of the Bayesian model demonstrated that higher pavement surface friction levels and proper use of restraints reduced the likelihood of severe injury. Based on these findings, several countermeasures may be proposed, such as those of pavement friction requirements, driver's education, and traffic law enforcement to mitigate injury severity concerns at intersections.

The major contributing factors of FR crashes sustained due to different variables, including road surface condition, weather, vertical and horizontal curves, and especially pavement surface friction, utilizing data from WYDOT belonging to the years 2010 through 2019. The 10-year crash data in Wyoming showed that, on average, 38 percent and 18 percent of crashes happen in interstate and non-interstate, respectively, due to wet weather, runoff, and swerve due to slippery what are considered as FR crashes. The importance of the variables was examined using the statistical analysis- binary logistic regression model and by determining marginal effects. As per its results, pavement surface friction, adverse roads, inclement weather, pavement surface type, median, shoulder, and geometric characteristics all influenced FR crashes. The intent of this research was to investigate the effects of pavement surface friction on FR crashes for interstate and non-interstate highways, and analysis was done accordingly. Both analyses confirmed that increasing the level of Friction number decreases the probability of FR crashes. The study's key findings, which were based on the assumption that all other factors were held constant, are summarized below.

Pavement friction was found significant, and the modeling results demonstrated that increasing the friction number from 35-40 to >50 would significantly decrease the risk of FR crashes. Horizontal curves and the combination of horizontal and vertical curves were found to increase FR crashes in both models. Therefore, tangent segments were found to experience fewer crashes. The presence of paved shoulders was found to reduce FR crashes. The number of FR crashes was found to be less when medians and shoulders were wider, though the effect of median width is negligible. Road surface condition was also found to be a critical factor influencing FR crashes. This study's unique contribution was identifying significant parameters affecting FR crashes and recommending an appropriate friction level with a cost-benefit ratio. This study also shows the crash reduction benefits of improving pavement friction. After the economic analysis, this study recommends maintaining pavement friction above 50. The findings will also help WYDOT in developing a more effective friction treatment policy for interstate and non-interstate highways.

CHAPTER 4: INCORPORATING PAVEMENT FRICTION MANAGEMENT INTO PAVEMENT ASSET MANAGEMENT SYSTEMS: STATE DEPARTMENT OF TRANSPORTATION EXPERIENCE

4.1 Background

For decades, transportation agencies have been studying the main components of pavement friction and associated characteristics to define appropriate maintenance and treatments on roadways. This is because there is a direct interaction between vehicle's tires and road surface textures and conditions (Ilse, 2015). Therefore, there is an imperative need to maintain the efficiency of the pavement friction in order to enhance the road safety by de-creasing the friction-related crashes (Najafi et al., 2017). The FHWA encourages transportation agencies, including governmental entities, to incorporate Pavement Friction Management (PFM) systems to address the road network friction demands on the different road classifications (Friction Management, 2022). Consequently, states' DOTs utilize various engineering practices to collect and analyze the friction-related data, crash data, and traffic data. However, state DOTs tend to employ different techniques and policies to manage the pavement performance and treatments related to pavement friction. Despite the previous efforts in studying pavement friction characteristics, some agencies are not supported with a clear guide and suitable approaches to maintain the pavement friction in cost-effective manners. Some agencies follow a proactive management system to develop multi-year maintenance plans while other agencies address only locations displaying friction-and-safety-related issues. Hence, the maturity levels of friction management vary among states where some programs are quite basic while others can be quite developed and sophisticated. The current practices of friction management among agencies, especially state DOTs, vary significantly due to different budget levels, strategic objectives, and climate conditions. Some agencies integrate the friction management to the state Pavement Management System (PMS) with preliminary and subjective analyses for decision making. Other programs integrate more advanced analysis and modelling to cope with the wide range of fiction demands on different road classifications and specific geometric conditions. Due to these diversified practices in friction management, this study intends to provide a comprehensive review of the state-of-the-practice among the state DOTs. Exploring the methods to manage the pavement friction, used by state agencies in the nation, will help researchers and officials know more about the strategies towards an effective pavement friction management. It also presents opportunities to enhance the approaches of the followed programs and highlight the gaps of the current practices. In addition, studying the current strategies at the nationwide level will discover the limitations and assess the merits of state policies so that improving the strategies and the approaches of the pavement friction management is made possible to save costs and resources.

The objective of this study was to investigate the nationwide practices of PFM and related programs currently employed by state DOTs. The WYT2 center is interested in discovering all the other experiences in managing pavement friction in other states so that beneficial guidelines and recommendations can be developed for not only WYDOT but also the whole nation. To achieve this, an online survey was developed and disseminated to the officials of all state DOTs who are responsible for managing the pavement friction and involved in the decision making of friction-related treatments. The survey comprises questions covering most related practices and techniques in managing the pavement friction. Feedback from 32 state DOTs was received. This paper summarizes the findings of the survey. The study depicts the current status of PFM and provides constructive discussions on how to address the limitations in order to increase the effectiveness of friction management strategies and promote safety.

In this study, the PFM techniques are collected then statistically correlated and analyzed using online survey questionnaires. The objectives are to address the following:

- Discover the state policies and targets in utilizing the PFM on the roadways managed by state DOTs.
- Define the state testing protocols, equipment, and data collection techniques to measure the pavement friction on the state highways.
- Investigate the strategies established by state DOTs to provide adequate pavement friction levels, especially at locations requiring higher friction demands.
- Highlight the trends of pavement friction management practices and activities currently existed and define their relevant effectiveness.
- Provide the best practices of managing and planning the maintenance plans of pavement friction considering the feedback from both state DOTs participants and literature.

The ultimate goal of this study is to:

- Develop an appropriate pavement friction management framework and guidelines for the state DOTs.
- Enhance road safety by developing a detailed process to treat the pavement friction.

4.2 Methodology

4.2.1 Survey Questionnaire

In order to understand all official practices of pavement friction management in USA, the survey questionnaire was designed to address the current situations of the practices for state DOTs. The survey was sent out to 42 state DOTs representatives where it was forwarded to the responsible individuals (e.g., research, materials, management, or design personnel). Some states were excluded due to either the small size of its road network or the unavailability of appropriate contacts. Feedback from 32 state DOTs was received with a response rate of 76 percent. The participating states are highlighted on the map shown in Figure 8 and they represent almost 65 percent of the total size of the USA (US Census Bureau, 2012). According to the Highway Statistics (2019) and in terms of the size of road networks, the participating state DOTs owe more than one million kilometers of public roads which constitute almost 80 percent of the U.S. public road network. It is worth mentioning the participating states form diverse agencies with anticipated different goals and resources. They are also distributed in different climate zones (Highway Performance Monitoring System, 2014). Therefore, the results of the survey are expected to provide various practices of PFM and related programs which provide several recommendations. In addition, any trend observations found in the study are not expected to be biased due to the limited responses, the size of state DOT's road network, or climate conditions. The survey questionnaire is divided into four sections described below.

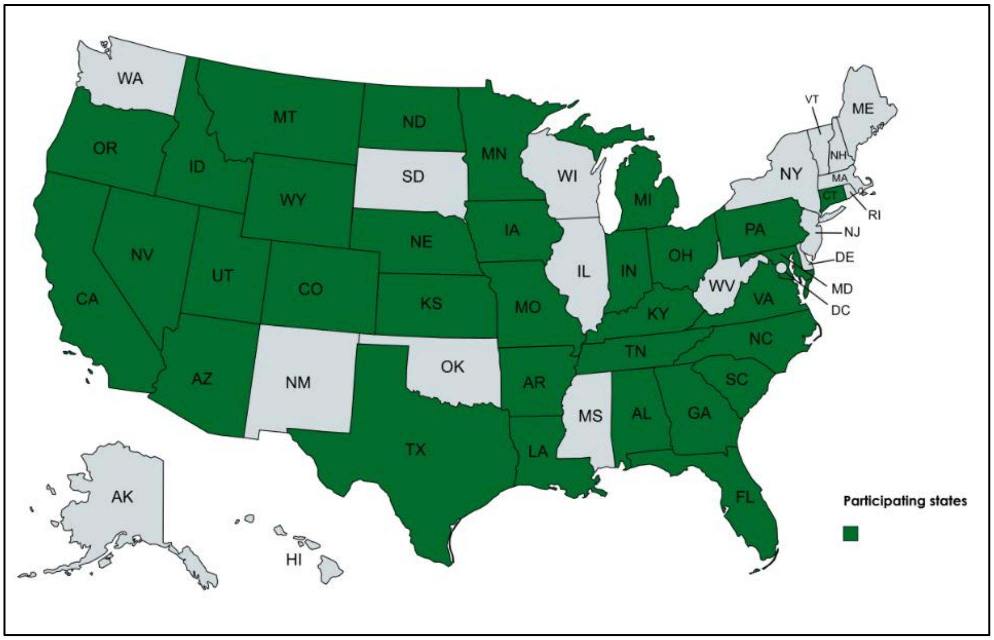


Figure 8. Map. Participating states in the Pavement Friction Management (PFM) survey of practice.

4.2.2 General Information

The first section of this survey intends to get some definition information about the agencies. It also investigates the general policy of skid resistance and pavement friction management in the state. In Addition, this section asks questions related to road classification and the main criteria chosen for testing and studying the pavement friction.

Furthermore, some questions in this section ask about the types of pavement surfaces used for measurements.

4.2.3 Data Collection

In this section, the survey discusses the methods used to measure the pavement friction and the protocols of data collections in terms of amounts and frequencies. It also discovers the devices used and their characteristics, including efficiency, ownership, and calibration. Moreover, the section solicits discussions of problems, limitations, and other concerns faced by state DOTs practitioners during the PFM data collection process.

4.2.4 Analysis and Performance

In this section, friction indices and types of analysis are explored among state DOTs to investigate if there is a specific technique followed for pavement friction performance modelling. In addition, the survey investigates if there are models or equations considered in the state DOT planning program to describe the effect of adding surface treatments on the friction performance overtime. Information about the minimum friction values and friction demand criteria are also collected in this section.

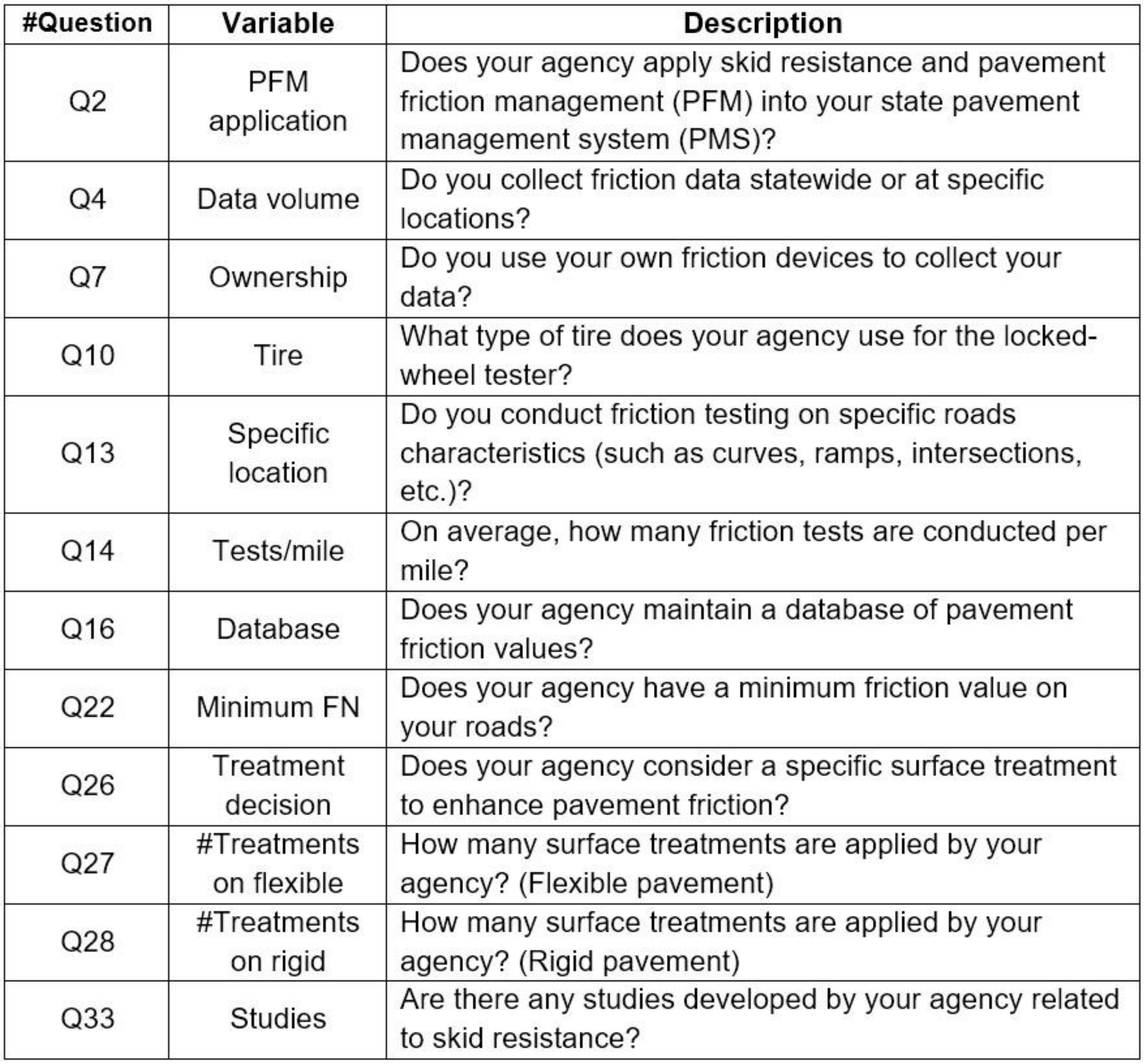
4.2.5 Treatments and Maintenance Planning

In this part of the survey, the practices of decision making and maintenance planning are collected from state DOTs to study if there is a standard techniques recommended by state agencies. The types of treatments followed on each pavement type are also investigated in this section. More questions are raised in this section to cover other aspects of maintenance and managing the pavement friction.

4.2.6 Data Correlation

A correlation analysis is key to explicate the relationships among the survey questions so that deeper interpretations can be attained from the respondent feedback. However, some survey questions are hard to analyze especially the multiple-response questions where more than one response is permitted. Also, the open-response questions are excluded from this analysis because they simply provide open discussions, and no statistical analysis can be considered. Some nominal questions in the survey are converted into scaled responses to enhance the statistical analysis. The single-response questions in the survey are filtered to include mainly the important aspects of managing the pavement friction. Table 21 lists the questions under investigation in addition to their defined variables and overall descriptions.

Table 21. Questions used in the correlation analysis and statistical tests.



