Network Roadway Surface Friction and Its Usage to Improve Safety and Project Performance along West Virginia Highways

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ABSTRACT

Roadway surface friction along the West Virginia Division of Highways’ roadway network is key to the safety of all traveling motorists. Being geographically located in the rugged Appalachian Mountains, the West Virginia Division of Highways’ roadway network faces innumerable geometric and design challenges, causing drivers to have to exercise the most care and attention when navigating the network.

This dissertation introduces the concept of network-level roadway surface friction management to this network. For decades, roadway surface friction has only been tested and checked on an as-needed basis at crash sites and intersections, in legal situations, and for pavement acceptance on construction projects. The research proposes a novel methodology to use the acquired data to develop sample safety performance functions and best crash estimates and use the results to assist and guide in the selection of friction improvement projects for the West Virginia Highway Safety Improvement Program.

This dissertation follows the manuscript format and is composed of three papers that represent the three main steps of the proposed methodology. The first step uses continuous network-level friction data and crashes to determine friction investigatory levels and illustrates their application in case study on one of the Division’s districts. The investigatory levels reflect the level of friction below which crashes start to increase significantly, and they are used to trigger road safety investigations to determine if a friction improvement treatment may be warranted.

The second step focused on the development of sample safety performance functions to estimate the average number of crashes along three roadway categories: Interstate, United States, and West Virginia routes, using negative binomial regressions that incorporate friction and geometric properties as explanatory variables. These safety performance functions are used to develop Empirical Bayes crash estimates before and after applying friction improvement treatments. This is used to forecast how crash counts should improve, given the application of various roadway improvements.
The third step integrates the network level measurement and safety analysis in a systemic and proactive benefit-cost methodology to identify optimum locations for High Friction Surface Treatments to include the West Virginia Highway Safety Improvement Program. The applicability and practicality of the methodology is illustrated though a case study.

The main conclusion of the study is that it is possible to enhance the decision-making process for selecting High Friction Surface Treatment projects to include in the Highway Safety Improvement Program. The results of applying the suggested methodology suggest that the expansion of the methodology to the statewide network could results in significant reductions in crashes and associated fatalities.
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GENERAL AUDIENCE ABSTRACT

The concept of roadway surface friction is based on the grip found on the surface of roadways that is recognized through vehicle tires as drivers make various maneuvers while driving. The West Virginia Division of Highways has always tested areas of roadway surface friction concern in spot locations throughout the network to check for roadway construction compliance, legal concerns, and crash locations but had never collected this information on a network level. The focus of this dissertation keys in on the three following aspects within a portion of the roadway transportation network:

1. Using network-level friction data and existing crash data to determine what the minimum acceptable amount of roadway surface friction needs to be for Interstate Routes, United States Routes, and West Virginia Routes.
2. Using these minimum acceptable roadway surface friction values for each route category, in conjunction with existing crash data to develop sample safety performance functions to estimate average crash rates, for each of the specified route categories.
3. To perform a case study using these minimum acceptable amounts of roadway surface friction and safety performance functions to determine the priority sites within the network where crashes would be reduced the most using the friction-enhancing technique of applying High Friction Surface Treatment.

After completion of these three aspects, several key findings were determined. First, the minimum acceptable amounts of roadway surface friction for the Interstate Routes was not able to be determined due to the inability to link the number of crashes with a friction level. On the other hand, the minimum acceptable amount for the United States Routes is a Grip value of 0.3 while the minimum acceptable amount for the West Virginia Routes is a Grip value of 0.24.

Second, sample safety performance functions were able to be developed using roadway surface friction, horizontal curve radius, roadway superelevation or crossfall, and Average Daily Traffic.
Third, the case study revealed that a $2 million statewide High Friction Surface Treatment Project budget, that 106 crashes over a 3-year period in just the District Ten jurisdiction alone can be realized.

This research is very important to motorists throughout the State of West Virginia for a number of reasons. First, it will help the Division of Highways determine the roadway surface friction values throughout the entire network. Second, it will help determine what average crash rates are for the network route categories and enable the portions of the network with higher than average values to be reviewed and corrected. Third, it will help the Division of Highways to be able to spend their limited Federal-Aid Highway Safety Improvement Program Funds wisely and more efficiently.
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CHAPTER 1 - INTRODUCTION

The roadway transportation network of the State of West Virginia, under the management and administration of the West Virginia Department of Transportation’s Division of Highways, is a critical infrastructure to the success and quality of life of the citizens of the State of West Virginia. It also serves the traveling public along the East Coast of the United States. To perpetuate a roadway transportation network of this magnitude, the network structure and safety must be maintained. One important aspect of roadway safety is that of roadway surface friction.

Roadway surface friction is a key safety component in roadway transportation. The interaction between this grip of the roadway surface with contact area of the tire’s tread allows vehicles to be driven and remain on the roadway during routine horizontal and vertical maneuvers, through all types of geometric configurations, weather conditions, and traffic scenarios. Although the concept of roadway surface friction appears very simple, it is a complex and diverse phenomenon.

Roadway surface friction changes over time. When roadway surfaces are new, friction is typically at or near its highest level. As the surface ages and wears, the friction decreases and deteriorates. Thus, friction has to be monitored over time, to assure a safe pavement surface. Although it is important for all roadways to maintain some level of friction, different types of roadways (i.e. Interstate Routes, United States Routes, and West Virginia Routes) and different roadway horizontal and vertical geometries (i.e. tangents, curves, and continuous grades) typically require, or demand, differing levels of friction.

It is critical to determine the level of roadway surface friction needed to eliminate roadway surface friction-related crashes and casualties. To clarify this statement, consider the various causes for vehicular crashes. Some causes are directly related to the roadway and its environment, such as lack of roadway surface friction, inadequate superelevation, lack of roadway clear zones, and other aspects of roadway horizontal and vertical geometry. Others, though, are related to human errors such as fatigue driving, being under the influence of alcohol, driving distracted, and even eating while behind the wheel. Improving the roadway surface friction will not prevent crashes and casualties resulting from all human error, but it may help prevent or reduce the severity of same crashes. Thus, it is important to identify and treat locations with inadequate roadway surface friction.

Once levels of minimum reasonable roadway surface friction, typically called investigatory levels, are recognized, it then becomes important to apply these concepts to the roadway network
level in the form of a Friction Management Program. This program establishes roadway surface friction levels for each of various types of routes and seeks to improve the friction of deficient roadway sections by applying surface friction-enhancing.

**PROBLEM STATEMENT**

Roadway surface friction is critical for the safe operation of motor vehicles over roadway networks. For decades, State Departments of Transportation have been testing roadway surface friction in very reactive situations: when a crash or other vehicle catastrophic event has occurred and when a pavement has been freshly placed and needs to meet certain criteria to be accepted on a construction project.

Network roadway surface friction testing enables State Departments of Transportation to assess the current friction conditions in the network and to be proactive by making the necessary improvements in the network prior to crashes and other events occurring. Currently, the State of West Virginia Division of Highways does not test the roadway network in its entirety, only specified locations.

**OBJECTIVE**

The objective of this dissertation is to establish a method in which the Division of Highways can begin network friction testing and using the data to develop a pavement friction management program that addresses the following concerns:

- What is the Investigatory Level of roadway surface friction necessary for each of the route categories across the network?
- Is it possible develop Safety Performance Functions for the various route categories that incorporate friction as a descriptive variable?
- How can the West Virginia Division of Highways best use its Highway Safety Improvement Program funds when selecting High Friction Surface Treatment Projects to affect the largest number of motorists?
ORGANIZATION OF THE DISSERTATION

This dissertation has been prepared in the manuscript format and consists of three papers. The first chapter introduces the dissertation and provides background information about the concepts of roadway surface friction.

The second chapter (first manuscript) discusses a pilot network roadway surface friction operation in the State of West Virginia in the Division of Highways’ District Ten jurisdiction. The data collected is used to assess the overall level of friction and define illustrative Investigatory Levels, or minimum level of roadway surface friction, for different road categories.

The third chapter (second manuscript) discusses the derivation of sample safety performance functions that incorporate friction as a descriptive variable. The regression models obtained using the data collected in chapter two are then used to produce network-level best crash estimates using the Empirical Bayes Method.

The fourth chapter (third manuscript) proposes a method to determine the optimum locations to place High Friction Surface Treatment on roadway segments with friction under the Investigatory Level. The method uses the safety performance function and empirical Bayes approach to estimate potential crash reductions and provides insight as to how Highway Safety Improvement Program (HSIP) funds can be used most effectively.

The fifth and final chapter presents the main findings of the dissertation, the conclusions derived from the research, and recommendations for future research.

SIGNIFICANCE

The significance of this dissertation is that it provides an approach that can help State Departments of Transportation with little to no experience in network level roadway friction testing, develop a pavement friction management program. This dissertation uses a safety analysis established method and provides guidance for its practical implementation.

In addition, the dissertation provides a cost-efficient fund distribution mechanism so that vital Highway Safety Improvement Program funds can be spent wisely.
CHAPTER 2 - ILLUSTRATIVE PAVEMENT FRICTION THRESHOLDS FOR THE WEST VIRGINIA DIVISION OF HIGHWAYS

ABSTRACT

The West Virginia Division of Highways (WVDOH), like most other State Departments of Transportation, addresses roadway surface friction needs on a reactive basis: testing and analyzing sites either after some type of roadway surface friction-related incident, in places with large number of accidents or on specific locations with known issues or problems. This is done using a Locked Wheel Friction Tester, obtaining information at spot locations.

This paper establishes an engineering-based procedure, using Continuous Friction Measuring Equipment, to perform network roadway surface friction testing and using that information to define friction investigatory levels. This is demonstrated by the testing the Interstate, United States, and West Virginia Routes within the District Ten jurisdiction of the Division of Highways and determining Investigative Levels of roadway surface friction for various route categories. The paper also highlights the challenges faced when performing the procedure in a network environment and compares the GripTester data to the Locked Wheel Friction Tester data obtained simultaneously to help relate the results to previous experience.

The study found that for the United States Routes and the West Virginia Routes, there is relationship between crashes and friction, showing lower crash rates as the roadway surface friction increases. Thus, it was possible to determine illustrative friction investigatory levels these two categories of routes. However, the same relationship is not evident for the Interstate Routes. This could be because of the better geometric standards and higher friction values on these types of routes or because of the small sample available for the analysis.

KEYWORDS

INTRODUCTION

Roadway surface friction is an important pavement property that impacts safety and is typically measured for investigation of crash sites, identification of potential crash sites, evaluation of aggregate sources and as part of asphalt and concrete pavement construction quality acceptance, and in some cases as part of a systemic analysis of the road network. Pavement friction testing can be done following reactive or proactive approaches. Reactive approaches focus on testing areas with high number of wet or total crashes. In the State of West Virginia, up to this point, most all of the pavement friction testing has been performed on a reactive basis. Testing is done mainly to investigate the pavement areas where roadway-related crashes occur. If the area is found to have less surface friction than the surrounding roadway, then the area is usually mitigated to reestablish proper pavement friction.

Proactive approaches, on the other hand, use systematic pavement friction management programs. Agencies may test the entire or most critical segments of the roadway network at regularly scheduled intervals. This has many tangible benefits. For example, problem areas may be discovered before crashes, liabilities, and safety concerns are generated. Although these programs require significant funding, they can be cost-effective, as they produce important economic benefits for the society. West Virginia has done some limited systematic efforts by testing new resurfacing projects to determine if they meet the minimum friction value of 0.30 required for new pavements (Walbeck 2019).