#Question	Variable	Description
Q2	PFM application	Does your agency apply skid resistance and pavement friction management (PFM) into your state pavement management system (PMS)?
Q4	Data volume	Do you collect friction data statewide or at specific locations?
Q7	Ownership	Do you use your own friction devices to collect your data?
Q10	Tire	What type of tire does your agency use for the locked-wheel tester?
Q13	Specific location	Do you conduct friction testing on specific roads characteristics (such as curves, ramps, intersections, etc.)?
Q14	Tests/mile	On average, how many friction tests are conducted per mile?
Q16	Database	Does your agency maintain a database of pavement friction values?
Q22	Minimum FN	Does your agency have a minimum friction value on your roads?
Q26	Treatment decision	Does your agency consider a specific surface treatment to enhance pavement friction?
Q27	#Treatments on flexible	How many surface treatments are applied by your agency? (Flexible pavement)
Q28	#Treatments on rigid	How many surface treatments are applied by your agency? (Rigid pavement)
Q33	Studies	Are there any studies developed by your agency related to skid resistance?

The design of the defined variables is shown in Table 22. The statistical question was raised during the preparation of these data. Some state DOTs tend to show different practices in managing the pavement friction depending on the overall policy of PFM. Therefore, the study explored whether the response for Question 2 (in Table 21) would affect the distribution of responses on the detailed practices in the other questions. To address this, the correlations were determined between the "PFM application" and the other questions. Considering the type of each variable, the correlation methodology was different. Since no association between two scaled variables were studied, the normal Pearson correlation was not used in the correlation analysis of this study. Phi correlation is normally used for two non-parametric variables where both variables are dichotomous. Cramer’s V correlation was applied for nominal variables with more than two categories. For scaled variables, Eta correlation was used to determine the association with the main binary variable for Question 2.

Table 22. Types of variables for the studied survey questions.

Variable	Type	Label	Value
PFM application	Categorical (Binary)	No	0
		Yes	1
Data volume	Categorical	No response	0
		specific locations only	1
		statewide	2
		both statewide and specific locations	3
Ownership	Categorical (Binary)	No	0
		Yes	1
Tire	Categorical	Do not use it/No response	0
		Smooth	1
		Ribbed	2
		Both	3
Specific location	Categorical (Binary)	No	0
		Yes	1
Tests/mile	Ratio	-	Scale
Database	Categorical (Binary)	No	0
		Yes	1
Minimum FN	Categorical (Binary)	No	0
		Yes	1
Treatment decision	Categorical (Binary)	No	0
		Yes	1
#Treatments on flexible	Ratio	-	Scale
#Treatments on rigid	Ratio	-	Scale
Ownership	Categorical (Binary)	No	0
		Yes	1

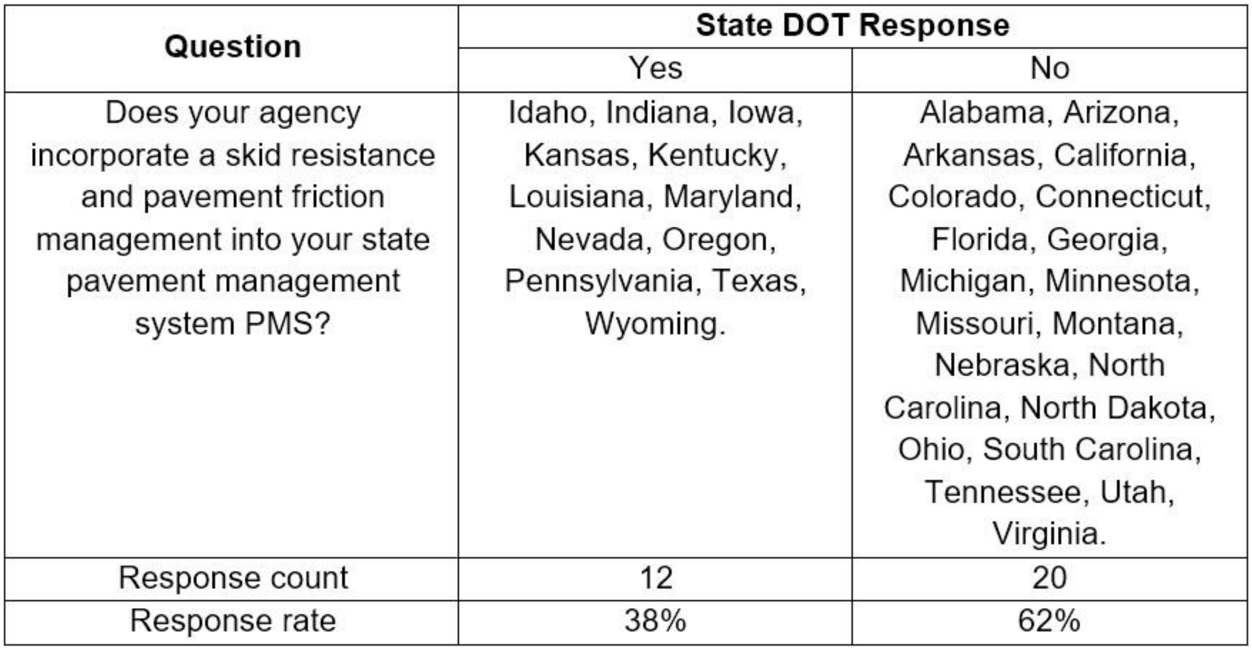
4.3 Survey Results

The discussions about the results and potential enhancements are introduced according to the main components of the PFM shown in the following sections.

4.3.1 Policy of Management

First of all, it was crucial to ask the state DOT representatives if the current practices of dealing with pavement friction issues are conducted through a typical PFM and whether it is incorporated into the state PMS program. The results of this inquiry are shown in Table 23. Out of the 32 participating DOTs, only 12 states follow a systematic practice to manage the pavement friction. The majority of DOTs (62 percent) do not conduct a typical PFM on a regular basis. They mainly address the pavement friction on roads by request when there is a skid resistance safety concern flagged by the safety program, especially for elevated wet weather crashers. Other DOTs, such as Colorado Nebraska, and North Dakota, do not either test or collect pavement friction at all. Ohio DOT is not permitted to apply a proactive friction testing and they only consider triggered requests such as wet crashes, front line workers observance, and law enforcement agency requests, among others.

Table 23. State DOT feedback of the general policy of the pavement friction management.



Question	State DOT Response	
	Yes	No
Does your agency incorporate a skid resistance and pavement friction management into your state pavement management system PMS?	Idaho, Indiana, Iowa, Kansas, Kentucky, Louisiana, Maryland, Nevada, Oregon, Pennsylvania, Texas, Wyoming.	Alabama, Arizona, Arkansas, California, Colorado, Connecticut, Florida, Georgia, Michigan, Minnesota, Missouri, Montana, Nebraska, North Carolina, North Dakota, Ohio, South Carolina, Tennessee, Utah, Virginia.
Response count	12	20
Response rate	38%	62%

The applied pavement friction testing and management were surveyed in terms of functional classification. As shown in Figure 9, state DOTs mainly apply relevant friction measurements and programs on both national and non-national highway systems.

However, higher practices are noticed on interstate and state highway systems. Other responses are received for only specific roads received safety concerns as explained previously. Another aspect of the PFM policy was asked if the pavement friction data is collected statewide or at specific locations only. Out of the 29 responses received, 35 percent of state DOTs collected the data at specific locations only while 65 percent collected the data either at the statewide level only or at both statewide and specific locations. It is interesting to see that none of the states responding to the survey collect friction data on county roads.

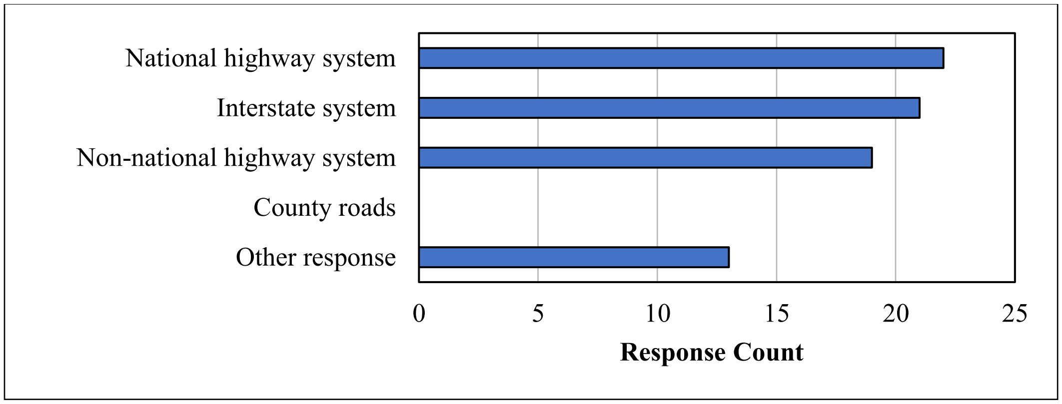


Figure 9. Chart. Road classifications tested for friction by state DOTs.

For those who collected pavement friction data at specific locations, a follow up question asked the participants about the criteria of selecting such locations. As shown in Figure 10, there is no doubt that the safety concern is the major issue when studying the pavement friction needs of roads. The research needs are also noticed as a contributing factor among state DOTs for collecting the pavement friction data due to the current studies of surface treatments, especially for the sponsored test sections of the HFST treatments which are mentioned by multiple DOTs. Other responses are mentioned for the selection criteria of testing pavement friction such as district requests, bridge decks, intersections, among other needs. The last aspect related to the policy of PFM and related programs is the type of pavement surface tested by the state DOTs. Out of the 29 responses, 26 state DOTs consider all types of pavement surfaces for friction study and testing. California and Montana DOTs consider primarily asphalt pavement for testing friction. Georgia DOT revealed that they only test pavement friction for HFST studies. They have sponsored several studies to investigate the effectiveness of HFST treatments to reduce potential run-off-road (ROR) crashes on specific locations such as sharp curves (Tsai et al., 2018).

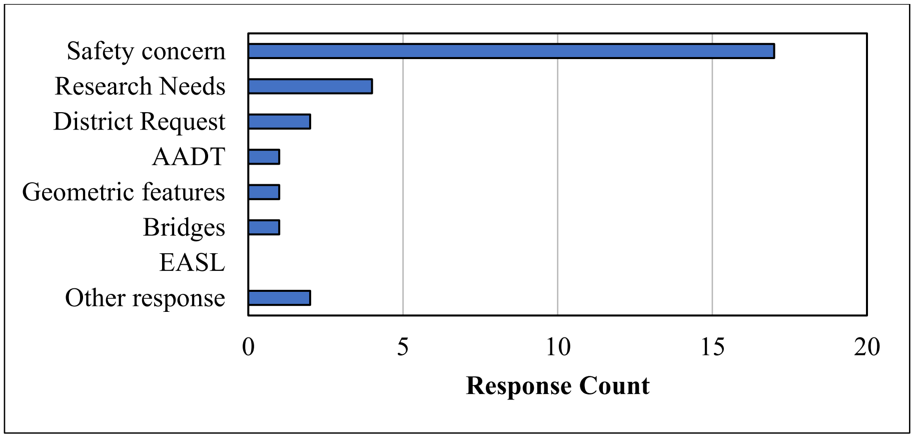


Figure 10. Chart. Selection criteria of testing pavement friction at specific locations.

4.3.2 Friction Testing and Data Collection

Data collection is a key component for an effective asset management system. When it comes to pavement friction, limited standards and testing are available for measuring the skid resistance levels on roadways. The results of the current survey reveal that quite similar practices are followed by state DOTs for pavement friction testing protocol, as shown in Figure 11. With the exemption of Nebraska, North Dakota, and Colorado participants, 26 state DOTs (90 percent) reported using the locked-wheel friction tester (ASTM, 2020). For decades, the locked-wheel testing has been the most acceptable friction testing method because it measures pavement friction response accurately and directly. It also represents one of the high-speed measurements which is practical for a network-level data collection process. The locked-wheel tester can be operated using either smooth or ribbed tires. According to the practice of state DOTs, 16 states use the ribbed tire and seven states use the smooth tire while four other DOTs use both types. However, the locked-wheel tester provides some limitations where it applies mainly on straight segments and within a specific sample length and operating speed (CPFM, 2022). The friction measurements from locked-wheel tester may not be valid on segments with high degrees of curvature. In addition, the locked-wheel methodology is discrete in nature and cannot provide a continuous format in measuring changes in the friction values on the road network. As a consequence, other methodologies, such as continuous pavement friction measurements (CPFM), were established to monitor the changes in friction levels along roads continuously, especially through tan-gents, curves and intersections. The CPFM was initiated by road authorities in European countries, including New Zealand and becomes a common practice in Australia and some airport authorities in the U.S. to measure friction on runways. That's why some state DOTs started to integrate other methods, including side-force and fixed-slip, to adopt the continuous measurements and overcome the limitations of using traditional locked-wheel friction measurements. However, such developments are noticed to be limited among participating state DOTs, as shown in Figure 11. For example, the North Carolina DOT employed a new tool of testing including measurements with the locked-wheel trailer currently used by NCDOT, a Grip Tester, and a SCRIM (Side-Force Coefficient Routine Investigation Machine (Izeppi et al., 2017). Other responses were received from Arizona DOT where they use the Dynatest 6875H Highway Slip Friction Tester (HFT) which can map friction values continuously at very short intervals (FHWA, 2014). In Ohio, visual and tactile subjective evaluations may be applied if the 64.4 km per hour (40 mph) speed of the locked-wheel tester cannot be operated.

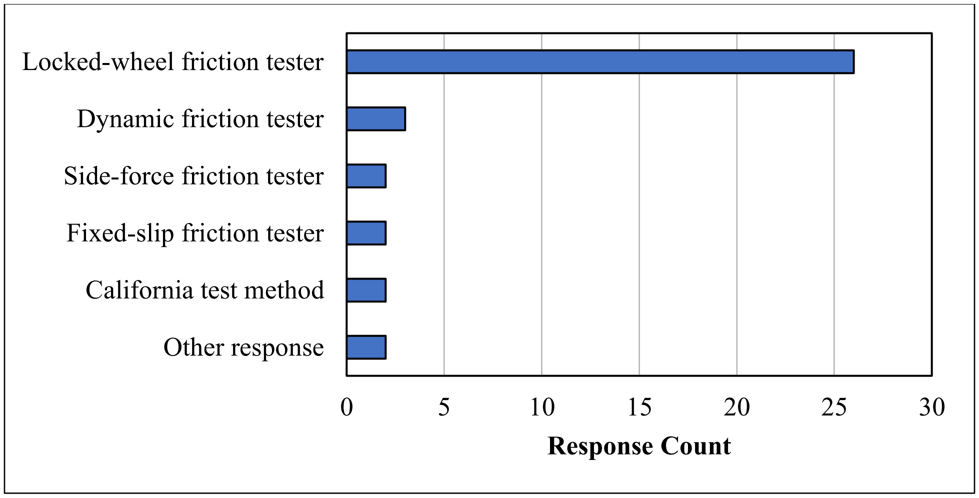


Figure 11. Chart. Pavement friction testing methods followed by state DOTs.

In terms of equipment ownership, 25 state DOTs (79 percent of participants) use their own friction devices to collect pavement friction data. All of these 25 DOTs were asked if they calibrate their devices, and their responses were affirmative. Those who do not own the friction testing equipment mainly hire a contractor to perform the friction testing. The data collection frequency was noticed to vary among the states as shown in Table 24. Collecting the data annually is found to be observed for nine DOTs while the friction data is collected as requested by six DOTs. Other DOTs collect the data on a frequency range from two years up to six years depending on road classification (i.e., the higher the road class is, the more frequent the friction data is collected). Some DOTs, such as Colorado, obtain friction data only through sponsored researchers while California DOT mentioned that the friction data is infrequently collected. With all the previously mentioned practices of data collection, the participants were asked if they maintain a database for pavement friction values, and 11 state DOTs responded “negative”. This is due to either the limited practices of pavement friction management or the reactive approach followed to address locations with higher monitored friction-related crash rates. Another possible interpretation for the lack of such a database is the fear of tort litigation. Pavement friction is a safety concern and some agencies may not have the capability to update their friction database in a timely manner. At some locations on the road network, pavement friction can change very quickly. With such a dated friction database, these agencies might be claimed liable for friction-related crashes.

Table 24. Pavement friction data collection frequencies.

Question	State DOT Response				
	By request	Every year	Every 2 years	Research needs only	Other response
How frequently does your agency collect friction data?	Arizona, Missouri, Montana, Ohio, Pennsylvania, Virginia.	Connecticut, Kentucky, Michigan, Minnesota, Nevada, Texas, Utah.	Oregon, Tennessee, Wyoming.	Colorado	Alabama, California, Florida, Georgia, Idaho, Indiana, Iowa, Kansas, Louisiana, Maryland, North Carolina, South Carolina.
Response count	6	7	3	1	12
Response rate	21%	24%	10%	3%	41%

The last aspect raised for data collection is testing the pavement friction on specific road characteristics. As previously mentioned, curves, ramps, and intersections display higher friction deterioration rates due to the frequent stop and slowing down conducted by travelling vehicles as well as the additional forces applied to the vehicle. Hence, the survey asked the participant if they collect friction data on these road facilities, and 19 (60 percent of participants) state DOTs responded “negative”. Other 11 DOTs mentioned that they collect such data by request when there is a safety concern. Kentucky DOT integrates particular mix design to enhance aggregate performance and they may test such mixtures on these specific road elements. Arizona and Virginia DOT combine the locked-wheel with the side-force equipment to test the pavement friction on rams, curves, etc. Indiana DOT collects pavement friction on bridge decks regularly.

4.3.3 Performance Measurements

In order to employ a proactive management for pavements, highway agencies must assess actual pavement condition and forecast future performance of the pavement asset so that multi-year maintenance plans can be developed. For pavement friction, there are few performance indices that describe the friction level. Yet, the friction number (FN), also known as the skid number (SN), is found to be the most applied index by state DOTs for describing the statewide friction performance, as shown in Figure 12. This is due to the use of locked-wheel tester which mainly measures the FN value.

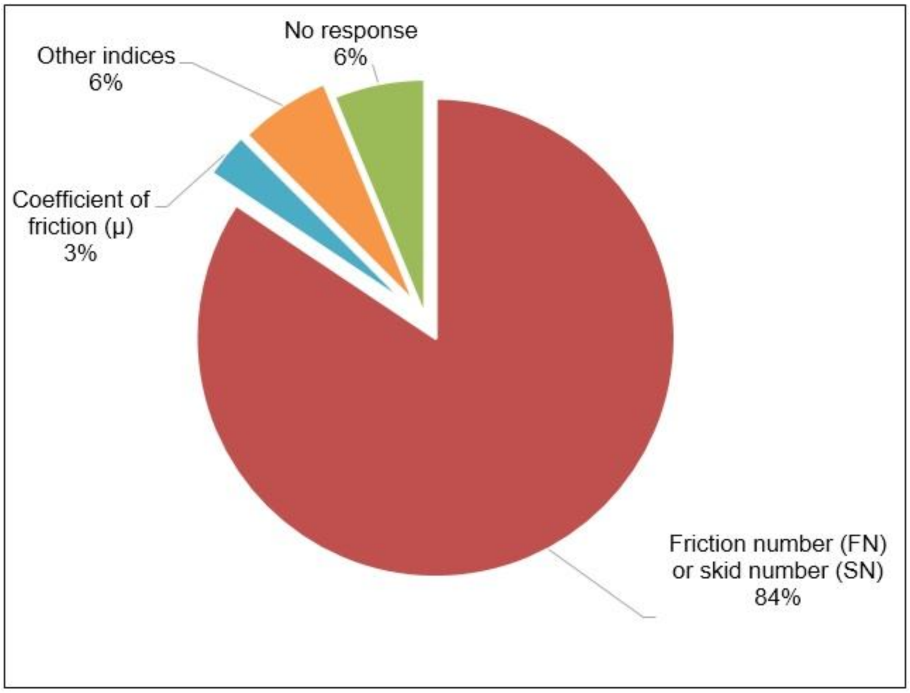


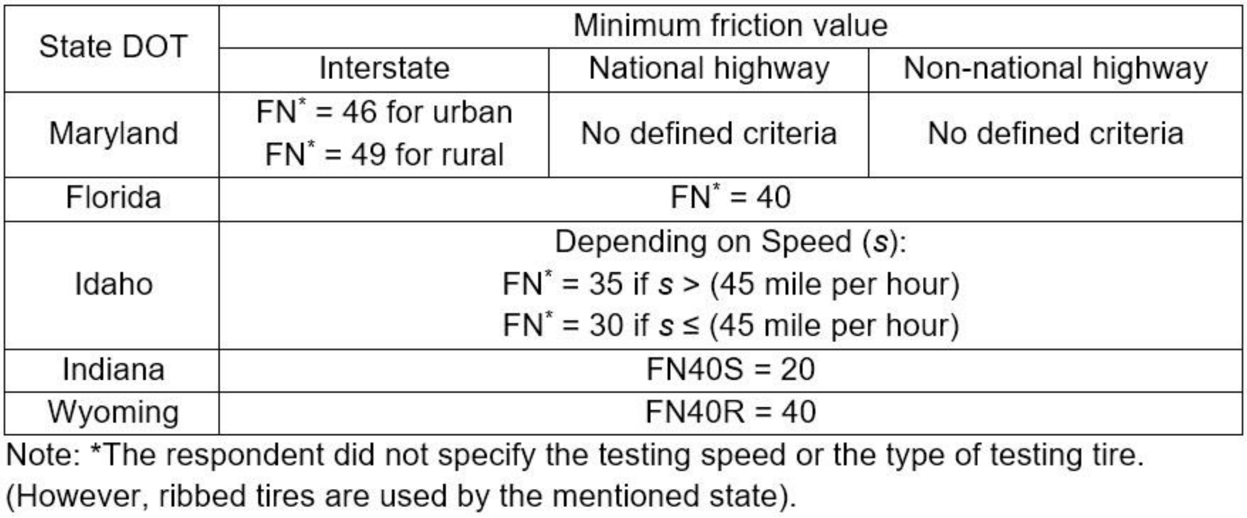
Figure 12. Pie-Chart. Pavement friction indices commonly used by state DOTs.

In general, friction deterioration occurs under many effects, including environmental effects and traffic applications, after years from opening the road to traffic (Li et al., 2011). The survey asked state DOTs participants if they developed a performance model describing the deterioration of pavement friction over time. Only two state DOTs provided some statistical equations that can predict friction values. The majority of state agencies do not consider any future predictions of the pavement friction to proactively consider a maintenance plan. This links with the current practices of addressing mainly the road with elevated crash rates and monitored friction-related issues.

4.3.4 Friction Demands and Categories

Another profound step in managing pavement friction effectively is to determine the friction requirements for each section of the roadway. Friction demand is described as the amount of friction required on the pavement surface to achieve safe driving maneuvers without slipping or sliding. Two friction categories are recommended to investigate: the investigatory level and the intervention level. The investigatory level is when the skid resistance reaches a low value that needs to be monitored to assess its effectiveness on crash rates. It is used to plan for some preventive and restorative treatment actions. The intervention level is the lowest acceptable friction value at which an agency must take immediate corrective action. The survey asked the participants if state DOTs consider minimum friction values as thresholds for maintenance. Excluding the “no response” from South Carolina and Nebraska DOTs, only five state DOTs (16 percent of participants) consider minimum friction values. Table 25 lists the minimum friction values derived from the locked wheel tester. It looks like the intervention level commonly ranges from 40 up to 49 for ribbed tires depending on the testing speed. No state DOTs mentioned investigatory levels considered to address the causes of low friction demands or the plans to overcome the defects. This is again consistent with the reactive approach followed by state DOTs to address only friction-related safety issues. The criteria of the defined intervention levels include pavement conditions, geometric features, functional classification, and speed limits.

Table 25. The minimum intervention friction levels considered by the surveyed state DOTs.



State DOT	Minimum friction value		
	Interstate	National highway	Non-national highway
Maryland	FN* = 46 for urban FN* = 49 for rural	No defined criteria	No defined criteria
Florida	FN* = 40		
Idaho	Depending on Speed (*s*): FN* = 35 if *s* > (45 mile per hour) FN* = 30 if *s* ≤ (45 mile per hour)		
Indiana	FN40S = 20		
Wyoming	FN40R = 40		

Note: *The respondent did not specify the testing speed or the type of testing tire. (However, ribbed tires are used by the mentioned state).

4.3.5 Treatments and Decision Making

Surface treatments are very essential to enhance the surface texture and improve the pavement friction capabilities. All state highway agencies are required to improve their road safety by using the suitable treatments. State DOTs are expected to consider different types of pavement treatments depending on their own practices and experiences. For this topic, the survey asked state DOTs participants if they consider specific surface treatments to enhance the pavement friction and the results are shown in Figure 13. Eight state DOTs (25 percent of participants) don’t apply surface treatments specifically to address the pavement friction. However, surface treatments are still applied to maintain the pavement condition as part of the state PMS.

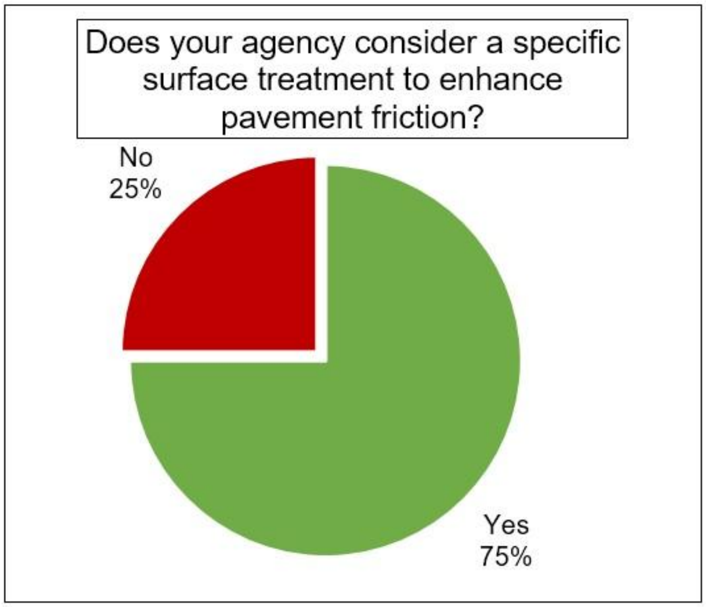


Figure 13. Pie-Chart. State DOTs feedback of about the pavement friction treatment practice.

There are special treatments considered for the friction of pavement depending on the type whether asphalt or concrete pavement. In terms of treatments for each type, the sur-vey collected the statewide practice of the participating state DOTs. Figure 14 summarizes the types of surface treatments for flexible asphalt pavement. First, 21 state DOTs adopt the HFST as a major treatment and it is one of the most common applied treatments among state DOTs. Most of participating state DOTs who apply friction treatment on asphalt do not use a single type. Rather, at least two different types are considered for roads depending on the friction needs and expected performance, in other words, the local experience. Kansas DOT reported that they have kind of decentralized practice and they follow a field evaluation process to select the suitable treatment because it is a rare situation having friction-only problems. However, if there is any problem related to friction, they prefer choosing the HFST as well.

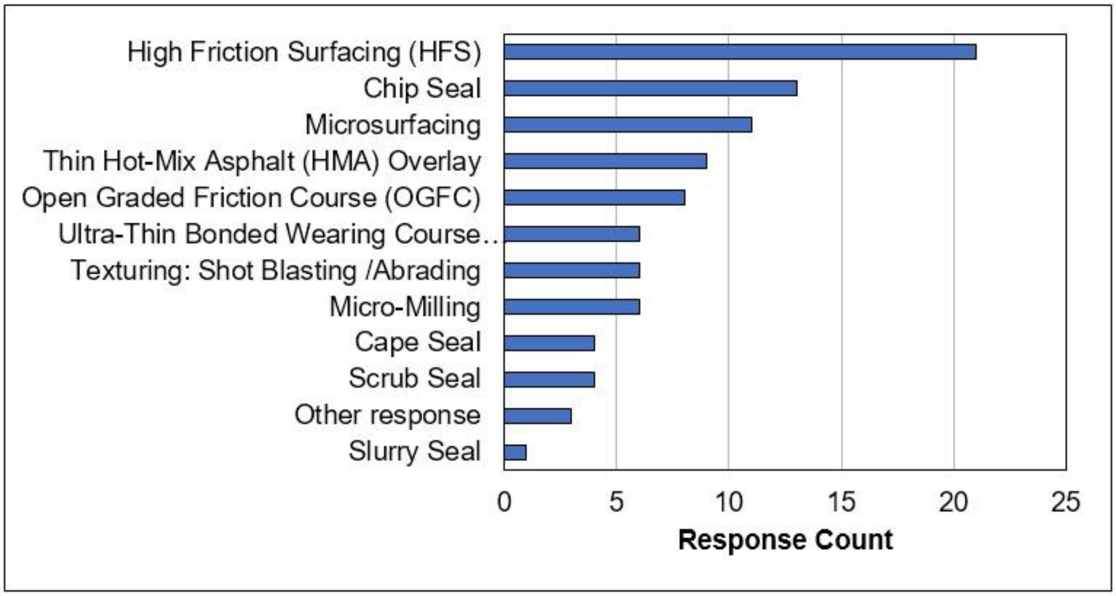


Figure 14. Chart. Types of pavement friction treatments considered for asphalt pavement.

For rigid pavement, Figure 15 shows the common treatment types employed by state DOTs. Diversified practices are noticed for maintaining the friction of concrete pavement. But generally, diamond grinding is the most common applied treatment which was proven to significantly enhance the macrotexture characteristics of pavement (Correa and Wong, 2001). Another notice is that HFS is not very common on rigid pavement compared to its application on asphalt pavement among state DOTs. Only 11 state DOTs reported their use of HFST on rigid pavement which represents almost one half of the state DOTs responded applying HFST on flexible pavement. Similarly, to flexible pavement, the treatments are not solely used but more than two treatment options are considered on rigid pavement in each state DOT. Other responses were received where Nevada DOT applies asphalt crumb rubber overlay (Khalili et al., 2016). Also, Alabama DOT combines diamond grinding and grooving for friction maintenance on rigid pavements.