Although the locked wheel friction tester is widely used for friction testing in the United States, the equipment has some limitations while used on a systematic network-level program, mainly because it only tests at spot or single locations. As State Departments of Transportation (DOTs) develop network-level friction testing programs, the use of continuous friction measuring equipment (CFME) appears to be more appropriate. These devices test friction continuously, creating a friction profile associated with the route’s milestones and critical locations.

Nationwide, the AASHTO Guide for Pavement Friction discusses a variety of friction-related concepts including friction testing equipment, friction testing methods, pavement characteristics to consider for friction, aggregate and surface types to promote pavement friction, and recommends the use of systematic friction management programs (AASHTO, 2008). Following the recommendations of this Guide, the West Virginia Division of Highways (WVDOH) decided
to explore the possibility and cost effectiveness of implementing systemic network-level friction management program to reduce crashes and associated facilities through a pilot effort.

OBJECTIVE

The objective of this paper is to describe the establishment of illustrative determination of the Investigatory Level of roadway surface friction for different road categories conducted as part of the development of a pilot network-level pavement friction management program for the WVDOH. The study analyzed Interstate, United States, and West Virginia Routes in the District Ten jurisdictional area.

BACKGROUND

To accomplish the objective, it is important to understand available friction management approaches for determining the investigatory level for network-level friction management, the equipment available for measuring pavement friction, and federal regulations related with pavement friction.

Pavement Friction Measurement

There are several methods and equipment to measure pavement friction. Before focusing on any pavement friction testing, it is critical to understand the mechanics of pavement friction. Pavement friction is the “force that resists the relative motion between a vehicle tire and a pavement surface” (Flintsch et al., 2012). Fig. 1 demonstrates this concept.
Most State DOTs rely on the Locked Wheel friction tester for measuring pavement friction. This equipment measures pavement friction by locking one of the tester’s tires as it travels through a film of water applied on the wheel path of the locked tire. It simulates braking maneuvers in vehicles not equipped with anti-lock brakes. This equipment is particularly useful for safety investigations by measuring spot or problem locations within roadway networks (Dynatest, 2016). The WVDOH Locked Wheel tester is shown in Fig. 2 and it complies with ASTM E274_E274M-11. Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire (ASTM, 2011).

Equipment that can measure friction continuously along the road are more appropriate for implementing pro-active pavement friction management programs. For example, in Europe, many countries use the Sideway-Force Coefficient Routine Investigation Machine (SCRIM). The SCRAM is a CFME that can measure 120 – 200 lane miles of pavement per day. This equipment uses a wheel that freely rotates at a yaw angle of 20° to the direction of travel behind a jet of water, like the other pavement friction testers (WDM, 2019). Fig. 3 Shows the SCRAM acquired by the Federal Highway Administration for demonstration as part of the Pavement Friction Management Support Program in the United States.
Another CFME is the GripTester that was used in this research and has been extensively used to test airport pavements. The GripTester is a pull-behind “fixed-slip” CFME that uses a smooth friction-measuring tire that slips constantly at a rate of 15% (AeroGroup, 2014). Like the Locked Wheel Friction Tester, a film of water is sprayed onto the path of the friction measuring tire while load and drag are measured and displayed graphically back to a connected laptop located in the
tow vehicle where all of the data is collected and stored. The GripTester acquired by FHWA and loaned for this project is shown in Fig. 4 and Fig. 5. Although the production of the Griptester is not optimal for network-level programs, it was used for this study because it was available at the time the field testing was conducted.

In addition to these high-speed methods of measuring roadway surface friction, there are also manual methods using portable equipment. These include the British Pendulum Tester and the Dynamic Friction Tester. The British Pendulum Tester is a base and frame device that determines friction through the swinging of a pendulum with a rubber pad on the end that makes contact with the pavement surface, generating a British Pendulum Number. The Dynamic Friction Tester tests roadway surface friction at various speeds by measuring the force on three small rubber sliders in a circle path as they slow down on a wetted pavement section. It provided the relationship between friction and speed (AASHTO, 2008).

Fig. 4 – Side View of GripTester.
Determination of Friction Thresholds

The analysis conducted for this paper generally followed the procedure outlined in the AASHTO Guide for Pavement Friction (AASHTO, 2008). The method chosen for defining friction investigatory and intervention levels is Method 3 - Establishing Thresholds Using Pavement Friction Distribution and Crash Rate—Friction Trend; which requires the following steps:

1. Plot a histogram of pavement segments and their corresponding Grip Number (in this case, 0.1 mile segments) along with the corresponding combined Wet to Dry Accident Ratio of the segments, as shown in Fig. 6.

2. Compute the mean pavement friction value as well as the standard deviation for the pavement friction histogram data.

3. Establish the Investigatory Level of the data by determining where the wet-dry crash ratio increases sharply. You may also compute the difference between this level and the network mean expressed as the number of standard deviations to (1.5 – 2.0) in the example to estimate the percentage of the network that will need to be investigated.

4. Establish the Intervention Level at a point where the Division of Highways would have the funding to correct the friction of that many pavement sections.
Although Method 3 includes guidance as to how to establish the investigatory and intervention levels, only Investigatory Levels (IL) are considered in this paper as the agency will not trigger corrective measures without a detailed investigation. Locations where the friction level is at or below the Investigatory Level, are investigated at the project level. After the investigation is conducted, the appropriate intervention and necessary treatment would take place is necessary.

**Fig. 6 - Histogram of Pavement Segments’ Grip Numbers vs. Wet/Dry Accident Ratio (AASHTO, 2008).**

The AASHTO Guide for Pavement Friction also specifies two other methods that were not considered in this research because they require historical pavement friction data, which are not available at the WVDOH.

**International Experience**

Prior research has been conducted in the development of establishing the Investigatory Level of road surface friction. One of the first countries to establish friction thresholds is the United Kingdom. Highways England established IL ranges for various types of roadway categories and geometric conditions, and the most recent values are summarized in Fig. 7. The agency measure friction using the parameter CSC, Characteristic Skid Coefficient, a representative roadway surface friction value measured using a Sideway-Force Coefficient Routine Investigation Machine.
(SCRIM) and adjusted to consider fluctuations due to weather and seasons effects throughout the year (Highways England, 2015).

<table>
<thead>
<tr>
<th>Site Category and definition</th>
<th>IL for CSC data (Skid data speed corrected to 50km/h and seasonally corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>A  Motorway</td>
<td></td>
</tr>
<tr>
<td>B  Non-event carriageway with one-way traffic</td>
<td></td>
</tr>
<tr>
<td>C  Non-event carriageway with two-way traffic</td>
<td></td>
</tr>
<tr>
<td>Q  Approaches to and across minor and major junctions, approaches to roundabouts and traffic signals (see note 5)</td>
<td></td>
</tr>
<tr>
<td>K  Approaches to pedestrian crossings and other high risk situations (see note 5)</td>
<td></td>
</tr>
<tr>
<td>R  Roundabout</td>
<td></td>
</tr>
<tr>
<td>G1  Gradient 5-10% longer than 50m (see note 6)</td>
<td></td>
</tr>
<tr>
<td>G2  Gradient &gt; 10% longer than 50m (see note 6)</td>
<td></td>
</tr>
<tr>
<td>S1  Bend radius &lt;500m - carriageway with one-way traffic (see note 7)</td>
<td></td>
</tr>
<tr>
<td>S2  Bend radius &lt;500m - carriageway with two-way traffic (see note 7)</td>
<td></td>
</tr>
</tbody>
</table>

Notes applicable to all:

1. The IL should be compared with the mean CSC, calculated for the appropriate averaging length.

2. The averaging length is normally 100m of the length of a feature if it is shorter, except for roundabouts, where the averaging length is 10m.

3. Residual lengths less than 50% of a complete averaging length may be attached to the penultimate full averaging length, providing that the Site Category is the same.

4. As part of site investigation, individual values within each averaging length should be examined and the significance of any values that are substantially lower than the mean values assessed.

Notes applicable to specific site categories

5. ILs for site categories Q and K are based on the 50m approach to the feature and, in the case of approach to junctions, through to the extent of the junction. The approach length shall be extended when justified by local site characteristics.

6. Categories G1 and G2 should not get applied to uphill gradients on carriageways with one-way traffic.

7. Categories S1 and S2 should be applied only to bends with a speed limit of 50 mph or above, except if the radius of the bend is <100 m, where the S1 and S2 categories shall be applied at all speeds.

**Fig. 7 – Site Categories and Investigatory Levels (Highways England, 2015).**
The English standard recommends that the roadway network be reviewed and tested at least once every three years, or approximately one-third of the network each year. In addition, consideration shall be given to sections of roadway network that have recently been changed or altered. The standard also recommends that each portion of the roadway network be allocated to a specific Site Category, which represent areas with different friction demands, and recommends ILs for each category given in conjunction with the crash risk of each portion. It is also important to note that the criteria in Fig. 7 is based on the strategic road network, a higher priority portion of the network. Thus, the values proposed may not be appropriate for local roads, which may not have the same design criteria as the strategic roadway network. Attention must be given to the different shading in the chart. The lighter gray shaded boxes signify that these values may be used in areas of low traffic flows, whereas the darker gray shaded boxes signify that these values may be used in areas of higher traffic flows (Highways England, 2015).

Transit New Zealand’s follows a similar roadway surface friction management approach to the United Kingdom. The agency originally adopted the United Kingdom standards and adjusted them as the agency gained experience. Roadway surface friction surveys have been taking place also since 1997, and historical trends have been developed. Transit New Zealand has developed a factor known as the Equilibrium SCRIM Coefficient to take into consideration that variations in the skid resistance vary regularly (NZTA, 2013).

Experiences from Other States

This section discusses the approaches used by other agencies for managing pavement friction in their networks.

*Virginia DOT’s Wet Accident Reduction Program (WARP)*

The Virginia DOT’s Wet Accident Reduction Program is an example of a successful reactive program. The purpose of this program is to determine locations where there are high occurrences of wet crashes along Virginia’s interstate and primary routes where the roadway surface friction may be questionable. In this program, the Virginia Department of Motor Vehicles (DMV) provides data for the WARP by sending crash data each calendar year to the Traffic Engineering Division. This cash data is used to determine Potential Wet Accident Hot Spots (PWAHS), which are areas where there are relatively higher numbers of wet crashes compared to dry accidents. These locations are recorded in the Highway Traffic Records Inventory System (HTRIS).
After the PWAHS are determined, the Pavement Design and Evaluation (PD&E) Section try to skid test each of the locations along the Interstate and Primary Routes. Prior to performing the skid tests, the group coordinate with the District Pavement Maintenance Engineers to see which of these locations are either already being corrected or are set to be corrected to avoid wasting time on unnecessary testing.

Lastly, the skid tests are performed, and the PD&E provides the skid data to the Central Office Virginia Information Technology Agency (CO VITA) for uploading back into the HTRIS. Historically, any location with a friction number using a smoot tire (FN400S) 20 or less is noted to require special attention. Recent research determined that a threshold of between 25 and 30 may be more appropriate (VDOT, 2009).

**Texas Wet Weather Accident Reduction Program**

The State of Texas also has a Wet Weather Accident Reduction Program (WWARP), which provides a “framework” for determining the pavement friction on existing facilities with high number of wet crashes. Results from this program has been used to spec the required friction on surfaces of new pavement, and to determine the effectiveness of the overall program. The program includes three interrelated phases: (1) analysis of wet-weather accidents, (2) selecting the optimum aggregate, and (3) conducting the skid testing.

The agency investigated different factors affect roadway friction demand, including geometry, traffic, number of trucks, and intersections. They found that climate also has a more profound impact and divided the State into the following four regions:

- Region I, wet with no freeze-thaw cycles,
- Region II, wet with freeze-thaw cycles,
- Region IV, dry with no freeze-thaw cycles, and
- Region V, dry with freeze-thaw cycles.