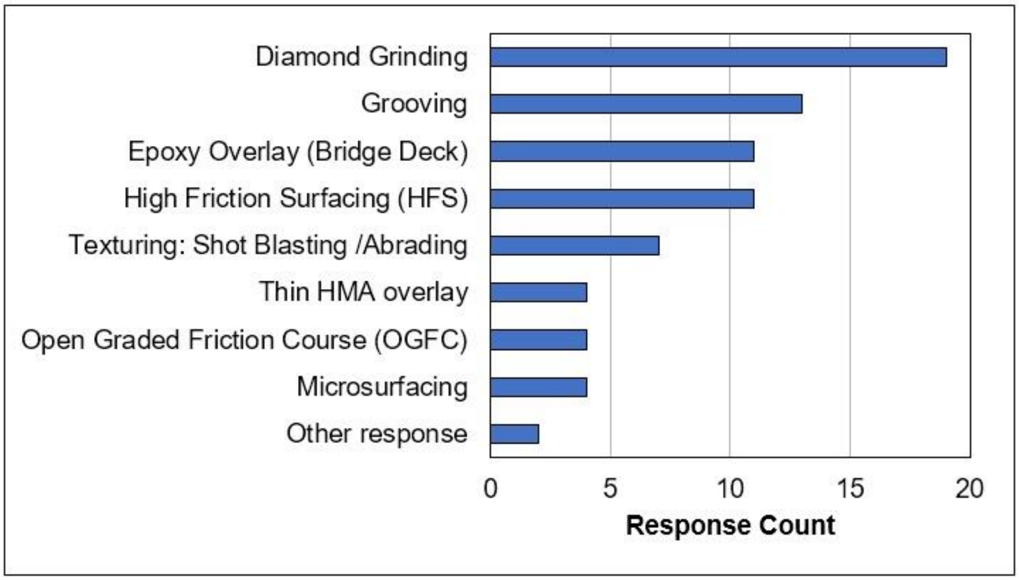


Figure 15. Chart. Types of pavement friction treatments considered for concrete pavement.

When it comes to the decision making, several criteria can be considered to select the appropriate treatment and maintenance strategy. It starts with knowing the effectiveness of each treatment on the different conditions. This can be done by monitoring the historical post-treatment performance of friction presenting by the friction index. The survey asked participants if they adopt such methodologies to correlate between friction values and coarse aggregate characteristics of surface treatments. The majority of the participating state DOTs (27 responses) did not develop such correlations. Maryland DOT implies that the consequence of each treatment is defined and integrated in the PMS decision trees. However, they are currently working on developing such correlations. Kentucky DOT mentioned that aggregates with higher acid insoluble content or higher $MgCO_3$ dolomitic aggregates were proved to provide higher friction. The last question related to decision making was about the main criteria/performance considered to enhance the overall friction demand on road network. The results of this question are shown in Figure 16. It is still evident that safety is the main motivation to select and address the pavement friction. Only three DOTs (Kentucky, Maryland, and Texas) develop a multi-year maintenance plan for friction. On the other hand, other DOTs do not think that dealing with pavement friction is conducted through a pre-defined criteria of asset management. Nevada DOT representatives, for example, believe that it is just internal contract-based maintenance projects. Other responses were received implying that friction does not drive a standard agency policy nor is considered by its own. Rather, it is mainly addressed within reactive activities to fix the friction demands.

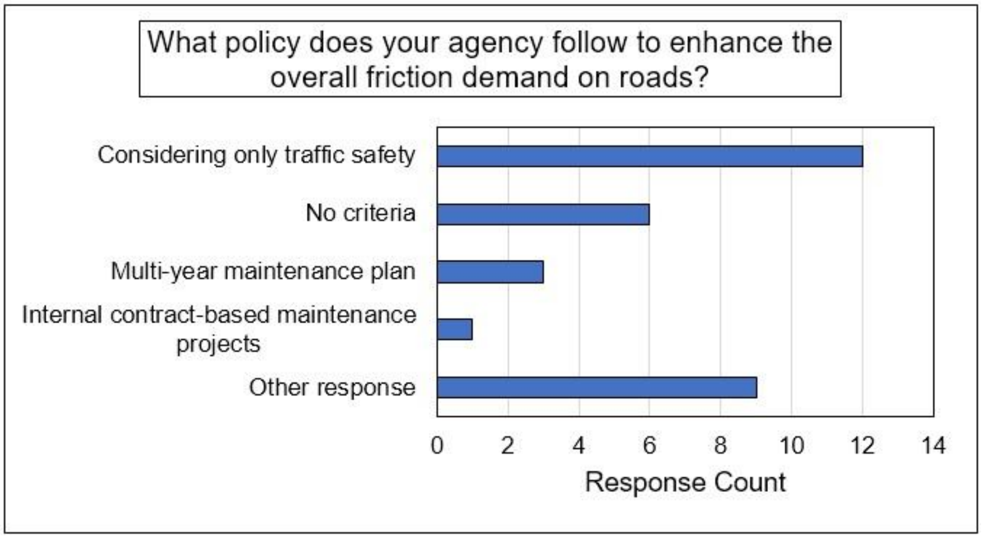


Figure 16. Chart. Overall criteria considered in decision making of managing pavement friction.

4.4 Statistical Analysis

The first results of the statistical analysis show the correlation between the different practices of managing pavement friction and the overall policy of management. The correlation results are shown in Table 26. Positive correlations are found between the PFM application and other practices. The interpretations of these factors imply that state DOTs applying a typical PFM as part of their asset management plan tend to have higher data volume of friction values, including a statewide database and data at specific locations with safety concerns (Crammer's V = 0.172). On the other hand, state not applying a typical PFM tend to collect friction values at specific locations only as requested. In addition, state DOTs applying PFM are more likely own their data collection devices, including the locked-wheel tester (Phi = 0.254) and they tend to use several types of testing tires (Cramer's V = 0.378). A minor association is found between collecting friction on specific locations, such as curves, ramps, and intersection, and the overall policy of managing friction (Phi = 0.119). This finding emphasizes that all state DOTs tend to collect pavement friction on these locations for safety concerns regardless of the PFM policy followed.

A strong association is found between the PFM policy and number of test sections required for measuring the pavement friction (Eta = 0.852). State DOTs applying a typical PFM tend to include higher number of test sections per mile for the benefit of data accuracy. Also, state DOTs applying a typical PFM tend to maintain a database for friction measurements for the benefit of decision making (Phi = 0.509). Limited number of state DOTs consider a minimum FN value on roads. However, an association from the overall PFM policy tends to affect the consideration of minimum FN values (Phi = 0.289). No association was found between the overall PFM policy and the decision to treat pavement frictions (Phi = 0.0). This implies that all state DOTs consider a surface treatment to enhance the friction performance of pavement at the statewide level or at specific locations as requested. In terms of the number of treatments considered by each state, state DOTs applying a typical PFM tend to include diversified treatments on the surface depending on the pavement type (for flexible: Eta = 0.2; for rigid: Eta = 0.503). Also, there is a higher research interest in which state DOTs applying typical PFM systems tend to sponsor related research projects compared to those who fix the pavement friction as requested (Phi = 0.279).

Table 26. Correlation Results between the policy of applying PFM and related practices.

Variable 1	Variable 2	Coefficient	Method
PFM application	Data volume	0.172	Cramer's V
PFM application	Ownership	0.254	Phi
PFM application	Tire	0.378	Cramer's V
PFM application	Specific location	0.119	Phi
PFM application	Tests/mile	0.852	Eta
PFM application	Database	0.509	Phi
PFM application	Minimum FN	0.289	Phi
PFM application	Treatment decision	0	Phi
PFM application	#Treatments on flexible	0.2	Eta
PFM application	#Treatments on rigid	0.503	Eta
PFM application	Studies	0.279	Phi

A decision about the previously described relationship can be made based on a cut off score that equals to 0.50. Hence, three associations can be further investigated which are number of test section per mile, maintaining database, and number of friction treatments on rigid pavement. The association between number of test sections per mile and the overall PFM policy is depicted in Figure 17. Those who provided no response due to the limited practices are excluded from the analysis. Tests of normality was conducted on the percentage of responses using Kolmogorov-Smirnov test. The null hypothesis states that there is no statistically significant difference between the values and the normal distribution. The results show that only the percentage of response for states applying PFM are significantly different from normal distribution (K-statistic = 0.345; df = 10; p-value < 0.001). Due to the violation of normality for one group, a non-parametric significance test was implemented using Mann-Whitney Wilcoxon. Although the results show insignificant difference between the mean rank of the two groups of state DOTs (Z = -0.397; p = 0.691), state DOTs applying a typical PFM tend to use two test sections per mile as a standard number of test sections for measuring pavement friction. On the other hand, state DOTs not applying a typical PFM consider more varied number of test sections de-pending on their needs (For state DOTs applying PFM: skewness = 2.426; For state DOTs not applying PFM: skewness = 0.431).

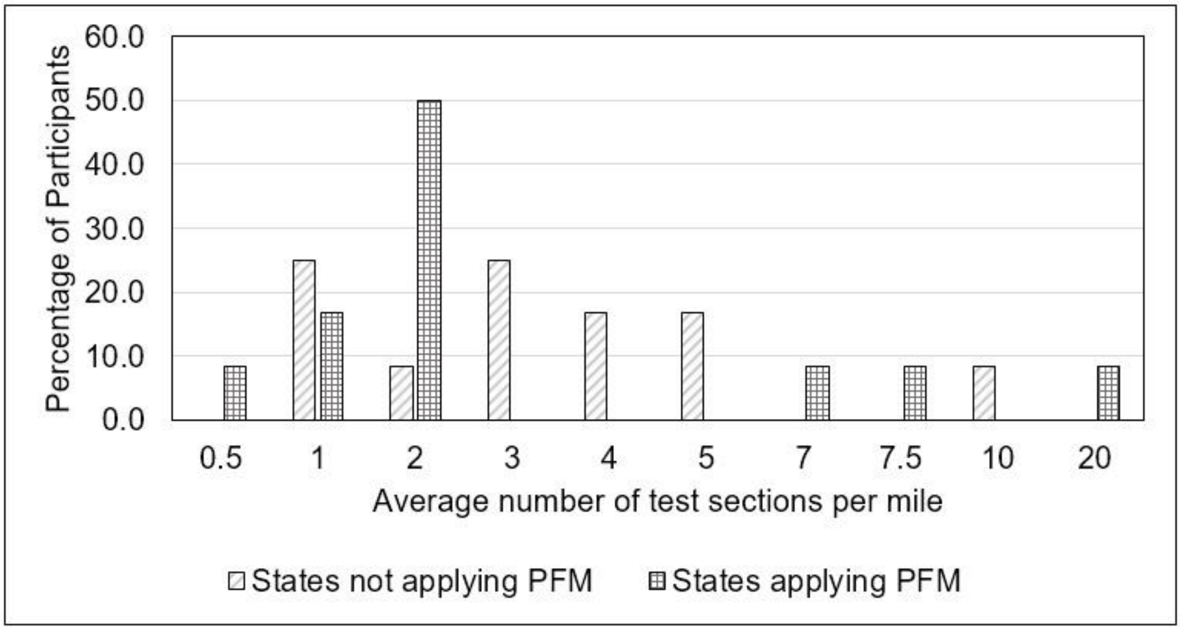


Figure 17. Chart. Average number of friction tests per mile for state DOTs.

The association between the overall policy of applying a typical PFM and maintaining a database for friction measurements is shown in Figure 18. It is very clear that state DOTs applying a typical PFM tend to maintain a database for the friction measurements and the corresponding geospatial data. This is important for the benefit of managing the maintenance plans and tracking the road network performance. The final association between the PFM policy and the number of treatments on rigid pavement is shown in Figure 19. The results reveal that higher number of treatments are observed to be implemented by states following a typical PFM. The skewness of the number of treatments for states not applying a typical PFM is -0.44 which implies a fairly symmetrical distribution in the number of treatments applications on rigid pavement.

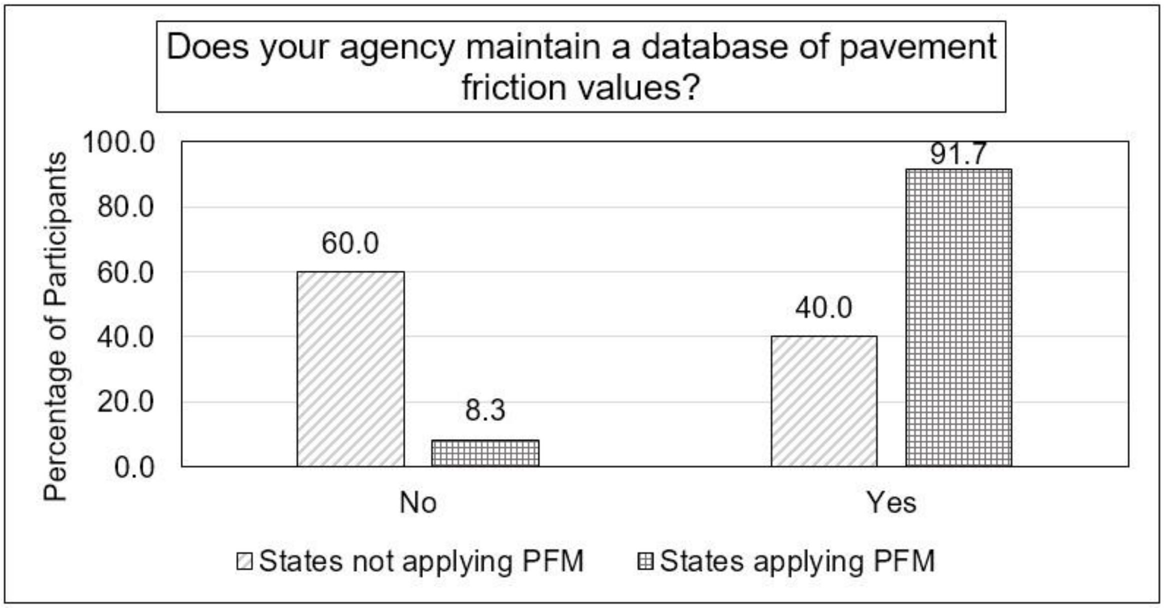


Figure 18. Chart. State DOTs practices of maintaining a database for pavement friction measurements.

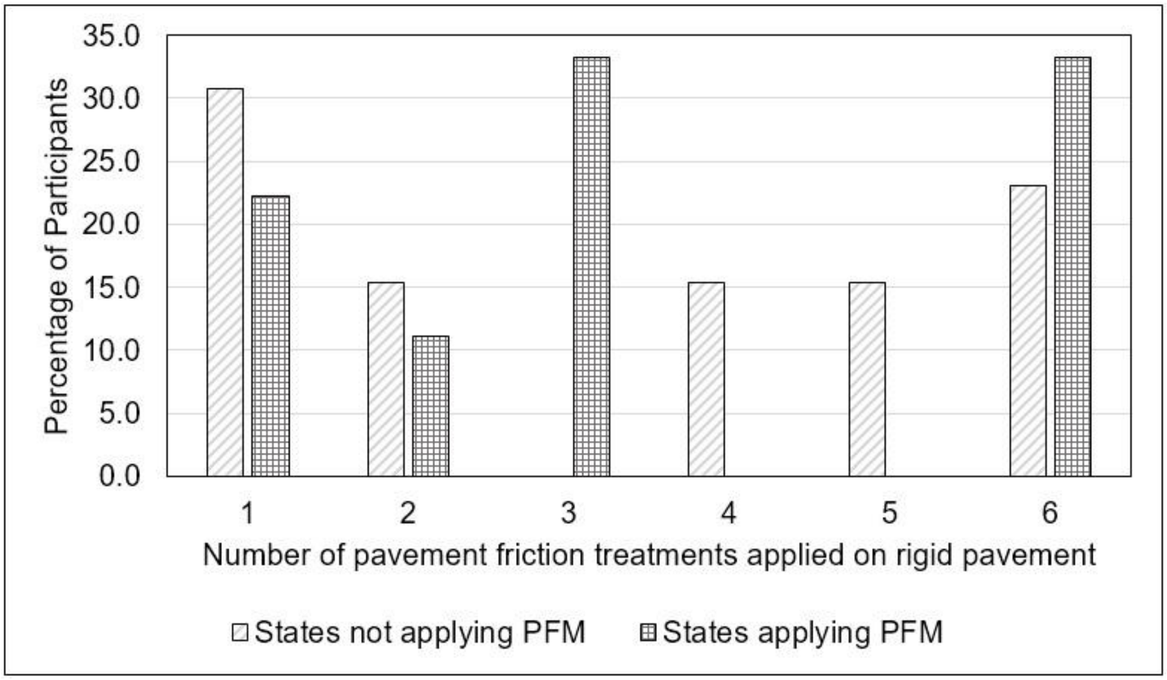


Figure 19. Chart. State DOTs practices of pavement friction treatments on rigid pavement.

4.5 Current Merits, Limitations, and Potential Enhancements

In terms of pavement fiction programs, there is no doubt that all state DOTs are following the HSIP federal policy to improve safety of their roadway network through the "data-driven" approach. With the impression received from the survey responses, most state DOTs valuate the importance of collecting and testing the pavement friction data in addressing friction-related issues. This can be derived from the diverse practices of friction testing, data collection, data collection frequencies, and performance indices. However, the asset management data does not merely describe the current condition of the assets. Rather, it supports the suitable means to act proactively to maximize the value of pavement performance. The lack of knowledge about future condition of friction does not allow state DOTs to clearly identify the segments requiring early preventive treatments to maximize the benefits on both the economic and safety scales. As a result, a large amount of funds may be wasted on emergency maintenance interventions, which have been proved to be less effective than proactive decisions of preventive and corrective maintenance operations. To improve the current practice, several guidelines and recommendations can be followed through a typical pavement friction management system developed to address the friction needs and demands on road networks. Several factors should be evaluated by state DOTs to secure plans for the best strategies and optimal timing of interventions relying on reliable pavement friction data, indices, performance models, and effective treatments.

Therefore, state DOTs can seek multiple rooms of adjustments to enhance the current practices of managing the pavement friction by state highway agencies. In terms of pavement performance modeling, more representative models are recommended to develop to predict the future conditions. Such models can be obtained using the historical performance of pavement friction. The performance of skid resistance can also be determined from other correlated performance indices. In some studies, the skid resistance was correlated with the pavement roughness. The measured average SN was seen to be significantly lower on relatively rougher pavement sections (Fuentes et al., 2010). Another study was held to show the relationship between the pavement friction trend, in terms of side-force coefficient and traffic levels in Equivalent Single Axle Loads (ESALs) (Susanna et al., 2017). The results show that pavement friction decreases due to the cumulative traffic while the International Roughness Index (IRI) increases through the time. Moreover, multiple proofs confirm that the number of crashes at wet pavements are increased as the skid friction values decreased. Thus, developing models with climate categories is essential to calculate the pavement friction and to predict the future performance. In the light of this, state DOTs can follow several modeling techniques developed in studies to predict the friction number from the asphalt materials properties, age, climate, and the traffic conditions (Noyce et al., 2005; Oh et al., 2010; Santos et al., 2021).

The HFST treatments have approved to be one of the best surface treatments for pavement friction. The HFST provides a high degree of skid resistance (Sprinkel et al., 2015). This treatment is very effective especially in asphalt roads at high risk of crashes. It is so important to choose the suitable surface treatments depending on several criteria such as the traffic volume, weather, and the cost of these materials. Another study shows a comparison be-tween some surface treatments such as chip seal and slurry seal and some other treatments to evaluate the effectiveness of these treatments and investigate the long-term variation of friction. The statistical results confirms that slurry seal causes great and significant friction number (Wang and Wang, 2013). Pavement treatments is a proactive step to extend the life and the effectiveness of the pavement without adding any structural supporters.

With the mentioned practices of selecting treatments, it is evident that simple and subjective processes are currently followed for selecting treatments. It is very necessary to apply the right treatment to the right road at the right time to avoid any unnecessary expenses (Chan et al., 2011). The effectiveness of decision making can be enhanced through integrating multi-criteria selection analysis, especially with the recent involvement in the artificial intelligence and machine learning approaches in all asset management systems. Such applications started to be applied in managing the pavement friction to link the friction with safety and pavement performance (Najafi et al., 2016, 2019; Marcelino et al., 2017). The last important aspect in decision making is relying on practical friction demand levels to both investigate and intervene the pavement friction needs.

4.6 Chapter Summary

Pavement friction is an important topic addressed by transportation agencies to reduce the number of traffic crashes and fatalities caused by poor friction between tires and pavement surface. Pavement friction management (PFM) provides the essential tools and techniques to effectively evaluate pavement friction conditions and provide informed maintenance decisions using surface treatments. State Departments of Transportation (DOTs) utilize various engineering practices to collect and analyze friction-related data, crash data, and traffic data. In addition, state DOTs tend to employ different techniques and policies to manage the pavement friction depending on budget levels, strategic objectives, and climate conditions. Due to these diversified practices in friction management, in this study, a comprehensive review of the state of the practice among state DOTs was documented. Online surveys were analyzed using descriptive and statistical correlation analyses to study the experience of state DOTs with managing pavement friction, considering feedback from 32 state DOTs in the USA. Exploring the methods to manage the pavement friction used by state agencies would help researchers and officials know more about the strategies towards an effective PFM. It also presents opportunities to enhance the approaches of the followed programs and highlight the gaps of the current practices. The results obtained from the survey would assist in identifying the practical policies and propose future enhancements to maximize the value of pavement assets and promote safety.

CHAPTER 5: EVALUATING THE EFFECTIVENESS OF SURFACE TREATMENTS ON PAVEMENT FRICTION PERFORMANCE USING DETERMINISTIC HISTORICAL DATA AND SURVIVAL ANALYSIS

5.1 Background

Transportation agencies have been investigating the pavement performance in terms of surface friction in order to enhance the safety performance of roadways. The reason relates to a direct interaction between vehicle's tires and road surface textures which affects the possibility of having various crashes, including rollover, rear end, and sideswipe crashes. Among the current evaluations of skid resistance is to assess the effectiveness of surface treatments on enhancing pavement friction performance and service lives. In terms of cracking and roughness, most surface treatments are typically applied as pavement preservations to increase the service life of pavement. While applying surface treatments, the pavement friction is enhanced showing different effectiveness on the skid resistance. Other innovative surface treatments, such as High Friction Surface (HFS), are applied as spot applications to increase friction levels at horizontal curves, bridges, steep grades, and intersections (Tsai et al., 2018). Throughout several studies, HFS treatments demonstrated nationally and internationally significant increases in friction for spot applications (HFST, 2021). Yet, the most common friction treatments applied on asphalt pavement are traditional surface treatments such as chip seal, microsurfacing, thin overlays, slurry seal, among other treatments. Hence, determining the effectiveness of surface treatments using in-place applications on road networks is of critical importance for making informed maintenance decisions.

Previous research efforts showed different impacts of surface treatments on pavement friction performance depending on the type of treatment, environment, traffic, and materials (Ahammed and Tighe, 2008; Kotek and Florková, 2014). This study seeks to evaluate the effectiveness of surface treatments applied on asphalt pavement to enhance the friction performance within pavement preservation strategies of 1-R categories. Several methods are adopted by agencies when addressing treatment performances. The most common tradition is by analyzing the Long-Term Pavement Performance (LTPP) data (Wang and Wang, 2013; Li et al., 2017) or constructing test sections (Li et al., 2011). Although test sections enable a detailed monitoring of the pavement performance, it may limit the findings to the local traffic and environmental conditions of the test sections. A more effective approach is by analyzing the historical performance of pavement friction using the pavement management system (PMS) database. This enables considering several factors of the whole road network in Wyoming and can provide more reliable results and conclusions.

In this study, a data-driven evaluation methodology was adopted to evaluate the effectiveness of chip seals, thin overlays, and microsurfacing on enhancing the preservation performance of pavement friction. The historical performances of friction metrics were linked with the treatment records. Then, a threshold-based evaluation method was utilized to classify the long-term effectiveness of treatments. Finally, a survival statistical analysis was applied to the classified treatments to determine the probability of survival for each treatment in the following five years. Survival analysis is a robust technique to address the effectiveness of countermeasures by analyzing the time to event data. Several studies showed that survival analysis can be utilized to various applications in pavement management systems to assess and predict several performances of pavement, including development of cracking (Wang et al., 2005; Dong and Huang, 2014), rehabilitation decisions on composite pavement (Chen et al., 2015), and pavement warranties (Luo et al., 2020). No survival applications were applied to determine the survival probability of surface treatments in terms of pavement friction performance.

The main objective of this study was to establish the methodology to evaluate in-practice surface treatments on pavement friction in Wyoming considering the historical performance of interstates, state highways, primary, and secondary roads. Then, the study evaluated the possibility of applying survival analysis to predict the probability of failure for each treatment. The benefits of treatments was addressed by considering the additional friction values obtained for the treated road within a 5-year post treatment time frame. The outcomes from this study are anticipated to enhance the understanding of the applied treatments and their characteristics in enhancing pavement textures. It also identified treatments that have been used successfully so that relevant recommendations are developed for WYDOT and other agencies.

5.2 Methodology

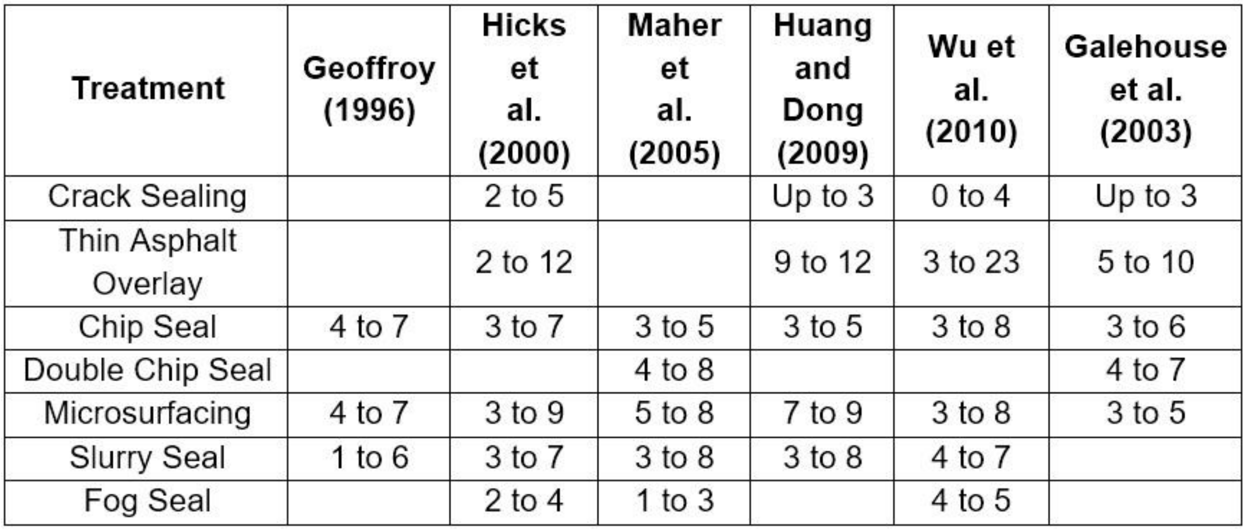
This section describes the pavement preservation and treatment evaluation criteria considered in this study. Also, the evaluation methodology of the historical performance of pavement friction after treatments is identified. The probabilistic technique of non-parametric survival analysis is briefly described and formulated for this study.

5.2.1 Pavement Preservation

The concept of pavement preservation has become an important treatment strategy especially with the limited resources and declined funding allocated for managing roads. Pavement preservation has the ability to keep the overall condition of pavement in higher levels by applying early and frequent applications of routine maintenance and minor rehabilitation.

All of the mentioned treatments have the ability to extend the serviceable life of pavements as long as the road is in relatively good condition. Life extension of roads using preventive preservation has been investigated extensively. The service life of pavement preservation is represented by the difference between the application time and the time when the performance index deteriorates back to the value just before application. Table 27 summarizes the expected life of the different types of preventive maintenance from previous studies. From the literature review, an average service life of five years is a reasonable time frame for studying the effectiveness of pavement preservation on pavement friction.

Table 27. Expected life extension in years of various treatments.



Treatment	Geoffroy (1996)	Hicks et al. (2000)	Maher et al. (2005)	Huang and Dong (2009)	Wu et al. (2010)	Galehouse et al. (2003)
Crack Sealing		2 to 5		Up to 3	0 to 4	Up to 3
Thin Asphalt Overlay		2 to 12		9 to 12	3 to 23	5 to 10
Chip Seal	4 to 7	3 to 7	3 to 5	3 to 5	3 to 8	3 to 6
Double Chip Seal			4 to 8			4 to 7
Microsurfacing	4 to 7	3 to 9	5 to 8	7 to 9	3 to 8	3 to 5
Slurry Seal	1 to 6	3 to 7	3 to 8	3 to 8	4 to 7	
Fog Seal		2 to 4	1 to 3		4 to 5	

5.2.2 Treatment Evaluation Criteria

The evaluation criteria depend on predefined threshold values used on the historical performance of FN to define the treatment effectiveness. Similar techniques showed that treatments can be effectively assessed using the PMS dataset of state DOTs (Hafez et al., 2019). As shown in Figure 20, the process combines the performance of road segments to develop individual performance models. Then, the historical treatment records are linked with the performance data using the linear reference of maintenance projects and road segments. The closing stage applies the predefined criteria to classify the treatments.