The first phase is that of the analysis of wet weather accidents. Performing the wet weather analysis will help to determine the locations of sites with wet weather crashes, the reasons behind the wet weather crashes at the locations, and how to take timely action in a systematic fashion; ensure that all pavement surfaces have an adequate amount of friction that will last; and ensure that all resources are used correctly to prevent wet crashed in the most economical way possible (TxDOT, 2006). The Traffic Operations Division determines which sites are “over-represented” with wet crashes and develops a list of sites to give to the Construction Division, Materials and
Pavement Section (CST M&P) to be distributed every year to the Districts. The Districts meet with the various local law enforcement and maintenance personnel to identify sites that potentially have problems and need for further investigation.

The friction information is also used for selecting the optimum roadway surface aggregate for various friction categories based on several different aspects. Table 1 illustrates these various aspects and their impact on roadway surface aggregate (TxDOT, 2006). The Low, Moderate, and High columns represent the designer’s consideration of required friction demand.

**Table 1 – Chart for Determining Surface Aggregate (after TxDOT, 2006).**

<table>
<thead>
<tr>
<th>Selection Guidelines for Bituminous Surface Aggregate Classification (SAC)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Demand for Friction</strong></td>
</tr>
<tr>
<td>Rain Fall (in./yr.)</td>
</tr>
<tr>
<td>Traffic (ADT)</td>
</tr>
<tr>
<td>Posted Speed (mph)</td>
</tr>
<tr>
<td>Trucks (%)</td>
</tr>
<tr>
<td>Vertical Grade (%)</td>
</tr>
<tr>
<td>Horizontal Curve</td>
</tr>
<tr>
<td>Driveways (per mi.)</td>
</tr>
<tr>
<td>Intersecting Rdwys (ADT)</td>
</tr>
</tbody>
</table>

| **Available Friction** | **Low** | **Moderate** | **High** |
| Cross Slope (in./ft.) | ≤ 1/4 | > 4 ≤ 2 | 3/8 - 1/2 |
| Surface Design Life (years) | > 7 | > 7 > 3 | ≤ 3 |
| Macro Texture of Proposed Surface | Fine (Examples: Microsurface, Type “F” HMAC) | Medium (Examples: HMAC Type “C” & “D”, CMHB, SuperPave, SMA) | Coarse (Examples: Seal Coat, PFC, OGFC) |

Skid testing is performed to determine whether the WWARP is being effective. Skid testing at 0.5-mile intervals takes place from May through August each year on sites requested by the CST-M&P. The skid data is stored and used later in program and project development as necessary (TxDOT, 2006).

**Caltrans Traffic Accident Surveillance and Analysis System (TASAS)**

The California Department of Transportation (Caltrans) initiated in 1972 the Traffic Accident Surveillance and Analysis System (TASAS) to identify areas where there were high amounts of crashes. The system also annually identifies areas with high amounts of wet crashes. Sites (0.2
mile) with 9, 6, or 3 wet crashes within either a 36 month, 24 month, or 12 month period, respectfully, are considered “significantly higher” in number than the statewide average. The Significance Test is based on the Poisson’s One-Tail Test.

The analysis is packaged into an annual report and is distributed to each of the 12 Caltrans Districts so the roads can be thoroughly reviewed based on several different criteria (i.e. friction, geometry, accident type) in the field during the rainy season. Sites that require interventions are placed in the queue for the appropriate method of repair, where most of them are funded through the FHWA’s Highway Safety Improvement Program (HSIP) (Caltrans, 2010).

Florida’s Crash Analysis Reporting (CAR) System

In the State of Florida, wet weather crashes are analyzed by the State Safety Office using the Crash Analysis Reporting System. A report is generated and given to each of the District Safety Engineers within the Florida Department of Transportation once a year.

The analysis is based on the previous five years’ worth of crash data, targeting roadway sections 0.3 mile in length that contain either four wet weather crashes with 25% or more wet weather crashes or 50% plus wet weather crashes over the previous five years. From this analysis, the District Safety request friction tests to be performed. If the friction tests are low, then the site is recommended for treatment. The DOT place all of their safety and improvement project into the Crash Reduction Analysis System Hub (CRASH) and computes their benefit/cost ratios.

In addition to the CAR System, Florida is one of the few states that has a systematic network-level friction testing program, in which roadways are tested once every three years (HNTB, UCF, and Wayne State University, 2008).

Michigan Department of Transportation (DOT)

The State of Michigan has been handling wet crashes for approximately 25 years. Although the analysis is not as elaborate as some of the other States, the Safety Programs Section maintains the list of locations requiring an investigation. The wet crash sites that make the list are based on routine friction tests where the Skid Number is 30 (SN40R) or below. The list, in turn, is given to each of the regions to review and evaluate to determine if further action or treatment is needed. Michigan DOT friction tests their roadway system once every three years (AASHTO, 2011).
Maryland State Highway Administration

The State of Maryland’s State Highway Administration, in 2009, contracted a research report to help the agency develop guidelines and policy to address roadway surface friction along their roadway network. The process included the definition of the network and friction demand categories (Table 2) with associated friction thresholds for SN40 (Speir, et. al, 2009).

<table>
<thead>
<tr>
<th>Site Category</th>
<th>Site Description</th>
<th>Threshold SN</th>
<th>Investigatory SN</th>
<th>Intervention SN</th>
<th>Demand Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Approach railroad crossings, traffic lights, pedestrian crossings, Stop and Give Way controlled intersections (SH only).</td>
<td>55</td>
<td>90</td>
<td>45</td>
<td>High</td>
</tr>
<tr>
<td>2</td>
<td>Curves with radius ≤250m, downhill gradients &gt; 10% and &gt; 50 m long. Freeway/highway on/off ramp.</td>
<td>45</td>
<td>40</td>
<td>35</td>
<td>High</td>
</tr>
<tr>
<td>3</td>
<td>Approach to intersections, downhill gradients 5 to 10%.</td>
<td>45</td>
<td>40</td>
<td>35</td>
<td>High</td>
</tr>
<tr>
<td>4</td>
<td>Undivided Highways without other geometric constraints which influences frictional demand.</td>
<td>40</td>
<td>35</td>
<td>30</td>
<td>Low</td>
</tr>
<tr>
<td>5</td>
<td>Divided highways without any other geometrical constraints which influences frictional demand.</td>
<td>35</td>
<td>30</td>
<td>25</td>
<td>Low</td>
</tr>
</tbody>
</table>

Federal Regulations of Roadway Surface Friction

In addition to understanding pavement friction principles and measuring equipment, it is important to highlight that authorities, such as the FHWA encourages the measuring pavement friction. Technical Advisory T 5040.38 states that in 23 Code of Federal Regulations, 626.3, it is recommended that each State DOT implement a “data-driven” Highway Safety Improvement Program and to have "A process for collecting and maintaining a record of... roadway... data on all public roads" (Federal Highway Administration, 2010). Federal funding is available for pavement friction testing in the Federal Statewide Transportation Improvement Program (STIP), of which the WVDOH already actively participates.

The STIP is the mechanism by which the West Virginia Division of Highways accesses its Federal-Aid funding administered by the Federal Highway Administration. This funding provides the ability to perform an additional estimated $425 million of construction projects each year.
within the roadway network. The STIP is broken into several core funds, including the Highway Safety Improvement Program (HSIP) (WVDOT, 2016b).

The expenses for roadway surface friction testing are eligible for reimbursement as part of the Highway Safety Improvement Program. Currently, the WVDOH has two open funding authorizations of this type. Both have been funded by apportionments of the Highway Safety Improvement Program in the STIP. They are in the amounts of $200,000 and $250,000. To begin friction testing the entire West Virginia Division of Highways roadway network, authorizations in the future will need to be significantly increased and instituted.

**DATA COLLECTION**

**Network Tested**

To initiate a network level friction management program, it is best to first focus on pilot that covers a manageable portion of the network. Thus this research measured a portion of the network that one can test and analyze using limited amounts of resources such as time, labor, equipment, and funding and refined the testing and process procedures, before applying the procedures to the entire roadway network (WVDOT, 2016a).

**West Virginia Division of Highways District 10**

The WVDOH is divided in ten Districts. Each District is normally comprised of four to six counties, depending on size. District 10 was selected for the pilot procedure because of its proximity to Virginia Tech and the data collector’s residency. The district is comprised of four counties: McDowell, Mercer, Raleigh, and Wyoming Counties. It includes a segment of Interstate 64, from the junction of the West Virginia Turnpike (Milepost 121) to the Sam Black Church Exit (Milepost 155), as well as several US, State and local routes.

**Routes Chosen for the Network Testing**

The District contains 3,176 miles of roadway, of which 2,373 miles are paved with asphalt or concrete pavement (WVDOH, 2014). To limit the time to test and cost of the pilot, it was decided to limit scope to the higher priority WVDOH routes within the District 10 area: Interstate, United States, and West Virginia Routes. In total, 43 miles of Interstate Routes, 115 miles of United States Routes, and 406 miles of West Virginia Routes were tested and analyzed.
Data Collection Challenges

Testing Speed

Prior to testing, it was decided to perform the testing at a test speed of 40 miles per hour; however, it was difficult to maintain a constant 40 miles per hour for a number of reasons. First, when conducting roadway surface friction testing in a network setting, there are a number of different roadway speed limits. Testing the Interstate Routes, the posted speed limit is 70 miles per hour. At 70 miles per hour, the testing vehicle became a traffic obstacle moving at just over half the rate of speed as everyone else. On the other side of the spectrum, when measuring the some of the United States Routes and the West Virginia Routes, there were posted speed limits in many locations of less than 40 miles per hour, often 25-35 miles per hour. In these cases, the roadway surface friction was tested as close to 40 miles per hour as possible, given the low speed limit and the amount of traffic and traffic flow impeding the testing.

Availability of Water in Rural Locations

When performing roadway surface friction testing at the network level, access to resources, such as water, is critical. The water tank of the GripTester available holds 250 gallons, allowing one to test up to around 15 miles of roadway with each tank load. Consequently, one spends almost as much time, or more, looking for and filling the water tank than performing the testing.

When the testing occurred near municipalities, access to water from fire hydrants was no problem. Fire departments and town water officials were glad to be of service and never charged the WVDOH for the estimated 11,000 gallons of water used throughout the entire testing period.

On the other hand, when network level testing in the rural areas of the network, water became a major issue. Therefore, a much larger water tank would be required if the pilot is expanded to cover the entire state.

DATA PROCESSING AND ANALYSIS

After the raw friction data has been collected, it must be cleaned and processed so that it can be analyzed. The raw data contained friction measurements taken every three feet at various speed and this had to be adjusted to reflect the friction at the designated friction testing speed. Next, crash data from each route was added to the friction data. The basic crash types needed for the analysis included wet crashes and dry crashes. Once the friction data has been processed and the
crash data assembled with the friction data, the data will then be ready for analyzing. A modified version of the Method 3 from the *AASHTO Guide for Pavement Friction* (AASHTO, 2008) was then used to investigate the relationship between friction and crashes.

**Grip Number Data Processing**

The first step in the analysis was to determine a characteristic friction value or Grip Number for each segment of each roadway section. To make this determination, several different methods could be used. This pilot subdivided each route into 0.1-mile segments and established a characteristic Grip Number for each segment. To determine the Grip Number for each 0.1 mile segment, the data was imported into a spreadsheet, including the columns for Chainage, GN (Grip Number), Load (measured in kg), and Speed (measured in miles per hour), as shown in Table 3. The raw Grip Number measurements needed to be corrected since the actual test speeds deviated from the ideal test speed of 40 miles per hour. These measurements were corrected by using the Eq. 1 (de León et al., 2016) and referred to as Modified Grip Numbers (labeled as “Modified GN” in Table 3):

\[
\text{Modified GN} = \text{GN} - ((40 - \text{Speed}) \times 0.007)
\]  

(1)

Next, the 60’ Moving Average Modified Grip Number was computed as it represents a compromise between disregarding very short variations and capturing the worst locations as it tested by the Locked Wheel Friction Tester, which averages the friction over 1 second (measuring 59’ at 40 mph). To reflect the worst condition with each management unit, the lowest value of the 60’ Moving Average Modified Grip Number within each 0.1-mile section of the route was selected.
Table 3 – Sample of GripTester Data from Calculations Spreadsheet.

<table>
<thead>
<tr>
<th>Chainage</th>
<th>Milepost</th>
<th>GN</th>
<th>Load</th>
<th>Speed</th>
<th>Modified GN</th>
<th>60' Moving Average</th>
<th>Tenth Mile GN</th>
</tr>
</thead>
<tbody>
<tr>
<td>3276</td>
<td>0</td>
<td>0.65</td>
<td>360</td>
<td>39.8</td>
<td>0.648</td>
<td>0.634</td>
<td>0.621</td>
</tr>
<tr>
<td>3279</td>
<td>0.000568</td>
<td>0.64</td>
<td>375</td>
<td>39.8</td>
<td>0.638</td>
<td>0.633</td>
<td></td>
</tr>
<tr>
<td>3282</td>
<td>0.001136</td>
<td>0.63</td>
<td>363</td>
<td>39.8</td>
<td>0.628</td>
<td>0.632</td>
<td></td>
</tr>
<tr>
<td>3285</td>
<td>0.001705</td>
<td>0.63</td>
<td>360</td>
<td>39.8</td>
<td>0.628</td>
<td>0.632</td>
<td></td>
</tr>
<tr>
<td>3288</td>
<td>0.002273</td>
<td>0.62</td>
<td>362</td>
<td>39.8</td>
<td>0.618</td>
<td>0.632</td>
<td></td>
</tr>
<tr>
<td>3291</td>
<td>0.002841</td>
<td>0.63</td>
<td>366</td>
<td>39.8</td>
<td>0.628</td>
<td>0.632</td>
<td></td>
</tr>
<tr>
<td>3294</td>
<td>0.003409</td>
<td>0.64</td>
<td>375</td>
<td>39.8</td>
<td>0.638</td>
<td>0.632</td>
<td></td>
</tr>
<tr>
<td>3297</td>
<td>0.003977</td>
<td>0.64</td>
<td>365</td>
<td>39.8</td>
<td>0.638</td>
<td>0.631</td>
<td></td>
</tr>
<tr>
<td>3300</td>
<td>0.004545</td>
<td>0.65</td>
<td>364</td>
<td>39.8</td>
<td>0.648</td>
<td>0.631</td>
<td></td>
</tr>
<tr>
<td>3303</td>
<td>0.005114</td>
<td>0.64</td>
<td>362</td>
<td>39.8</td>
<td>0.638</td>
<td>0.630</td>
<td></td>
</tr>
<tr>
<td>3306</td>
<td>0.005682</td>
<td>0.64</td>
<td>363</td>
<td>39.8</td>
<td>0.634</td>
<td>0.630</td>
<td></td>
</tr>
<tr>
<td>3309</td>
<td>0.00625</td>
<td>0.64</td>
<td>368</td>
<td>39.8</td>
<td>0.638</td>
<td>0.629</td>
<td></td>
</tr>
<tr>
<td>3312</td>
<td>0.006818</td>
<td>0.63</td>
<td>356</td>
<td>39.8</td>
<td>0.628</td>
<td>0.629</td>
<td></td>
</tr>
<tr>
<td>3315</td>
<td>0.007386</td>
<td>0.63</td>
<td>361</td>
<td>39.8</td>
<td>0.628</td>
<td>0.629</td>
<td></td>
</tr>
<tr>
<td>3318</td>
<td>0.007955</td>
<td>0.63</td>
<td>355</td>
<td>39.8</td>
<td>0.628</td>
<td>0.629</td>
<td></td>
</tr>
</tbody>
</table>

Comparison of Friction Results

Because of the higher spatial resolution of the measurements, only the GripTester measurements were used for determining the Investigatory Levels. However, to be able to relate these values to current practice, the WVDOH-owned Locked Wheel Friction Tester tested in tandem at 0.5-mile intervals and these values were compared with the corresponding GN values. The Locked Wheel Tester was equipped with an ASTM E501 ribbed test tire.

The 60' rolling average Grip Number measurements at locations of the Locked-Wheel Friction Tester measurement were compared to the Skid Numbers at those locations. The Skid Numbers, unlike the Grip Numbers, were not corrected for speed because most all of the measurements were within a few miles per hour of the 40 mph preferred testing speed. The values were compared using orthogonal regression; the analysis was done for each route type and for all the tested network. Fig. 8 shows the results of the orthogonal regression for all routes.
Fig. 8 – Orthogonal Regression of Skid Number and Grip Number for All Route Types.

Table 4 compares the descriptive statistics and orthogonal regression results for the two pieces of equipment on the Interstate, United States, West Virginia, and all route categories analyzed in combination.
Table 4 – Orthogonal Regression comparison of GN and SN/100.

<table>
<thead>
<tr>
<th>Route Type</th>
<th>Interstate</th>
<th>United States</th>
<th>West Virginia</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locked-Wheel Skid Number / 100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.52</td>
<td>0.56</td>
<td>0.52</td>
<td>0.53</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.07</td>
<td>0.09</td>
<td>0.12</td>
<td>0.11</td>
</tr>
<tr>
<td>GripTester Grip Number</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.43</td>
<td>0.52</td>
<td>0.42</td>
<td>0.45</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.09</td>
<td>0.15</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>Orthogonal Regression</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variance Ratio</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.42</td>
<td>0.67</td>
<td>0.74</td>
<td>0.72</td>
</tr>
<tr>
<td>Intercept</td>
<td>-0.58</td>
<td>-0.68</td>
<td>-0.42</td>
<td>-0.47</td>
</tr>
<tr>
<td>Slope</td>
<td>1.93</td>
<td>2.12</td>
<td>1.61</td>
<td>1.73</td>
</tr>
<tr>
<td>LowerCL</td>
<td>1.26</td>
<td>1.87</td>
<td>1.52</td>
<td>1.64</td>
</tr>
<tr>
<td>UpperCL</td>
<td>3.41</td>
<td>2.42</td>
<td>1.72</td>
<td>1.83</td>
</tr>
<tr>
<td>Alpha</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

The analysis resulted in equations 2 through 5. A review of the results suggests that the model for the routes provides the best representation. Since the sample size for each of the individual route categories is relatively small, combining the route categories provides a better sample size. In addition, combining the route categories also maximizes the exposure to all of the possible roadway factors that may affect this relationship and provides a wider range of friction. Therefore, equation 5 is recommended.

\[
SN = 51.8*GN + 30 \text{ for Interstate Routes} \quad (2) \\
SN = 47.2*GN + 32 \text{ for United States Routes} \quad (3) \\
SN = 62.1*GN + 26 \text{ for West Virginia Routes} \quad (4) \\
SN = 57.8*GN + 27 \text{ for All Routes Combined (Preferred)} \quad (5)
\]

Crash Data Processing

To determine the number of crashes for each 0.1-mile route segment, the WVDOH Traffic Engineering Division personnel searched for all crashes occurring within a three-year period prior to the testing and extracted all of the crash information into a spreadsheet.

Each of the crashes in the database include a large number of attributes; however, the primary category of interest to this analysis is the “RoadSurfaceCondition” column, which indicated whether the crash occurred on a wet road surface, dry road surface, or other type of road surface such as frost, ice, snow, and mud. The crashes were filtered out by date and sorted by milepost so
that each crash could be associated with a particular 0.1-mile segment. Following the procedure of the AASHTO Guide, only the wet crashes and dry crashes over a three-year period prior to the pavement friction testing were included in the calculations.

Many of the 0.1-mile sections of the District Ten network had zero recorded wet and dry crashes. These sections, of course, did not contribute to the wet crash / dry crash ratio calculations; however, they were included as a part of the vehicle miles travelled, and therefore, factored in to the Normalized Crash Rate calculations, as discussed following.

**Modification of AASHTO Method 3**

Although Step 4 of Method 3 in the AASHTO Guide for Pavement Friction recommends establishing Intervention Levels, they were not used in this study because highway agencies will not automatically trigger any kind of maintenance treatment to correct deficiency without a proper investigation. Interventions are only triggered if the investigation concludes that it is necessary. Therefore, only Investigatory Levels (IL) as threshold values.

In addition, plotting the Wet–Dry Crash Ratio against friction provided little or no tangible relationships. Since both wet and dry crashes are reduced with the increase of friction (Najafi et al, 2015), instead of using a Wet-Dry Crash Ratio, a Normalized Crash Rate, computed as (wet + dry crashes)/ hundred million vehicle miles travelled (HMVMT), was used.

**RESULTS**

This section presents the results of the analysis of the relationship between crashes and friction for each route category.

**Interstate Routes**

As mentioned previously, 43.5 miles, comprised of 436 0.1-mile segments, of Interstate 64 were tested. Fig. 9 shows the friction distribution and the average crash rates for each friction bin. There are no apparent trends in the Normalized Crash Rate (which stays below approximately 100 crashes per 100 million vehicle mile travelled) with respect to roadway surface friction on the surveyed Interstate Routes as indicted by the trend curve, which showed no increase in crash rate with reduced friction. Therefore, it was not possible to define an investigatory level. This results are consistent with those reported in Parry and Viner (2005), shown in Fig. 10, which shows a very weak relationship between crash risk and skid resistance on the English motorways. As Interstate
Routes are designed using established geometric design standards and maintained to better levels than the other routes, friction may not be as critical as in the other categories. However, it must be noted that the 43.5 miles measured may not provide enough sections in this category to determine a clear relationship between crashes and friction.

![Normalized Crash Rate Graphical Representation of Test Results for Interstate Routes.](image)

**Fig. 9 – Normalized Crash Rate Graphical Representation of Test Results for Interstate Routes.**
**United States Routes**

The relationship between crashes and friction for the 114.6 miles of United States Routes tested is depicted in Fig. 11. In this case, there is a much clear relationship as illustrated by the approximate trend line overlaid to the plot, which shows an increase in the slope at a GN level of approximately 0.30 (mean – 1.5 standard deviations). This friction level corresponds to an approximate crash rate of 270 crashes per 100 million vehicle miles travelled.
The results for the 403.00 miles of West Virginia Routes are presented in Fig. 12. The figure shows a strong association between crashes and friction, with an increase in crashes as friction decreases. However, no sharp increase in crashes can be observed, which makes it harder to define a threshold Investigatory Level. One possible reason is that the distribution of friction seems bimodal as it shows two different picks suggesting that this category includes two different types of roads. In addition, West Virginia Routes have typically lower posted speed limits than Interstate and United States Routes, which will result in lower friction requirements. They also include more intersections with even lower volume roads. Even though crash data and roadway surface friction impact fluctuate more so than in the United States Routes data, the routes have typically lower speeds and thus may have lower friction demands. A value lower than the one selected for the United State routes seems appropriate; and a GN was 0.24 selected for illustration purposes (mean...
– 1.4 standard deviations), which corresponds approximate to the same “risk” level than for the one corresponding to the Investigatory Level selected for the United States routes.