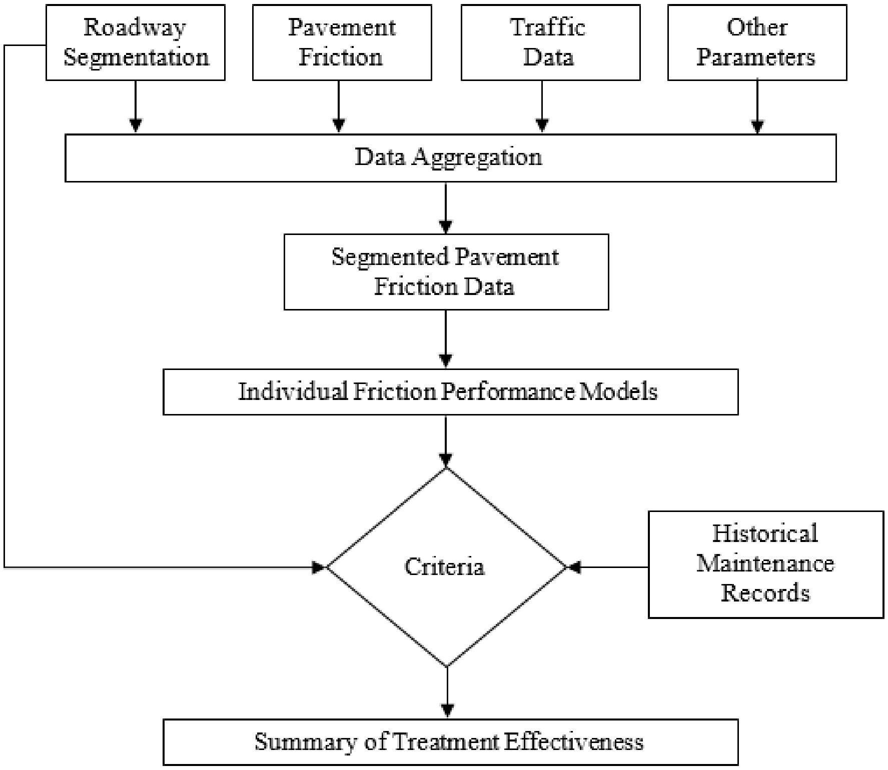


Figure 20. Flowchart. The overall evaluation methodology of pavement friction treatments.

When it comes to FN values, the rate of deterioration is relatively low compared to other pavement performance indices such as Pavement Serviceability Index (PSI) and Pavement Condition Index (PCI). Hence, representative amounts of improvements and rate of deterioration must be predefined. These cut-off values can be determined considering the variability of FN in the WYDOT's PMS dataset. The most important factor when considering the effectiveness of treatments is the achieved benefit. In PMS, the achieved benefit can be estimated using the area-under-the-curve method. As shown in Figure 21, treatment benefits can be expressed in terms of the additional friction value obtained just after treatment (ΔFN) and the time it takes to deteriorate this amount (Δt). Longer lived treatments normally create more area under the curve. Some surface treatments are expected to provide immediate improvement in the FN which is an indication of effectiveness. However, the post-treatment performance can classify the long-term performance by measuring Δt until the FN is degraded back to the initial value. Other cases will provide minor enhancement in pavement friction while preventing more deterioration in the performance. Such effectiveness will be classified as a uniform performance. When no improvement is noticed on the initial performance jump as well as over time, the treatment can be classified as "ineffective".

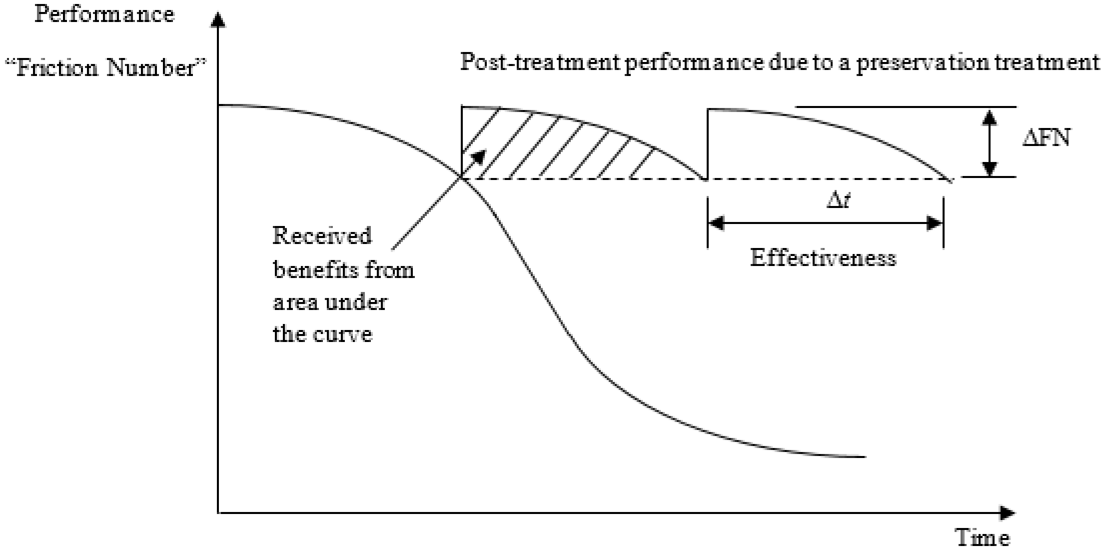


Figure 21. Diagram. Expected improvement in the pavement friction due to a surface treatment.

Accordingly, the treatment evaluation criteria for the different categories are listed in Table 28. The long-term effective treatment is expected when the amount of increase in the FN is 5 or more. In addition, the obtained benefit of friction improvement is expected to remain for more than two years after treatment application. If the time Δ*t* is two years or less, this will be an indication of lower benefits and less area under the curve. Hence, treatment will be classified as a short-term effective. The uniform performance tends to display variation in the FN within a range less than 3. However, the received benefits are represented by reducing the rate of deterioration. When data shows decline in the FN between 3 and 5, then the treatment will be considered as ineffective. The 'other' category includes any other cases than specified.

Table 28. Treatment evaluation criteria for pavement friction.

Effectiveness Category	**ΔFN**	**Δ*t***
Long-term effective	Increase: 5 or more	More than 2 years
Short-term effective	Increase: 5 or more	2 years or less
Uniform performance	Increase/Decline: Less than 3	Per year
Ineffective	Decline: 3 to 5	First year
Other	Other than specified	Other than specified

5.2.3 Survival Analysis

Survival analysis is one of the most effective statistical analysis that deals with a time-to-event data. The survival probability *s*(*t*) is commonly mentioned in biomedical and healthcare sciences to model the observing time to death of either patient or laboratory animals. However, the outcome of survival analysis does not merely include death, and similar applications can be considered. In this study, the survival analysis investigates the time observed for the improved friction number to deteriorate to the pre-treatment value. Several modeling techniques have been adopted to model the pavement performance, including linear and non-linear regression, logistic regression, and Bayesian analyses. These techniques follow a normal distribution of the response and predictor variables. Modeling the time of an event basically include non-negative time data, and the survival analysis can effectively model the data without the normal distribution assumption. In addition, survival analysis is capable of dealing with the censored data, which includes the last time of incomplete observations before the end of the study timeline. This incomplete data cannot simply be excluded because these data points still do not suffer from the event of interest until the censored time. Hence, survival analysis technique makes a unique use of this information in the estimate of the probability of the event.

The actual time of the event (T) denotes the response for the i^{th} road segment when it loses all the friction enhancement after surface treatment, see Equation 17. For ($T \geq 0$), the survival descriptive functions are formulated as shown in equations 18 and 19 (Dong et al., 2021). The risk function is a conditional probability and can be defined as a function of predictors X_i to consider the effects of predictors. In this study, the focus is on the survival probability $S(t)$ due to the diversified conditions of roads for the case study in Wyoming. It includes several road classes and varied traffic and environmental conditions.

$$T_i = t_i | (FN_t = FN_0) \quad \forall i = 1 \; to \; M \tag{17}$$

$$S(t) = \Pr(T > t) = 1 - \int_0^t f(u)\, du \tag{18}$$

$$h(t) = \lim_{\Delta t \to 0} \left(\frac{\Pr\left(t \leq T \leq t + \Delta t\right)}{\Delta t} \right) = \frac{f(t)}{S(t)} \tag{19}$$

where,

T_i: Time at the event (years) for i^{th} segment of total segments M.

FN_0: Friction number just after treatment application (at post-treatment time = 0).

FN_t: Friction number at post-treatment time t.

$S(t)$: the probability that the event will not fail at time t.

$h(t)$: the risk that the event will fail at time t.

$f(t)$: the probability density function of T.

It is also expected that some of the friction data will be considered as censored cases. This when a particular road segment received a rehabilitation or another surface treatment within the post-treatment period of five years. In this case, the post-treatment performance along the five-year time frame is incomplete and can be considered as a censored data point. Therefore, a non-parametric statistical technique is adopted using the Kaplan-Miere estimator, also known as the product limit estimator (Stalpers and Kaplan, 2018). The survival *S*(*t*) can be calculating by taking the product of the subsequent interval probabilities Pr(*i*) until Pr(*i*=*t*). Equation 20 formulates the Kaplan-Meier product-limit estimator.

$$S(t) = \prod_{i=1}^{t} \left(1 - \frac{d(i)}{n(i)}\right) \tag{20}$$

For censored data, the Kaplan-Meier approach assumes that censoring is independent of the likelihood of developing the event of interest. To classify censoring, the event indicator δ_i is formulated in the analysis as shown in Equation 21 depending on the last time just before the additional rehabilitation or another treatment C_i. The final observed response of censored cases will be the minimum of the T_i and C_i, see Equation 22.

$$\delta_i = \begin{cases} 1 & \text{if the event was observed } (T_i \le C_i) \\ 0 & \text{if the response was censored } (T_i > C_i) \end{cases} \tag{21}$$

$$Y_i = \min(T_i, C_i) \tag{22}$$

5.3 Case Study: Pavement Friction Performance in Wyoming

WYDOT is responsible for managing over 7,400 miles of roadways, including interstate NHS, non-interstate NHS, and non-NHS systems. The roads are distributed amongst 5 engineering districts as shown in Figure 22. The following subsections describe the main components of the PMS datasets and treatments considered in this study.

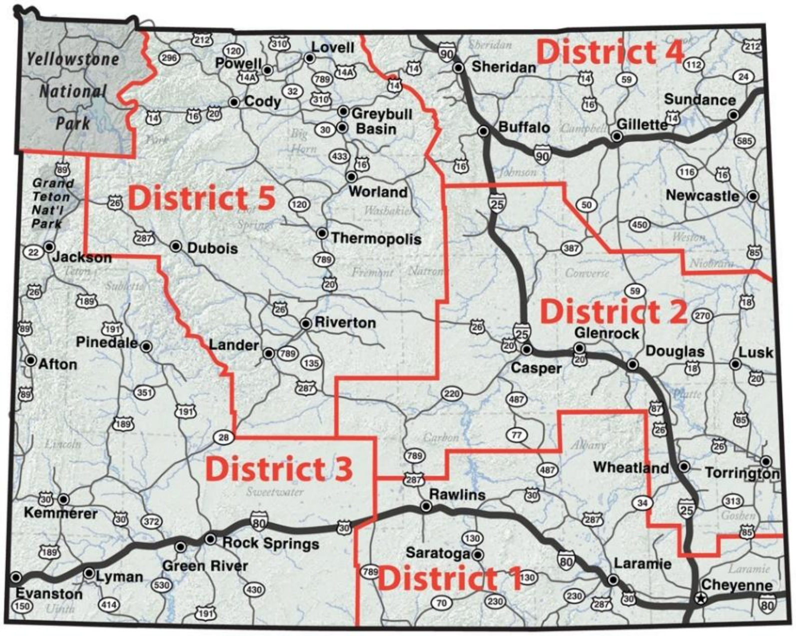


Figure 22. Map. Wyoming Department of Transportation engineering districts (WYDOT, 2022).

5.4 Pavement Performance Data Set

The pavement performance data set was received from WYDOT through *AgileAssets®* software. The performance data was received from the time from 2010 to 2020. The data was summarized and listed in consistent format. The data includes major asset management parameter, including ML code, beginning mile post (BMP), ending mile post (EMP), classification system, PCI, PSI, Rut, last year rehabilitation, year of construction, pavement type, traffic data, among other parameters. In WYDOT data set, the road systems are mainly classified as interstate (I), primary (P), secondary (S), state highway (SH), and urban roads (U). Table 29 shows an example of the combined data set. The asphalt pavement is coded as ASP.

Table 29. An Example of the Combined Data Set.

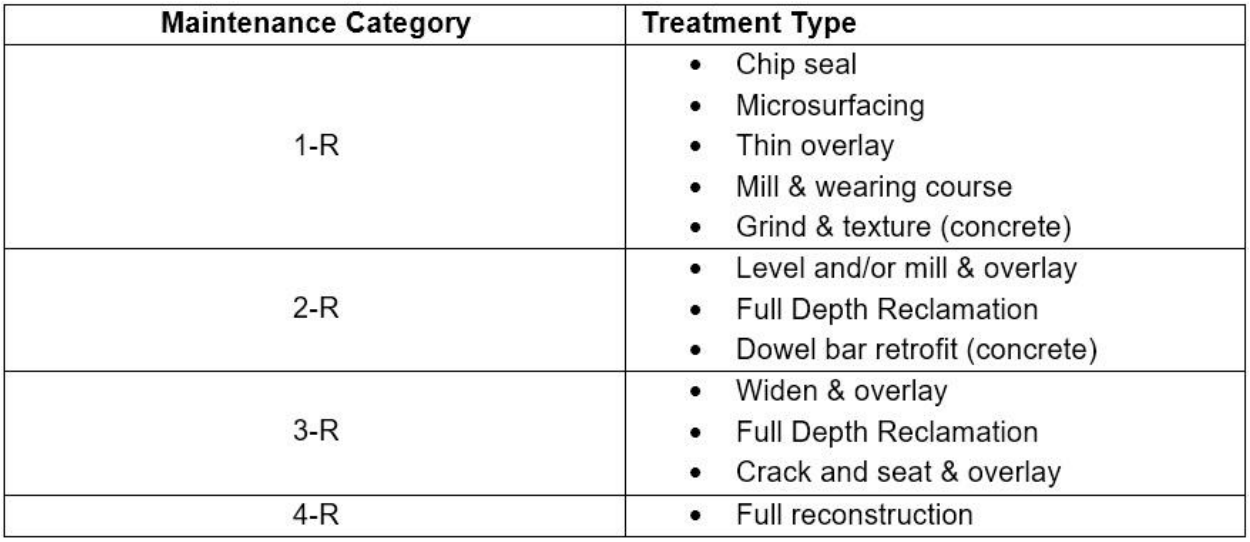
Route	Direction	BMP	EMP	Length	WC	District	System	Truck ADT	ADT	PCI	PSI	PSR	IRI	Rut	FN
ML10	Both	54.93	63.997	9.067	ASP	3	P	100.8	680.9	99.8	4.0	4.0	62.7	0.0	
ML10	Both	63.997	71.99	7.993	ASP	3	P	115.4	695.5	61.7	4.0	2.8	64.1	0.1	
ML10	Both	71.99	77.957	5.967	ASP	3	P	116.9	754.5	69.3	3.8	2.8	74.1	0.1	
ML10	Both	77.957	84.11	6.153	ASP	3	P	148.2	1554.9	80.1	4.1	3.4	58.1	0.2	

Although this study focused on pavement friction, summaries of the pavement performance were also studied in terms of PSI. The reason is that pavement serviceability can influence the surface friction by changing the surface texture. Hence, pavement deteriorations affect the pavement friction performance to some extend (Wang and Wang 2013).