![Graphical Representation of Grip Number vs. Normalized Crash Rate for West Virginia Routes.](image)

**Fig. 12 - Graphical Representation of Grip Number vs. Normalized Crash Rate for West Virginia Routes.**

**DISCUSSION**

In the original instructions from Method 3, the Wet/Dry Crash Ratio is to be plotted. However, trends observed were not clear as illustrated in Fig. 13.
For this reason, the Normalized Crash Rate was used instead. Although the crashes are not necessarily proportional to the traffic level, it was considered that it was important to normalize for exposure to be able to assess the level of “risk” associated with various friction levels as discussed previously in the paper.

For the Interstate Routes, no correlation between Grip Number and Normalized Crash Rate was observed. For the United States Route Category, a correlation between Grip Number or Skid Number and Normalized Crash Rate was very prevalent. For the other two categories, the trends were clearer, showing a decreasing crash rate as friction increased. Table 4 shows the illustrative Investigatory Levels determined and the corresponding crash risks. The IL for the United States Routes are higher than for the West Virginia routes probably because of the higher speed limits.

Table 4 - Crash Risk at Selected Investigatory Level for Each Route Category.

<table>
<thead>
<tr>
<th>Route Category</th>
<th>Investigatory Level</th>
<th>Crash Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GN</td>
<td>~ SN</td>
</tr>
<tr>
<td>Interstate</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>United States</td>
<td>0.30</td>
<td>46</td>
</tr>
<tr>
<td>West Virginia</td>
<td>0.24</td>
<td>41</td>
</tr>
</tbody>
</table>
The current study only considered three friction demand categories associated with the route category. According to the Federal Highway Administration, roadways must have the amount of pavement friction that allow drivers to safely maintain their vehicle in their lane without incident. This amount of friction that vehicles require for safe maneuvering is Friction Demand (FHWA, 2016). Thus, the amount of Friction Demand depends not only on the type of roadway facility that the vehicle is traversing at the time but also on other factors. For example, on horizontal tangent sections vehicles require less friction than in the other areas of critical need such as intersections, horizontal curves, and steep grades. In these areas of critical need, additional roadway friction is necessary because of vehicle maneuverability, vehicle stopping ability, and vehicle tire traction (FHWA, 2016). Additional research (including additional data collection) to further separate curves, intersections and section with ramps.

CONCLUSIONS

The following conclusions can be drawn from the pilot analysis of friction and crashes on District Ten of the WVDOH:

1. For the United States Routes and the West Virginia Routes, there is relationship between crashes and friction, showing lower crash rates as the roadway surface friction increases.
2. The same relationship is not evident for the Interstate Routes. This could be because of the better geometric standards and higher friction values on this type of routes, or because of the small sample of Interstate segments available for the analysis.
3. It was possible to determine illustrative friction investigatory levels the United States Routes and the West Virginia Routes that can be used by the agency to identify potentially hazardous locations that would need safety investigations. A larger study would be needed to verify these values, as the sample used was relatively small.

In addition to these conclusions, lastly, this procedure has established a baseline that will serve as a launch point for the West Virginia Division of Highways’ pro-active pavement friction management program. It has also provided valuable lessons learned while going through the data acquisition portion to the analysis portion that will also prove to be valuable for many years to come.
ACKNOWLEDGEMENTS

The GripTesters was made available from the Federal Highway Association with the support of the Surface Properties Consortium Pooled-Fund Project. The support of Shahriar Najafi, Edgar de Leon Izeppi, and William “Billy” Hobbs from VTTI and Donna Hardy, Steve Marshall, Jason Criss, Ray Spencer, Guy Wolfe, and Alan Reed from the WVDOH for the data collection was instrumental for the completion of the project.
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CHAPTER 3 - FRICTION-BASED SAFETY PERFORMANCE FUNCTIONS FOR THE WEST VIRGINIA DIVISION OF HIGHWAYS ROADWAY NETWORK

ABSTRACT

The safety of traveling motorists is a priority when operating any roadway transportation network. The West Virginia Division of Highways manages a large roadway network that traverses a mountainous topography with an array of unusual horizontal and vertical alignments as well as intersections. Vehicle crashes are prone to occur while traffic navigates the network, and pavement surface properties have an impact on when and how these crashes occur.

This paper presents the development of sample safety performance functions and associated best crash estimates using the empirical Bayes method for a sample of roads in one of the West Virginia Division of Highways districts. The data collected included traffic, crashes, friction, and geometric information for a sample of roadway network sections in the district. The models for the U.S. and West Virginia routes incorporated traffic, roadway surface friction (grip number), and other geometric parameters. Results of this work suggest that safety improvement treatments can result in crash reductions on the types of roadways sampled. Finally, a case study is presented to illustrate how the safety performance functions can be used to support a systemic approach for identifying friction improvement projects for the state’s Highway Safety Improvement Program.

Keywords: Safety Performance Function, Empirical Bayes Method, Roadway Surface Friction, GripTester
INTRODUCTION

The West Virginia Division of Highways’ (WVDOHs’) roadway network is composed of 38,770 miles of roadway and traverses a mountainous topography with an array of unusual horizontal and vertical alignments (www.transportation.wv.gov). The safety of traveling motorists is a priority in this roadway network’s operations. However, as is true for any roadway facility, vehicle crashes are prone to occur in various locations within the network for a variety of reasons.

To reduce the number of these crashes and their associated injuries and fatalities, it is important for the WVDOH to be aware of the locations of crash-prone areas, understand the expected average crash rates for each type of roadway, and determine which sections have above average crash rates so these sections may be improved. This can be accomplished through the development of safety performance functions (SPFs).

Safety performance functions are regression equations that determine average crash frequencies given certain influencing traffic and roadway parameters. The American Association of State Highway and Transportation Officials’ (AASHTO) Highway Safety Manual discusses in detail the concepts of SPFs and their usage (AASHTO, 2010). Srinivasan et al. (2013a) recommended that each state Department of Transportation (DOT) or transportation entity develop its own SPFs to predict traffic crashes along their roadway network instead of relying on those already developed and used in various publications.

In addition to creating SPFs, crash analyses typically develop best crash estimates using SPFs in conjunction with the empirical Bayes (EB) method. This method produces crash estimates that reduce the bias between a regression and its corresponding mean value. The method assigns a weight to both, the observed number of crashes and the regression-determined number of crashes, to produce the best estimate of the expected crashes at each location (Hauer, et. al, 2002).

OBJECTIVE

This paper documents the development of sample SPFs for interstate, U.S., and WV routes that incorporate roadway surface friction and geometric characteristics. The paper also illustrates the use of the SPFs in conjunction with the EB method to determine best crash estimates,
identify sites for friction improvement treatment, and estimate the potential crash reductions resulting from the improvements.

BACKGROUND

West Virginia Pilot Pavement Friction Management Program

The work presented in this paper is part of a bigger effort to develop a pilot Pavement Friction Management Program for the WVDOH, the goal of which is to reduce crashes and associated injuries and fatalities by implementing a systematic, proactive methodology to identify and correct friction deficiencies in the state roadway network. Previous steps included the investigation of friction levels in various road categories and the determination of Investigatory Friction Levels for the interstate, U.S., and WV routes.

The SPFs and EB crash estimates presented in this paper are being incorporated into a network-level analysis process that will identify the roadway sections with the highest potential for crash and fatality reductions that could result from the application of friction improvement interventions.

Examples from Other State Agencies

Several states, such as Colorado, Illinois, and North Carolina, have chosen to develop their own SPFs for their specific needs rather than calibrating those found in the Highway Safety Manual (Srinivasan et al., 2013). Other states that have taken significant steps in this direction include Pennsylvania (Donnell et al., 2013) and Virginia (de León et al., 2015).

Colorado

The Colorado DOT developed SPFs for 10 different intersection configurations. The state collected mainline annual average daily traffic (AADT) and crash data along with side-street AADT from the years 2000 to 2004 to develop the SPFs (Persaud et al., 2009).

Illinois

In Illinois, SPFs were developed for various roadway segments as well as intersection configurations. The data used to develop the SPFs—traffic volume, roadway segment length, and regression parameters—were used for Type-A Injury, Type-B Injury, and Fatal and Injury
crashes. To develop SPFs for intersections, major and minor route traffic volumes and regression parameters were used for the same injury crashes (Tegge et al., 2010).

**North Carolina**

In North Carolina, SPFs for both roadway segments and intersection configurations from the Highway Safety Manual were calibrated using North Carolina data; however, new SPFs were also developed for various roadway segments. These SPFs were developed using only AADT (Srinivasan et al., 2011).

**Pennsylvania**

Donnell et al. (2014) provide details of the methodology used to develop the SPFs in Pennsylvania. The researchers used existing roadway management system files containing information on existing traffic volumes, roadway functional classifications, roadway cross-sections, speed limits, traffic control, and intersection locations to develop their SPF functions on two-lane rural roadways and intersections.

**Virginia**

A pilot study performed for the Virginia DOT (VDOT) within the jurisdiction of the Salem District, developed SPFs that incorporated roadway surface friction and horizontal curvature of the roadway alignment. The segment length used in this pilot study was also 0.1 mile (de León et al., 2015). The study discussed in this paper builds upon the VDOT study and incorporates additional elements, such as cross-slope or superelevation.

**METHODOLOGY**

**Data Collection**

The development of SPFs is based upon data collected from different sources within the WVDOT and additional friction values measured directly in the field. The State of West Virginia is broken into ten highways Districts. District Ten, the southernmost district in the state, was selected for this study because it has some of the most challenging terrain and unique roadway layouts in West Virginia. The Interstate Routes, United States Routes, and West Virginia Routes within the District were broken into 0.1-mile analysis segments, and various types of data were associated with each segment. The data collected included traffic, roadway surface friction,
geometrical characteristics, and wet and dry crashes for a 3-year period prior to testing the roadway surface friction. The friction, curvature and cross-slope were considered potentially influential variables in the negative binomial regression to develop the safety performance functions for each of the roadway categories.

All data collected were integrated in a Microsoft Excel workbook with a separate spreadsheet for each roadway category. Having all the data in one location facilitated data transfer and processing.

Traffic

AADT values are critical in developing SPFs, as without traffic there would be no crashes. The traffic data at the time of the study were obtained from the department’s databases.

Roadway Surface Friction

The roadway surface friction (Grip) was also selected as a potential predictor variable because it is necessary for proper vehicle control. The roadway surface friction on the road network investigated was measured using a continuous friction measuring device (GripTester) and was expressed in terms of Grip Number (GN). Since friction data was collected every 3 feet, the data were processed to assign each 0.1-mile segment a representative GN. To do this, the friction was averaged on a 60-foot rolling average, and the minimum 60-foot rolling average within each 0.1-mile section was selected as the representative GN for that section.

Roadway Geometric Characteristics

The horizontal curve radius (CVRAD) was also considered a predictor due to its impact on vehicular travel. The smaller the horizontal CVRAD, the more carefully and slowly vehicles must traverse the roadway. Although roadways are typically designed to provide appropriate traversing speeds for the road category, throughout WV, roads have frequently evolved from existing paths and some alignments do not meet any design criteria. Roadways such as these are often a challenge for motorists to traverse and are prone to inducing crashes in many locations.

Roadway cross-fall or superelevation is also important. The rate of superelevation assists motorists in traversing horizontal curves, and roadways that are not sloped or “banked” correctly can cause vehicle crashes. In the original data, superelevation values for left-hand curves were assigned negative values, whereas superelevation values for right-hand curves were assigned
positive values. For the purposes of the SPF development, all of the superelevation values (XFALL) were made positive, so that both left-hand and right-hand curves were evaluated equally.

The dominant horizontal geometry and cross-fall were computed for each 0.1-mile segment. The data were obtained from a pavement survey by Fugro using an Automatic Road Analyzer (ARAN®) System. The available data included the various horizontal geometric elements, such as the starting and ending milepost, length, curve direction, degree of curvature, curve radius, whether the geometry was a curve or tangent, and the roadway superelevation.

The data were matched based on the centerline progressive, and the actual horizontal and vertical geometries that occupied the majority of the 0.1-mile centerline were chosen as the representative geometries.

**Wet and Dry Crashes**

The crash data were provided by the WVDOH’s Traffic Engineering Division. A 3-year period prior to the 2012 roadway surface friction study was used to determine the number of wet and dry crashes. Ice/snow/other crashes were not used in any of the calculations. The wet and dry crash counts were accumulated for each of the 0.1-mile segments.

**Development of the Safety Performance Functions**

SPF development typically begins as a review of crash data within a determined segment length of the roadway. According to Lord and Mannering (2010), since crash-frequency data are non-negative integers, the use of standard ordinary least-squares regression that assumes continuity of a dependent variable is not appropriate. Because the data are non-negative integers, the Poisson regression model was initially considered.

However, when comparing the Poisson distribution to real traffic scenarios, the actual fluctuation is considerably higher than the calculated variance of the Poisson distribution, and the variance is larger than the conditional mean. This is known as over-dispersion. Over-dispersion is caused by other factors not considered in the model that affect vehicle crashes. To counteract the over-dispersion, it is recommended that a Gamma distribution or negative binomial distribution be used to estimate crash rates for segments with similar characteristics. In the negative binomial regression model, the Poisson parameter is rewritten as shown in Equation 6 (Lord & Mannering, 2010):
\[ \lambda_i = \text{EXP}(\beta X_i + \varepsilon_i) \]  \hspace{1cm} (6)

where

\[ \lambda_i = \text{Expected number of crashes per year for road segment } i \]

\[ \beta = \text{Vector of model parameters} \]

\[ X_i = \text{Vector of roadway characteristics for segment } i \]

\[ \text{EXP}(\varepsilon_i) = \text{gamma-distributed error term with mean 1 and variance } = \lambda_i + \alpha \lambda_i^2 \]

\[ \alpha = \text{over-dispersion parameter}. \]

These regression models, developed based on years of crash data from similar roadways with varying AADTs, are known as SPFs.

**The Empirical Bayes Method and Its Mathematical Form**

As mentioned previously, the EB method can be used to determine “best” future crash estimates along roadway segments with similar characteristics and attributes, using both the mean value from developed SPFs and the observed crashes.

The EB method achieves this result by first assigning weights to both the estimated mean values and the observed crash counts. The weight for each of these data is calculated from Equation 7. The best crash estimate value (B) then can be determined from Equation 8 (Hauer et. al., 2002).

\[ W = \frac{1}{1 + (\alpha \times \lambda_i))} \]  \hspace{1cm} (7)

where,

\[ W = \text{factor assigned to the expected crashes value} \]

\[ \lambda_i = \text{the number of accidents expected on similar roadway segments (from the SPF)} \]

\[ \alpha = \text{over-dispersion parameter}. \]

\[ B = (W \times \lambda_i) + (1 - W) \times \text{OC} \]  \hspace{1cm} (8)

where \( \text{OC} \) are the observed crashes along a roadway segment.
RESULTS AND DISCUSSION

Once all the data were entered in the software to develop the model for each of the roadway categories, the model associated with the minimum Akaike criterion information (AIC) value was selected for each of the roadway categories.

Interstate Routes

A correlation matrix was developed for each of the data elements considered a potential predictor variable. Table 5 shows that traffic has a relatively high correlation with wet, dry, and total crashes. In addition, it also shows high correlation between the friction and the traffic, suggesting that higher traffic roads are maintained to a higher friction level. Finally, as expected, the total wet and dry and total crashes are correlated. This is reasonable, as roadway areas that are prone to crashes under dry conditions would probably also have crashes under wet conditions. The results for the “best fit” negative binomial regression for the interstate routes using the RStudio software are presented in Table 6.

Table 5 – Correlation Matrix of Interstate Routes Data.

<table>
<thead>
<tr>
<th></th>
<th>GRIP</th>
<th>CVRAD</th>
<th>XFALL</th>
<th>LNAADT</th>
<th>Wet</th>
<th>Dry</th>
<th>TotalWD</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRIP</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CVRAD</td>
<td>0.0179</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XFALL</td>
<td>0.0448</td>
<td>0.0323</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LNAADT</td>
<td>0.604</td>
<td>0.00373</td>
<td>0.0963</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet</td>
<td>0.166</td>
<td>-0.0169</td>
<td>0.0301</td>
<td>0.246</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry</td>
<td>0.175</td>
<td>-0.0848</td>
<td>0.00315</td>
<td>0.279</td>
<td>0.588</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>TotalWD</td>
<td>0.189</td>
<td>-0.0712</td>
<td>0.0122</td>
<td>0.296</td>
<td>0.779</td>
<td>0.965</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 6 – Statistics from RStudio on Interstate Route Coefficients.

|             | Estimate | Standard Error | Z Value | Pr(|z|)    |
|-------------|----------|----------------|---------|----------|
| Intercept   | -16.0    | 2.34E+00       | -6.86   | 6.80E-12 |
| LNAADT      | 1.68     | 2.43E-01       | 6.91    | 4.87E-12 |
| CVRAD       | -4.24E-10| 1.93E-10       | -2.19   | 0.0282   |
The resulting Equation 9 is provided following. The AIC value for this model is 1063.3 and the 2 x log-likelihood value is -1055.3.

\[
SPF = ADT^{1.68} e^{(-16 - 4.24 \times 10^{-10} CVRAD)}
\]  
(9)

where,

SPF = estimated average number of crashes over a 3-year period
AADT = annual average daily traffic, and
CVRAD = horizontal geometry curve radius in feet

It is interesting to note that roadway surface friction was not significant; however, this is consistent with the results reported by Musick and Flintsch (2019) and Parry and Viner (2005) while trying to establish friction thresholds for this category of roads. The result is probably due to the high standard of maintenance of this type of road, the positive correlation between friction and AADT and or the relatively small size of the interstate sample included in the District.

It should also be noted that the horizontal curve radius has a small effect, probably because the interstate routes are predominantly designed to the highest-level design criteria.

**United States Routes**

Table 7 shows the correlation matrix for the U.S. state routes. The strongest correlations are between traffic, wet, dry, and total crashes. The results for the best fit: negative binomial regression for the state routes are presented in Table 8 and result in Equation 10. The AIC value for this model is 3714.9 and the 2 x log-likelihood value is -3706.9.

**Table 7 – Correlation Matrix of United States Routes Data.**

<table>
<thead>
<tr>
<th></th>
<th>GRIP</th>
<th>CVRAD</th>
<th>XFALL</th>
<th>LNAADT</th>
<th>Wet</th>
<th>Dry</th>
<th>TotalWD</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRIP</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CVRAD</td>
<td>0.0404</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XFALL</td>
<td>-0.0915</td>
<td>0.000469</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LNAADT</td>
<td>0.0328</td>
<td>0.0907</td>
<td>-0.222</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet</td>
<td>-0.128</td>
<td>0.0438</td>
<td>-0.0307</td>
<td>0.186</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry</td>
<td>-0.119</td>
<td>0.0500</td>
<td>-0.0385</td>
<td>0.244</td>
<td>0.798</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>TotalWD</td>
<td>-0.126</td>
<td>0.0504</td>
<td>-0.0360</td>
<td>0.239</td>
<td>0.880</td>
<td>0.989</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 8 – Statistics from RStudio on United States Routes.

|       | Estimate | Standard Error | Z Value | Pr(>|z|) |
|-------|----------|----------------|---------|----------|
| Intercept | -6.99    | 7.18E-01       | -9.73   | < 2E-16  |
| LNAADT  | 1.01     | 8.00E-02       | 12.66   | < 2E-16  |
| GRIP    | -3.42    | 4.30E-01       | -7.96   | 1.66E-15 |

SPF = ADT^{1.01} e^{(-6.99 \cdot 3.42 \cdot \text{GRIP})}

where,
SPF = the estimated average number of crashes over a 3-year period
AADT = the annual average daily traffic
GRIP = the GripTester measurement of the roadway surface friction.

The U.S. routes’ SPF takes roadway surface friction as an additional significant factor with respect to the interstates. The reason for this could be the fact that the design criteria standards for this category of roadway ranges is considerably lower than that of the interstate routes and there is a higher demand for friction in this type of roads than for the interstates.

**West Virginia Routes**

The correlation matrix for the West Virginia Routes is shown in Table 9. The table shows that, again, there is a high correlation between AADT, wet, dry, and total crashes for the same reasons stated previously. In addition, there is correlation between GRIP and AADT. This correlation suggests that the route with higher traffic are maintained to a higher level of friction. However, while this may be true in many instances, this assumption cannot be considered absolute.
Table 9 – Correlation Matrix of West Virginia Routes.

<table>
<thead>
<tr>
<th></th>
<th>GRIP</th>
<th>CVRAD</th>
<th>XFALL</th>
<th>LNAADT</th>
<th>Wet</th>
<th>Dry</th>
<th>TOTALWD</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRIP</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CVRAD</td>
<td>0.0676</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XFALL</td>
<td>0.0259</td>
<td>0.0213</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LNAADT</td>
<td>0.282</td>
<td>0.0685</td>
<td>-0.0135</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wet</td>
<td>-0.0384</td>
<td>0.0484</td>
<td>-0.0489</td>
<td>0.209</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry</td>
<td>-0.0166</td>
<td>0.0432</td>
<td>-0.0474</td>
<td>0.287</td>
<td>0.719</td>
<td>1</td>
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<tr>
<td>TotalWD</td>
<td>-0.0210</td>
<td>0.0470</td>
<td>-0.0514</td>
<td>0.282</td>
<td>0.839</td>
<td>0.981</td>
<td>1</td>
</tr>
</tbody>
</table>

The results for the best fit: negative binomial regression for the WV routes are presented in Table 10, which results in Equation 11. The AIC value for this model is 7184 and the 2 x log-likelihood value is -7174.003.

Table 10 – Statistics from RStudio on West Virginia Route Coefficients.

|        | Estimate | Standard Error | Z Value | Pr(>|z|) |
|--------|----------|----------------|---------|---------|
| Intercept | -9.17    | 5.23E-01       | -17.52  | <2E-16  |
| LNAADT  | 1.07     | 5.96E-02       | 17.95   | <2E-16  |
| GN      | -1.92    | 2.74E-01       | -6.99   | 2.75E-12|
| XFALL   | -9.22E-02| 2.77E-02       | -3.33   | 0.000881|

\[
SPF = \text{ADT}^{1.07} e^{(-9.17 - 1.92\cdot GN - 0.0922\cdot XFALL)}
\]  

(11)

where,

\(SPF\) = the estimated average number of crashes over a 3-year period

\(\text{AADT}\) = the annual average daily traffic

\(\text{GRIP}\) = the GripTester measurement of the roadway surface friction

\(\text{XFALL}\) = the roadway superelevation in %

The friction parameter (GRIP) is still very significant and the superelevation variable is also significant. The WV routes have considerably lower design criteria than the U.S. routes within
the network and thus superelevation, in addition to friction, also assists vehicles in traversing the roadway.

**Example Use of Safety Performance Functions**

As an example of a potential application for the sample SPFs, the equations were used to systematically screen the network to determine locations with potential problems that may benefit from friction improvements, e.g., a high friction surface, resulting in a positive effect on crash rates. To illustrate the approach, Fig. 14 displays multiple variables simultaneously along WV Route 16 in Raleigh County. This route includes sections with low (less than 1,000 vehicles per day) and high (more than 2,000 vehicles per day) traffic counts, as well as intermediate levels of traffic, as indicated in the figure.