5.5 Pavement Treatments

In the State of Wyoming, WYDOT utilizes a wide scale of pavement treatment categories depending on the current conditions, budget availability, functional classifications, and needs. Within the PMS program, four main maintenance categories are considered at the network level. These maintenance categories and treatment types are listed in Table 30.

Table 30. Types of pavement treatments considered by WYDOT.



Maintenance Category	Treatment Type
1-R	• Chip seal • Microsurfacing • Thin overlay • Mill & wearing course • Grind & texture (concrete)
2-R	• Level and/or mill & overlay • Full Depth Reclamation • Dowel bar retrofit (concrete)
3-R	• Widen & overlay • Full Depth Reclamation • Crack and seat & overlay
4-R	• Full reconstruction

The treatment data set was also received from WYODOT for all the previous year. For the purpose of this study, the data was filtered to consider the treatment records from 2010 to 2020. The data includes information about the location of treatments by milepost materials, year of construction, work code, among other parameters. Table 31 lists the total length and number of project cases considered in this study from 2010 to 2015. Chip seal is the most commonly applied treatment on primary and secondary roads in 1-R strategy. Relatively, microsurfacing and thin overlays are less applied on roads, but they are more considered on interstates since chip seals are not recommended on high-speed roadways such as interstates. It should be noted that few cases of these values were excluded from the evaluation and survival analysis due to the different mileposts of the treatment projects where they are not aligned with the linear reference of segments.

Table 31. Surface treatment summary for 1-R work code from 2010 to 2015 in Wyoming.

Year	Total Length, mile	No. of Projects	Performance Monitoring	
			From	To
Chip Seal				
2010	411.7	88	2010	2015
2011	399.3	56	2011	2016
2012	464.1	78	2012	2017
2013	96.4	12	2013	2018
2014	330.2	34	2014	2019
2015	165.9	20	2015	2020
Microsurfacing				
2010	43.8	45	2010	2015
2011	0.0	0	2011	2016
2012	0.0	0	2012	2017
2013	13.6	15	2013	2018
2014	28.8	32	2014	2019
2015	16.8	17	2015	2020
Thin Overlay				
2010	20.6	21	2010	2015
2011	26.6	23	2011	2016
2012	15.1	16	2012	2017
2013	6.9	7	2013	2018
2014	4.7	5	2014	2019
2015	0.0	0	2015	2020

5.6 Treatment Evaluation Results

Using the evaluation methodology described earlier, all the applied treatments were assigned to a treatment category. Then, summaries were developed for the total miles of segments receiving treatments from each treatment category as shown in Figure 23. Microsurfacing and thin overlay display higher effectiveness on the long-term compared to chip seal. This is due to the fact that chip seals normally show low durability due to the aggregate loss. Hence, it is long-lasting treatment when traffic volumes are low. However, chip seal shows the highest uniform performance of pavement friction due to the enhancement in the pavement macrotexture characteristics. The applied aggregate can provide various wavelengths at the macrotexture scale which enables the pavement surfaces to hold a better adhesion between tire and pavement surface, especially during wet pavement conditions. On the other hand, microsurfacing shows the highest mileage of ineffectiveness of the addressed road segments. This could be due to the low number of projects conducted by WYDOT in Wyoming. In fact, chip seal and thin overlays are the most common treatments applied in Wyoming for pavement preservation. Moreover, previous studies showed that microsurfacing showed significantly varied friction performance at the early age depending on the curing process (Li et al., 2011). Curing affects the development of mix strength and surface skid resistance. Another important behavior found specifically for chip seals is the application of chip seals after rehabilitation that took place two years earlier. In the study time period, WYDOT treated almost 60 miles of road with chip seals two years after rehabilitation. The historical performance emphasized on the long-term effectiveness of such strategies on the pavement friction performance. The FN values were enhanced with a minimum performance jump of 8 and showed extremely low deterioration rates on the post treatment performance.

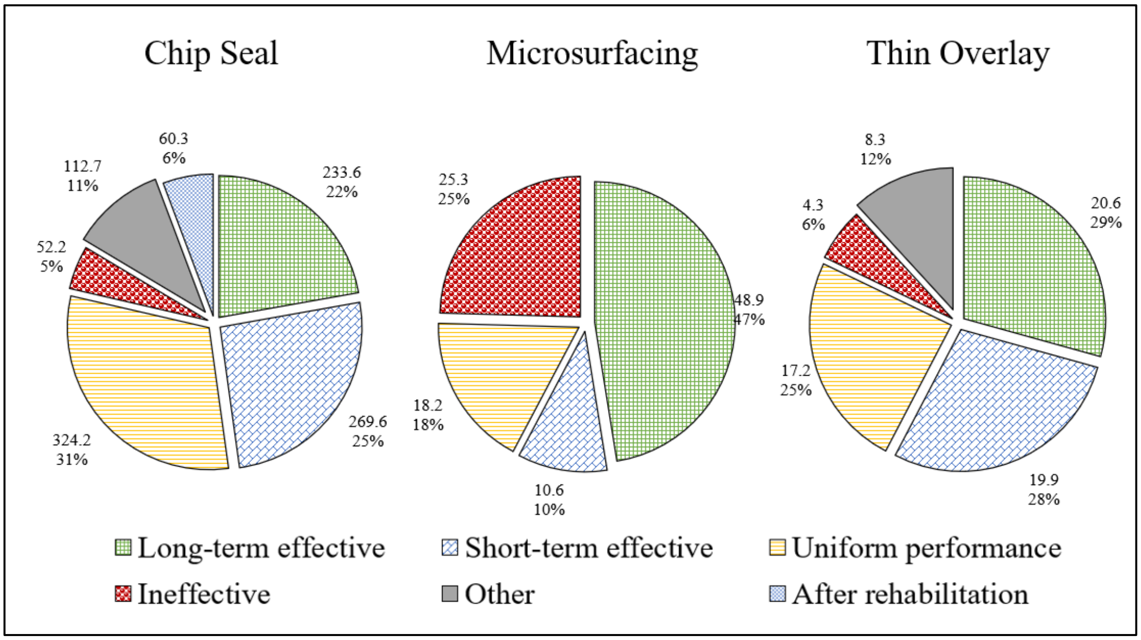


Figure 23. Pie-Chart. Treatment effectiveness summary for pavement friction by total length.

To increase the understanding of the effectiveness of treatments on pavement friction, statistical summaries are developed for each effectiveness category. As shown in Table 32, chip seals can enhance the long-term performance of pavement friction for roads with relatively higher FN compared to microsurfacing and thin overlays. Microsurfacing and thin overlay can address low friction values effectively. The uniform performance seems to be the same for the treatments and this can emphasize on the effectiveness of all treatments as effective preservation strategies. Similarly, the long-term effectiveness of chip seals is found on roads with relatively higher pavement serviceability compared to microsurfacing and thin overlay, as shown in Table 33.

Table 32. Summary statistics of friction number for treatment categories.

Effectiveness	Min	Average	Max	Std. Deviation
Chip Seal				
Long-term effective	39	56	69	9
Short-term effective	30	53	65	10
Uniform performance	36	54	68	7
Ineffective	51	57	66	5
Other	36	55	69	8
After rehabilitation	41	62	70	6
Microsurfacing				
Long-term effective	34	44	57	8
Short-term effective	48	52	55	5
Uniform performance	57	58	61	2
Ineffective	58	59	59	0
Thin overlay				
Long-term effective	36	43	51	11
Short-term effective	42	54	62	7
Uniform performance	57	57	58	0
Ineffective	60	60	60	0
Other	59	61	63	3

Table 33. Summary statistics of pavement serviceability index for treatment categories.

Effectiveness	Min	Average	Max	Std. Deviation
Chip Seal				
Long-term effective	2.4	3.6	4.3	0.5
Short-term effective	2.0	3.4	4.3	0.6
Uniform performance	2.5	3.5	4.3	0.4
Ineffective	3.1	3.4	3.9	0.3
Other	1.6	3.3	4.2	0.6
After rehabilitation	2.8	3.7	4.2	0.4
Microsurfacing				
Long-term effective	3.5	3.7	4.2	0.3
Short-term effective	3.4	3.5	3.6	0.2
Uniform performance	3.8	3.8	3.9	0.0
Ineffective	4.1	4.1	4.2	0.1
Thin overlay				
Long-term effective	2.6	3.4	4.2	11
Short-term effective	1.9	2.9	4.0	7
Uniform performance	3.5	3.8	4.2	0
Ineffective	4.2	4.2	4.2	0
Other	4.2	4.2	4.2	3

Moreover, the distribution of treatment effectiveness categories is addressed among the WYDOT's districts. The summary is shown in Figure 24. It's clear that pavements in District 3 shows the highest number of miles for roads receiving long-term effective friction treatments. The reason could be directly related to the environmental conditions in District 3 which is uniquely classified as a dry zone. The annual precipitation in District 3 is 0.0 (USDA, 2012). Although there is no study fully approved the direct impact of temperature and annual precipitation on pavement friction performance, recent studies have found a compound effectiveness of climatic zones and other parameters on friction performance using LTPP data (Rezapour et al., 2022).

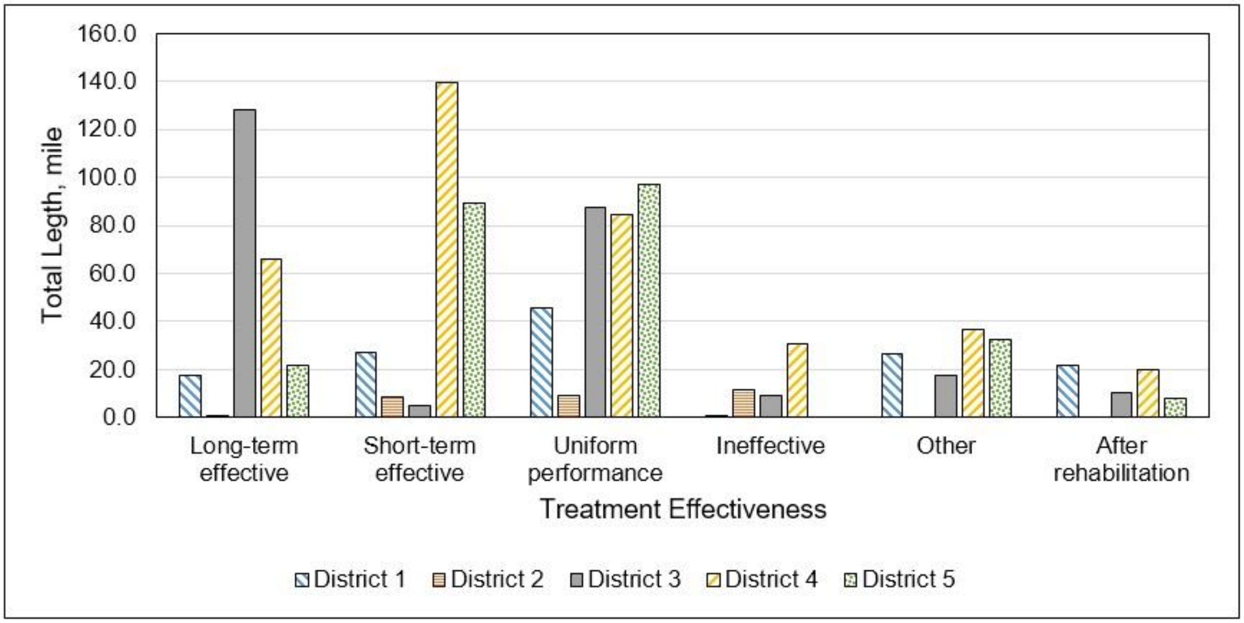


Figure 24. Mileage distribution of treatment effectiveness among WYDOT's districts.

5.7 Survival Results

Previous studies conducted statistical and correlation analysis to define the effectiveness of several factors on friction treatment performance. In this study, due to the high variability of the parameters obtained from WYDOT's PMS dataset, such correlations are expected to be low and can bias the research results. Hence, the survival analysis was conducted to determine the overall probability of survival for each treatment every year. The case summary of the analysis is shown in Table 34. The censored data in this study represents the road segments that have received rehabilitation or another surface treatment before the end of the fifth year after surface treatment application. The post-treatment performance along the five-year time frame is incomplete in this case and can be considered as a censor data. For chip seals, 13.3 percent of cases received another treatment before the end of the fifth year while 11.4

percent of the thin overlay segments received treatments. An overall censored data of 9 percent is found in this study.

Table 34. Case processing summary for survival analysis.

Treatment	Total Number of Cases	Number of Events	Censored	
			Number	Percent
Chip Seal	181	157	24	13.3
Microsurfacing	103	103	0	0.0
Thin Overlay	70	62	8	11.4
Overall	354	322	32	9.0

The survival function is depicted in Figure 25. At 50 percent survival rate, the value is commonly known as the median time to failure (MTTF). Chip seals show the highest MTTF while microsurfacing and thin overlays display similar MTTF values. For microsurfacing, the survival analysis shows higher probabilities of friction loss in the first year. The initial enhancement in the pavement friction is not obtained immediately. However, the friction of microsurfacing is increased gradually depending on the curing method (Li et al., 2011). After 12 months (1 year), the friction performance of microsurfacing can be increased and enhance the survival probability to be close to chip seals and thin overlay performance at the mid-age of post treatment. After almost 36 months (3 years), the friction performance tends to decrease signifcantly to include only 19 percent survival cases of microsurfacing. These results are supported by the findings from the test sections conducted in Indiana (Li et al., 2011) where the friction performance of the microsurfacing became more stable after 12 months and the friction reaches its maximum performance. Then, the friction performance of microsufacing tend to decrease continuously over a 42-month service life period. The highest survival probabilities within the first five years of service are found for chip seals with a gradual descend. This is due to the highest mileage of roads classifying into long-term and uniform performance treatment categories. For overlays, the survival probability decreases significantly after the third year to end up with almost 35 percent by the end of the fifth year.