![Fig. 14 - Grip Number and Crash Data for WV 16 in Raleigh County, West Virginia.](image-url)
The existing GN is displayed by the blue line for each 0.1-mile segment of the roadway using the scale at the left of the figure. The total number of crashes at each 0.1-mile segment over a 3-year period is plotted as red dots, and the EB best crash estimate is plotted in green dots to reflect the anticipated number of crashes within each 0.1-mile segment over a 3-year period with the existing attributes.

For the sections with roadway surface friction below an investigatory level of 30 GN (Musick and Flintsch, 2019), the analysis triggers a potential intervention. The effect of applying a high friction surface treatment was estimated by improving the GN to 0.90 and computing “treated” best crash estimates, which are shown as blue dots. The analysis shows three locations that show a high potential for reduction in crash counts, as highlighted in the plot. In the high traffic area, there is one section at milepost 15.3, highlighted by the blue box, which has a high number of crashes and low friction. In this section, the application of a high friction surface treatment could potentially eliminate up to 26 crashes, making that section a good candidate for a project-level investigation. Similarly, there are two sections with potential friction problems in the low traffic section at mileposts 0 and 5.5; however, because of the lower traffic counts, the potential crash reductions estimated using the SPF/EB approach are much lower (6 and 2 crashes, respectively), but this section may also warrant a safety investigation.

In addition, it should be noted that there are a couple of locations (mileposts 17 and 17.4) in the high traffic area that also have a large number of crashes but are not triggered for friction-related safety investigations because the level of friction is above the investigatory level adopted for the example. The spike in crashes is likely caused by other factors.

**Implementation Recommendation**

After the SPFs have been put in place and verified across the WV network, the WVDOH can begin to use them for the preparation of its Highway Safety Improvement Program (HSIP). Traditionally, HSIP funding in WV, contrary to popular belief, has been difficult to allocate and spend. This is because HSIP funding must meet stringent criteria before projects are deemed eligible for HSIP federal aid safety funds. One way to use SPFs is to review locations that have similar roadway and operating characteristics but have crash rates higher than the SPF for the roadway facility to assist in meeting federal aid criteria. These roads, which at one time may not
have been deemed worthy of review, could then be evaluated as potential sites for federal aid safety funding.

CONCLUSIONS

This paper presented the development of SPFs for the District Ten portion of the WVDOH roadway network. Safety performance functions included friction and geometric characteristics, and application of the SPF for selecting location for high-friction surface application was illustrated with an example. The main lessons learned include the following:

- The SPF for the Interstate Routes in District Ten did not include friction, suggesting that it may not be a significant factor in predicting crashes for the short network tested. This is probably due to the high design standards for this type of road, which is consistent with what was found in other countries. The lack of correlation between friction and crashes can also be impacted to the small sample size of the interstate routes in the district studied.
- Friction had a significant impact on the SPFs for the other two route categories: United States Routes and West Virginia Routes. This suggests that safety improvement treatments can result in crash reductions for these roadway categories, as illustrated in the case study that identified critical locations on one of the roads.
- Based on the two previous observations, friction seems to be more important in preventing crashes on roadways without proper or optimum roadway geometric design.

The SPFs developed should only be considered as illustrative examples because they were developed using a relatively small sample of pavement routes. Further research is needed to develop more robust equations, which would be ready for implementation. However, the research conducted confirmed that the approach is feasible, and it can be used to support a systemic approach for identifying friction improvement projects for the state’s Highway Safety Improvement Program.
REFERENCES


CHAPTER 4 - INCORPORATING SURFACE FRICTION IMPROVEMENTS INTO THE WEST VIRGINIA HIGHWAYS SAFETY IMPROVEMENT PROGRAM

ABSTRACT

The State of West Virginia, like other states, is required to have a Highway Safety Improvement Program. To enhance the decision-making process during project selection for High Friction Surface Treatment projects in the Highway Safety Improvement Program, network roadway surface friction testing and the development of safety performance functions and corresponding best crash estimates have been introduced and a case study executed using the West Virginia Division of Highways District Ten roadway network.

The methodology proposed used continues friction and road surface geometry measurements to identify route segments that had friction lower than the Investigatory Level. Then, it estimates the number of crashes that could potentially be reduced by applying a High Friction Surface Treatment in each of these sites using friction-based safety performance functions and best crash estimates and selects the sites with highest potential benefit/cost ratios.

The case study illustrated how the network level testing allowed to identify locations where friction was questionable (below an Investigatory Level) and can be useful to allocate resources for high friction surface treatment based upon the potential economic benefits as a result of reductions in chases and associated fatalities. Based on the success of this case study, it is recommended to apply the methodology to the statewide roadway network.

KEYWORDS


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1 This paper, co-authored by R. Musick and G. Flintsch, has been accepted and scheduled for presentation at the 99th Annual Meeting of the Transportation Research Board.
INTRODUCTION

Safety is paramount in the West Virginia Division of Highways (WVDOH) roadway network, which encompasses 38,770 centerline miles of roadway situated in the rugged topography of the Appalachian Mountains (WVDOT, 2017a). Section 148 of Title 23 of the United States Code required states to have a current Highway Safety Improvement Programs comprised of three main components: the Strategic Highway Safety Plan, the Highway Safety Improvement Program Plan of Projects, and the Railway-Highway Crossing Program. Some states also have a High Risk Rural Roads Program (FHWA, 2017).

The 2017-2021 West Virginia Strategic Highway Safety Plan (WVSHSP) is an encompassing document that focuses on five major areas: roadway departures, alcohol and drug impaired driving, occupant protection, speeding and aggressive driving, and improving highway safety data. The plan attribute statewide statistics on fatalities and serious injuries to the factors shown in Fig. 15 (WVDOT, 2017b). The West Virginia Highway Safety Improvement Program (WVHSIP) addresses the emphasis areas from the WVSHSP to develop methods to counteract the problems and identify the projects to be funded by the Federal-Aid Highway Safety Improvement Program funds (FHWA, 2016).

![Fig. 15 - Statewide Fatalities and Serious Injuries by Related Factors (WVDOT, 2017b).](image-url)
Most of the safety-related factors can potentially be at least partially mitigated by appropriate roadway surface friction. Crashes, attributable to various factor, can be reduced by having an appropriate amount of roadway surface friction that allow maintaining control of the vehicle or reducing the braking distance. Roadway surface friction can help overt crashes, and partially compensate for lack of driving experience and impaired ability. In addition, the effect of roadway surface friction could potentially be magnified on roadways with poor geometric characteristics.

**OBJECTIVE**

The objective of this document is to enhance the decision-making process for selecting High Friction Surface Treatment projects. The proposed methodology uses network roadway surface friction testing and benefit cost analysis based on Safety Performance Functions and Empirical Bayes Method best crash estimates.

**BACKGROUND**

**Friction Testing Practice in West Virginia**

For many years, roadway surface friction testing in West Virginia has not been performed on a network level. It has been limited to questionable pavement sites that may potentially promote vehicle crashes and construction acceptance of new or rehabilitated pavement sections within the Division of Highways roadway network.

These measurements depend upon available equipment, personnel, and funding. Although the testing is conducted using in-house equipment and personnel, the funding for labor, equipment usage, and invoices (i.e. water, other supplies) normally comes from a Highway Safety Improvement Program Federal-Aid project, designated specifically for skid testing. The current project, *Skid Testing 2017*, contains $200,000 of authorized funding for June 28, 2017 through January 28, 2020. This project covers accident site pavement testing and construction acceptance testing.

**Network Roadway Surface Friction Testing**

To identify areas of questionable fiction is necessary to evaluate friction levels throughout the network. Network roadway surface friction testing is the process by which roadway surface
friction testing is conducted continuously along all routes within a roadway network. Network-level friction testing allows transportation agency to:

1. Assess the condition of the network roadway and set Investigatory Levels at which the roadway surface friction should become a safety concern.
2. Optimize the allocation of resources for surface friction improvements. Knowing the condition of the network allows the transportation agency to spend funds where they need to be spent to create a safer, more reliable network.

However, network-level friction testing also has its challenges. This type of program requires the acquisition and maintenance of the testing equipment or contracting of the services.

Friction-based Safety Analysis

De León et al. (2016) proposed a methodology to identify candidate locations for friction improving treatments based on estimating crashes and potential crash reductions because of friction improvements using the safety analysis tools recommended by AASHTO.

Safety Performance Functions

Safety Performance Functions (SPF) are regression models used to estimate crashes based on roadway and traffic characteristics that influence crashes and crash rates using a Negative Binomial Distribution. These models allow a transportation agency to determine whether a roadway segment has a higher or lower than normal crash rate, compared to other facilities with similar characteristics and can be used in conjunction with the Empirical Bayes (EB) Method to estimate crashes based on existing data and conditions, both in pre and post treatment application scenarios.

Fiction Improvement Treatments

There are several treatments that can be used to restore friction in areas where the demand for friction exceed that supplied by the existing pavement surface, including various types of surface treatments, milling and/or replacing the surface layer, and grinding and/or grooving.

One of the most efficient methods to improve roadway surface friction along friction-deficient roadways is the use of High Friction Surface Treatments (HFST). A High Friction Surface consists of the application of a polymer binder to an existing roadway topped with a high-grade aggregate. This type of application was first developed in the United Kingdom as
early as 1967 and has been slow to be applied in the United States. It was first applied to bridge decks sealing and later used to correct and promote surface friction (FHWA Safety, 2019).

For asphalt pavements, the existing roadway surface can be lightly milled to restore the frictional characteristics. For concrete pavements, the existing roadway surface can be diamond-ground to restore the frictional characteristics as well. These treatments, in the State of West Virginia, cost roughly one-fourth to one-half of the cost of applying a HFST, meaning that the funding will go longer and help more motorists.

In addition, regular preservation treatments, such as surface treatments, slurries, micro-surfacing, and thin overlays can also be used to restore friction, in addition to extending the pavement life (Walker, 2019).

Although the paper focuses on HFST application for illustration the proposed methodology, it is recommended that these other solutions be investigated in the future.

**Experiences from Other States**

Through the years, several states have used HFST on an experimental basis. For example, the City of Bellevue, Washington placed a HFST in October 2004. After exhausting other crash-reduction countermeasures such as lights, markers, and raised pavement buttons, the city applied HFST to the westbound intersection approach of Forest Drive with Cole Creek Parkway. This resulted in a 78% crash reduction and an 83% crash cost reduction (FHWA, 2019a).

The Pennsylvania Department of Transportation (PennDOT) applied HFST along a dangerous curve on a state route 611. The HFST was applied only in the southbound direction, reducing the number of wet crashes from 13 over a ten-year period to no wet crashes over the following 8 years after the application. Since then, PennDOT has drafted a standard provision for HFST and has increased the number of applications throughout the state to over 150 sites as of 2015. The agency is currently developing a process to allocate the Federal-Aid Highway Safety Improvement Program funds to treat the most effective locations (FHWA, 2019b).

The South Carolina Department of Transportation (SCDOT) applied a HFST to a one-mile section of US 25, a four-lane with a deteriorated concrete and a median dividing the lanes. The facility had drainage issues and improper superelevation. The originally proposed $5 million project for addressing the facility’s needs included updating the barrier wall and replacing the drainage structures; however, SCDOT applied a HFST for only $1 million and obtained great
results. The project resulted in a 56.5 % reduction in total crashes and a 68.1 % reduction in wet crashes (FHWA, 2019c).

PROPOSED METHODOLOGY

The methodology proposed for selecting candidate roadway section for HFS treatment consists of a multi-pronged *Network-level Pavement Friction Management Program*, which includes the following steps:

1. Data acquisition
2. Data processing and analysis
3. Securement of funding
4. Cyclical retesting and review

Data Acquisition

*Roadway Surface Friction*

The first step is to determine the current level of roadway surface friction across the statewide roadway network. Although the methodology is illustrated for one district in this paper, all the ten Districts’ roadway network will require both an initial and repeated measurements on a regimented basis.