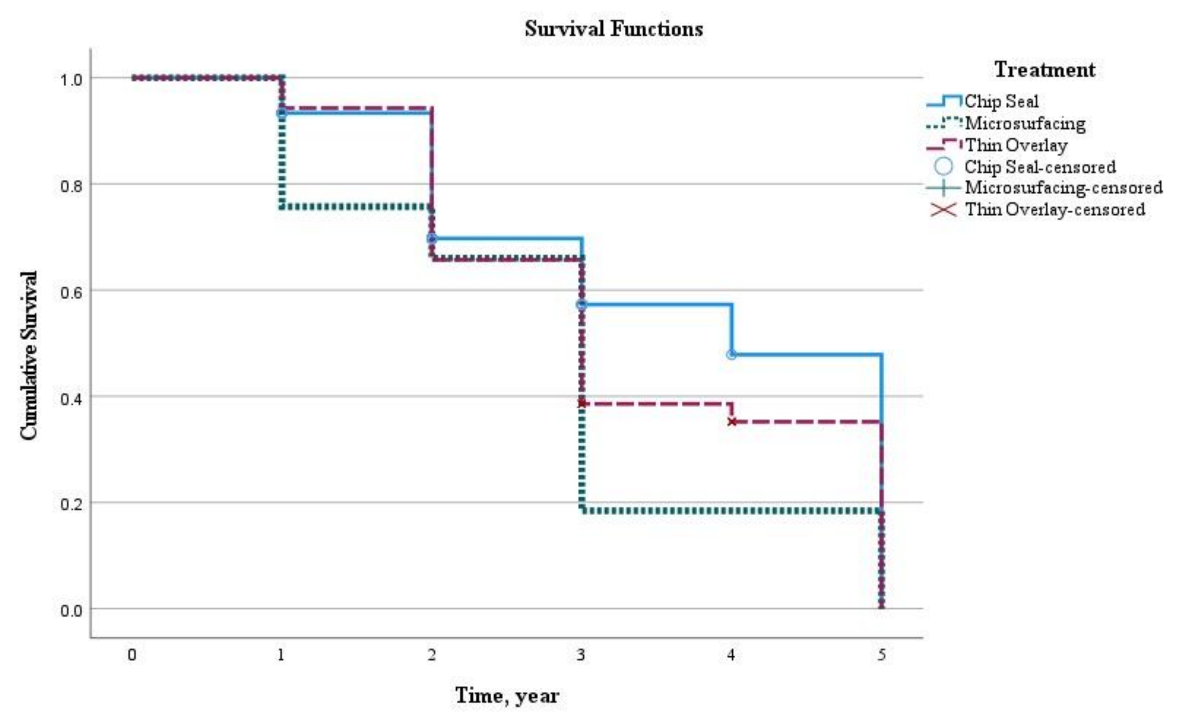


Figure 25. Diagram. Survival functions of surface treatments in the context of pavement friction performance.

The last step in the survival analysis was to test the significance in the survival behavior of the surface treatments. According to this study, three statistical tests were conducted. The first test was the non-parametric log-rank test, also known as Mantel-Cox test, which compares the survival of samples from different populations. It is usually used to compare the survival by the end of the study time period since it gives equal weight to all time points (Xie and Liu, 2005). The second test was Breslow-Wilcoxcon test which gives more weight to deaths at the early time points. Therefore, its results are used to compare the survival behavior of treatments at the beginning of the post-treatment performance. The last test was Tarone-Ware method which is used to test the behavior at the time points in the middle age. The null hypothesis states that the two groups have identical hazard functions. The results are listed in Table 35. All tests showed significance differences between the surface treatments. Hence, it can be clearly stated that the chip seal provides the highest probability of survival by the end of the fifth year. Also, microsurfacing displays higher probability to fail at the early age of treatment.

Table 35. Overall comparisons and significance results.

Test	Chi-Square	*df*	Significance
Log Rank (Mantel-Cox)	22.954	2	P<0.001
Breslow (Generalized Wilcoxon)	21.413	2	P<0.001
Tarone-Ware	22.652	2	P<0.001

5.8 Chapter Summary

Pavement friction is an important safety concern since it contributes to the interaction between vehicle’s tires and road surface, affecting the probabilities of friction related crashes. Hence, transportation agencies have been evaluating the effectiveness of surface treatments on pavement friction performance. Pavement preservations are typically applied at the early age of pavement to extend its service life and enhance the surface friction. In this study, a data-driven evaluation methodology was adopted to evaluate the effectiveness of chip seals, thin overlays, and microsurfacing on enhancing the preservation performance of pavement friction. The historical performances of friction metrics were linked with the treatment records. The surface treatments were classified on the long-term and short-term basis by addressing the benefits received from the area under the curve of FN performance models. Then, a survival analysis was adopted to account for the variability in the PMS data set as well as the censored data of frequent treatments along the post-treatment performance of the same segment. The results showed different survival behaviors at the different stages of the post-treatment performances. The findings from this study would increase the understanding of the factors affecting the friction performance of surface treatments, including environment, materials, and construction issues.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

In this study, the effects of pavement surface friction on traffic crashes were first investigated by utilizing data from WYDOT. In addition to pavement friction, several geometric characteristics, road surface condition, vehicle body types were also investigated. Crash data, friction data, and geometric data belonging to the years 2010 through 2019 were processed. SPFs were developed for different functional classifications of roadways including rural interstates, rural principal arterials, rural major collectors, rural minor arterials, urban interstates, and urban principal arterials. Since crashes on urban minor arterials, urban major collectors, urban minor collectors, and rural minor collectors were few, such facilities were not considered for further analysis. The SPFs were developed for both total crashes and equivalent PDO crashes. The results of SPFs from total crashes as well as EPDO crashes revealed several important findings. Pavement friction was found significant and inversely proportional to the occurrences of total crashes for all functional classes of roadways except for rural principal arterials and rural minor arterials. Also, when SPFs were developed for EPDO crashes, it was found that pavement friction was significant for urban principal arterials, and rural major collectors. The findings suggested that increasing friction number would decrease total crashes as well as EPDO crashes. AADT was also found to be significant for all facilities. The results from SPFs suggested that friction not only impacts wet-condition crashes, but also dry-condition crashes. This study is unique in the sense that both total crashes and EPDO crashes were considered to investigate how friction and a wide variety of other factors influence such crashes.

The second analysis entailed an investigation of the major contributing factors of severe injuries sustained as a result of intersection crashes, especially pavement surface friction. The importance of the variables was examined using the random forest method. As per its results, pavement surface friction, improper use of safety restraints, manner of collision, speeding, reckless driving, intersection traffic control type, and adverse weather all influenced crash injury severity risk substantially. A Bayesian ordinal probit model was developed to explore the impact of the contributing factors on crash severity risk. The modeling results demonstrated that increasing the friction number from 35 to 55 would significantly decrease the risk of observing severe injuries and fatalities. The findings also indicated that improper use of safety restraints may increase the probability of a severe injury by 24 percent on average. Furthermore, according to the Bayesian model's results, signalized intersections would be less likely to experience fatal, serious injury, and minor injury crashes than unsignalized intersections.

The third analysis examined the impact of pavement surface friction on traffic crashes, considering various factors such as geometric characteristics, road surface condition, and vehicle body types. Data from WYDOT spanning from 2010 to 2019 were analyzed to develop SPFs for different types of roadways. Pavement friction was found to have an inverse relationship with total crashes for most types of roadways. On the interstate highways, the marginal effect of friction number (FN) decreased from 4.68 percent for FN(35-40) to 1.28 percent for FN(>50), indicating a decrease in the probability of FR crashes as friction levels increase. Similarly, on non-interstate highways, the marginal effect changed from 8.04 percent for FN(35-40) to 1.50 percent for FN(>50).

Road segments with horizontal curves, especially when combined with vertical curves, experienced increased crash probabilities. The presence of both types of curves increased FR crash occurrences on interstate and non-interstate highways by 4.45 percent and 3.21 percent respectively. Adverse road surface conditions such as ice, snow, and wetness increased the probability of FR crashes on both interstate and non-interstate highways. Various treatments, such as HFST and diamond grinding, improve pavement friction. Although costs vary, the benefits of increasing pavement friction outweigh the costs, as indicated by positive benefit-cost ratios. This underscores the importance of investing in pavement friction improvement for enhanced safety and economic welfare.

In the fourth analysis, the profound principles and methodologies of pavement friction management were investigated through the current practices of state DOTs and a literature review. The results received from the survey of practice highlighted the practical policies and proposed future enhancements to maximize the value of pavement assets and promote safety. The survey results indicated that most state DOTs do have some form of PFM and related programs. It ranges from simple and subjective techniques to a very sophisticated system that includes routine testing, multi-year planning, and research relating friction treatments. However, the majority of their policies do not follow a standard management system nor define a solid maintenance targets and plans. State DOTs test pavement friction mainly using the locked-wheel testing methodology to measure the friction number which is found to be the most common equipment employed by state agencies. However, it provides some limitations of measurements on curved segments and in a continuous data collection format. Therefore, some state DOTs started to evolve a continuous pavement friction measurement to continuously collect the network-level friction data, especially at locations requiring higher friction demands such as curves, ramps, intersections, etc. However, the development of continuous friction measurements is adopted by few state DOTs. In addition, the statewide practice of data collection frequency varies from very frequent processes as annually up to six-year cycles depending on road classification. A very high number of state DOTs collect the friction data only by request from either district engineers or from the safety program. However, state applying a typical PFM are statistically correlated to collect more data at both the statewide levels and at specific locations. They have also correlated practices of maintaining a database of friction measurements. The safety concern is found to be the most affecting factor to investigate the friction demand and needs. That is why most state DOTs rely on reactive maintenance activities with less-standardized PFM proactive policies. Moreover, the feedback received from state DOTs practices and literature review supports the effectiveness of high friction surface treatments to enhance the overall friction performance. However, it is used more frequently on asphalt pavement. Diamond grinding is the most common treatment strategies on concrete pavements.

In the fifth analysis, the effectiveness of pavement preservation on enhancing the performance of pavement friction and skid resistance was evaluated using the historical performance of WYDOT's PMS datasets. Three surface treatments were classified on the long-term and short-term basis. Then, the survival probabilities were determined showing different survival behaviors at the different stages of the post-treatment performances. The following are drawn based on the results of this study:

- The historical friction performance of surface treatments on pavements can provide a more comprehensive evaluation process since it considers cases from different locations experiencing varied traffic volumes, materials, and environments.
- The developed evaluation methodology further classifies the effectiveness of surface treatments on pavement friction by considering thresholds for friction number. Higher initial improvement with lower deterioration rates can provide long-term effective treatment. The recommendations derived from the evaluation process maximize the benefits received out of the area under the post-treatment curve.
- In Wyoming, chip seals and thin overlays are the most commonly applied treatments on roads within pavement preservation programs. Chip seals exhibit better performance on road with relatively lower speed limits to minimize the flying chips and aggregate loss. Hence, chip seals are more applied on primary and secondary roads while thin overlays and microsurfacing are mainly applied to interstate. Moreover, chip seals are extensively applied on lower class roads due to the low costs.
- Chip seals are found to maximize the benefits of the increased friction performance under the curve due to its ability to long-term preserve the increased FN and provide a steady-state performance of pavement friction. Chip seals also shows the highest survival probabilities along a five-year service life.
- Microsurfacing is a long-term effective surface treatment that can enhance the skid resistance of pavement surfaces. However, the general trend of survival function for microsurfacing follows an early-time drop in the survival probability followed by improvements in the failure probability. The immediate drop on some

cases at early time points could relate to similar findings due to materials and curing properties.

- Significant differences of chip seals, thin overlay, and microsurfacing performances are seen in the survival analysis considering the overall trend, at the early age, and at the late age of the post-treatment FN performance. Moreover, the survival analysis can consider incomplete observations of the treatment performance due to the frequent maintenance or rehabilitations considered on the same segment. The censored friction performance data contribute to the performance modeling to some extent.
- The deterministic evaluation methodology and Kaplan-Meier survival estimator can increase the understanding of pavement preservations and their effectiveness on pavement friction properties.

6.2 Recommendations

The intent of first study was to investigate the effects of pavement surface friction on highway crashes for different roadway functional classifications. The results of this study would be beneficial to define the desirable friction threshold. The findings would help WYDOT in developing a more effective friction treatment policy for the interstate and the state highway systems. This study would also lay a foundation in identifying locations, also known as hotspots, which suffer from crashes because of low pavement friction numbers. Several recommendations are made based on this study's findings. One is to investigate safe friction thresholds by roadway functional classification and traffic volume. Another is to regularly maintain the pavement friction above acceptable levels to ensure safe traffic operations. In addition, in-depth studies ought to be conducted on intervention strategies to reduce safety restraint improper use/non-use rates, speeding, and reckless driving. These strategies pertain to driver's educational and enforcement campaigns. When it comes to crash types, implementing countermeasures that reduce severe crashes, such as angle crashes, as documented in the Crash Modification Factors (CMF) Clearinghouse is suggested.

Although the second analysis offered several remarkable findings, it had some limitations. One was the sample size based on Wyoming intersections only. A similar approach may be selected for a future study on larger datasets from other states. With larger data, random parameters may be incorporated to infer unobserved heterogeneity of the parameters on crash injury severity risks.

Based on the findings of the third analysis, it is recommended to prioritize measures that increase pavement friction, such as High Friction Surface Treatments (HFST) and diamond grinding. Additionally, attention should be given to addressing adverse road surface conditions, particularly during inclement weather, to mitigate the increased risk of crashes. Furthermore, road design considerations should account for the impact of horizontal and vertical curves on crash probabilities, with measures implemented to minimize risks associated with these geometric features. Investing in pavement friction improvement is crucial for enhancing road safety and economic welfare. Overall, proactive investments in pavement friction enhancement can yield substantial benefits in terms of reducing crashes and associated costs, thereby promoting safer and more efficient transportation systems.

In the fourth analysis, the findings derived from the points of merits and limitations of the current practices encourage state DOTs to avoid simple and subjective evaluation of the pavement friction performance and decision making. Rather, state DOTs are recommended to consider the several studies and methodologies developed to support an effective PFM. Among these studies, state DOTs can use the developed correlated models of pavement fiction number and affecting factors such as pavement roughness, pavement material characteristics, traffic, and environmental conditions. In addition, the pavement friction demand should be addressed proactively using investigatory levels so that preventive maintenance can be defined to avoid higher crash rates on road segments. Moreover, the multi-year maintenance decision making can also be supported using artificial intelligence techniques and optimization analysis to maximize the benefits of managing the pavement friction proactively and avoid extra expenses.

Based on the fifth analysis, transportation agencies are recommended to consider the pre-treatment condition of pavement in terms of cracking and friction before applying pavement preservation. To maximize the benefits, care should be exercised when applying chip seal to pavement with lower PSI since it could end up with a short-term or negative effectiveness on pavement friction. Also, the aggregate types, texture, and properties are important considerations when applying chip seals to enhance the pavement friction performance. Although thin overlay has the ability to enhance the friction performance under different pre-values of PSI and FN, it is prone to reflective cracking. Hence, additional investigation can be conducted to address the benefit-cost impact of thin overlays especially it is relatively inexpensive preservation treatment. Finally, microsurfacing would be durable and adhere to high standard in terms of construction and quality control to maximize its friction characteristics.

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