The testing could be conducted by either purchasing a continuous friction-measuring equipment or by contracting this service out to a contractor. In both cases, the funding authorization will need to be supplemented accordingly. If the testing is conducted in house, it should be carried out by the Materials Control Soils and Testing (MCS&T) Division. This additional workload will need to be scheduled in conjunction with the existing responsibilities of the division.

Since the funding source for roadway surface friction testing and rehabilitation is usually Federal-Aid, it is recommended that the entire network be tested once every four years. The four-year interval will support the Federal Statewide Transportation Improvement Program four-year planning and financial document. According to Flintsch et al. (2012), some state Departments of Transportation test every year, while others test every two to five years.

One additional item to consider is what type of routes within the system will be friction tested. It is recommended that the Interstate, United States, and West Virginia Routes be tested
on a regular basis. However, some of the lower priority routes, such as County, the Park and Forest Routes and Home Access Road Program Routes could be tested as-needed, due to the lower Annual Average Daily Traffic (AADT).

**Other Road Data**

Traffic data are, of course, needed to develop the SPFs. In addition, other data to consider in this process include horizontal geometric curvature and superelevation or cross-fall of the roadway sections. This data is already being obtained by a contractor using an Automatic Road Analyzer (ARAN®) System on a regular basis on each of the Interstate, United States, West Virginia, and County Routes throughout the State at different intervals. Interstate and Appalachian Development Highway Routes are typically surveyed every year, and the other routes every two years.

**Wet and Dry Crashes**

The final type of data to consider for this process is the wet and dry crash counts. These are normally collected by the WVDOH Traffic Engineering Division and stored in their crash database. Crash data should be obtained for a period of three years prior to the time of roadway surface friction testing.

**Data Analysis**

The data analysis process includes the pre-processing and synchronization of the data, determination of friction investigatory levels, development of SPFs, using the SPFs in conjunction with the Empirical Bayes methodology to estimate crashes before and after treatment, and conducting a benefit analysis to identify the friction improvement projects with the maximum potential benefit cost ratios.

**Data Processing**

Once the data has been collected, it will be necessary to prepare and analyze the data. The data need to be reviewed to remove bad measurements and inconsistencies, processed to a common analysis unit, and matched based on location.

Since continuous friction-measuring devices measure roadway surface friction continuously (or at least on short intervals such as every 3 feet), it will be necessary to assign a friction value for a workable length of roadway. For example, for the case study that follows, the researchers
used 0.1 long segments. The example computed 60 feet rolling averages over the entire length of each 0.1 mile of roadway and selected the minimum friction value for each 0.1-mile segment.

Wet and dry crash data must be accumulated for the same segment length and matched with the friction and geometric data based on the state’s linear referencing system. The WVDOH Traffic Engineering Division maintains a statewide crash database containing all recorded vehicle crashes.

After the roadway surface friction data has been collected, it is recommended that the data are uploaded to the department Geospatial Transportation Information network. As an example, Fig. 16 shows a screen capture of the roadway surface friction data being displayed in ArcMap.

![Fig. 16 - Display of the District Ten Friction Data in ArcMap.](image)

The line along the horizontal location of the route gets color-coded to reflect the approximate value range of the friction measurements, green representing higher friction values to red representing lower friction values. This will allow identifying areas of high friction demand, such as intersections and horizontal curve areas where drivers depend on a significant amount of friction for proper vehicle operation. Intersections and crossing areas in this example are not separated out from the rest of the network in the case study because the sample size for the District was too small. However, it is recommended that these locations be separated in the final implementation, as they may represent different friction demand categories. The visual display may also help identify locations with severe friction loss or areas where problem may be occurring.
**Friction Investigatory Levels Determination**

The next critical step is to determine what friction needs exist throughout the network and to establish investigatory thresholds for the various friction demand categories. For example, the AASHTO Guide for Pavement Friction proposes several methods, including the *Establishing Thresholds Using Pavement Friction Distribution and Crash Rate—Friction Trend (Method 3)* (AASHTO, 2008). This method calls for the development of a histogram of number of roadway sections having various ranges of friction values. The average wet to dry crash rates in the original method are determined for each level of friction and superimposed to the histogram. The investigatory level is determined at the point where the crash rates starts to increase significantly. For this research, the method was modified and total crash rate was used instead of the wet-to-dry ratio as it is a more robust indicator because both wet and dry crashes increase as friction decreases.

**Safety Performance Functions**

After determining the roadway surface friction needs, another distinct method to compliment roadway surface friction is to develop Safety Performance Functions for each of the route categories. Safety Performance Functions are basically crash frequency regression equations that help determine average crash rates for specific roadway characteristics (AASHTO, 2010).

To develop these Safety Performance Functions, Negative Binomial regression equations are developed for each of the route categories using data that would influence vehicle crashes such as average annual daily traffic, roadway surface friction, horizontal curve radii, actual wet and dry crash rates, along with other roadway data that may be applicable. Once these Safety Performance Functions are developed, the Empirical Bayes Method can then be used to develop best crash estimates for each location. As variables change, such as roadway surface friction improvements, before and after crash rates can be estimated as noted in the next section. If the crash rates for the roadway facility are higher than the average crash rates for a particular type of facility, then roadway surface friction may be a concern.

**Before and After Crash Estimates**

After the SPFs have been developed for the various friction demand categories, before and after crash estimates can then be calculated in terms of the average number of crashes over a three-year period for each 0.1-mile section. First, the before crash estimates are based on the
SPF calculations given the existing roadway surface friction. After the SPF for each 0.1-mile section was calculated, the Empirical Bayes Method can be used to estimate the expected average number of crashes in 0.1-mile sections with these same characteristics throughout the network.

Second, the after-treatment crash estimates are based on the SPF calculations corresponding to a roadway surface friction grip value of 0.9 for any 0.1-mile section that the existing roadway surface friction value is less than 0.3, the Investigatory Level. The grip value of 0.9 is typical for high friction surface treatments. The after-treatment crash estimate for each 0.1 mile section can be calculated by multiplying the before-treatment expected crash estimate by the ratio of the after-crash SPF divided by the before-crash SPF.

**Benefit Cost Analysis**

After the before and after crash estimates are determined, a benefit cost analysis should be performed to determine the efficiency of placing high friction surface treatment along the 0.1-mile sections with the greatest potential crash reductions. Assuming a cost of $20 per square yard to apply the high friction surface treatment, based on the Average Unit Bid Price from the West Virginia Division of Highways website [www.transportation.wv.gov](http://www.transportation.wv.gov), and a value of life of $100,000 per crash, a benefit cost analysis is performed.

**Securing of Funding**

Like any type of transportation improvement, funding is required. Roadway surface friction testing and rehabilitation are activities that qualify for Federal-Aid funding, particularly as part of the Highway Safety Improvement Program (HSIP) in the Federal Statewide Transportation Improvement Program (STIP). The Federal STIP is the funding mechanism by which State Departments of Transportation acquire their federal funding for capital improvement projects on Federal-Aid eligible roadways and bridges.

By law and statute, the Federal STIP is a four-year fund planning document required by the Federal Highway Administration to be in place and financially constrained each year to the established limits of obligation authority. In the State of West Virginia, the Secretary of Transportation normally requires the Federal STIP to be a six-year document, the last two years being shown for information purposes only. The reason for this is the fact that the WVDOH maintains a six-year Capital Improvement Program, so the document in this form marries well
with its counterpart, the State-Funded portion of the STIP. It is critical that the Safety Engineer “carve” out an adequate amount of HSIP funding to initiate and maintain roadway surface friction within the roadway network.

Cyclical Plan Updating

The last step of the proposed Network-level Pavement Friction Management Program in support of the WVHSIP and the WVSHSP is to periodically retest the roadway network. According to the Federal Highways Administration Technical Advisory on Pavement Friction, the higher priority, higher volume roadways, which present a higher “risk” with respect to vehicles making maneuvers should be tested every year, whereas the lower “risk” roadway can be tested every two to three years (FHWA, 2017). As in this application, the data are used to enhance decision-making for HSIP project selection, the entire network should be tested once every four years, to match the Federal-Aid funding cycle of the Federal STIP.

Another aspect to consider with roadway surface friction testing is that continued periodic testing allow to establish friction loss trends. These trends would allow to measure friction degradation along stretches of roadways, as well as intersections. In addition, re-testing at specified time intervals will also bring an awareness of the various unique locations with high friction degradation, such as locations with certain horizontal maneuvers, intersections with awkward approach entrance and exit slopes, and other one-of-a-kind situations.

CASE STUDY

The proposed methodology is illustrated by applying it in District Ten. This case study identifies areas of low friction, estimates crashes before and after an HFST treatment to quantify the potential benefits of the treatment, and selects the locations that provide the greatest impact in crash reduction per dollar invested.

Data Collection

Roadway surface friction, traffic, roadway geometry, and crash data were collected and matched for the network investigated, which include the Interstate, United States and West Virginia routes in the district. The compiled data is illustrated in Table 11.
Table 11 – Example of Friction, Geometry, and Crash Data (Segment of US 52 in McDowell County).

<table>
<thead>
<tr>
<th>Milepost</th>
<th>Tenth Mile Grip Number Value</th>
<th>BEG_MP</th>
<th>END_MP</th>
<th>LENGTH (feet)</th>
<th>CURVE_DIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.566</td>
<td>0</td>
<td>0.415</td>
<td>2175</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>0.539</td>
<td>0</td>
<td>0.415</td>
<td>2175</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>0.603</td>
<td>0</td>
<td>0.415</td>
<td>2175</td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>0.567</td>
<td>0</td>
<td>0.415</td>
<td>2175</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>0.658</td>
<td>0.415</td>
<td>0.568</td>
<td>803</td>
<td>Left</td>
</tr>
<tr>
<td>0.5</td>
<td>0.666</td>
<td>0.415</td>
<td>0.568</td>
<td>803</td>
<td>Left</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CURVE_DEG</th>
<th>CURVE_RAD (feet)</th>
<th>CURVE_T</th>
<th>XFALL (%)</th>
<th>BEG_MP</th>
<th>END_MP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Tangent</td>
<td>-0.1</td>
<td>0.032</td>
<td>0.064</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>Tangent</td>
<td>-0.1</td>
<td>0.121</td>
<td>0.173</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>Tangent</td>
<td>-0.1</td>
<td>0.189</td>
<td>0.427</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>Tangent</td>
<td>-0.1</td>
<td>0.189</td>
<td>0.427</td>
</tr>
<tr>
<td>4</td>
<td>-1415.8</td>
<td>Arc</td>
<td>-1.5</td>
<td>0.427</td>
<td>0.653</td>
</tr>
<tr>
<td>4</td>
<td>-1415.8</td>
<td>Arc</td>
<td>-1.5</td>
<td>0.427</td>
<td>0.653</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LENGTH (feet)</th>
<th>CURVE_T</th>
<th>SLOPE_S (%)</th>
<th>SLOPE_E (%)</th>
<th>Accident Data (3 year Total)</th>
<th>ADT (vehicles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>169</td>
<td>Crest</td>
<td>6</td>
<td>3.5</td>
<td>Wet 7 Dry 0 Other 0</td>
<td>2882</td>
</tr>
<tr>
<td>275</td>
<td>Crest</td>
<td>-0.5</td>
<td>-5</td>
<td>0 0 0</td>
<td>2882</td>
</tr>
<tr>
<td>1246</td>
<td>Crest</td>
<td>-6</td>
<td>-7.5</td>
<td>0 0 0</td>
<td>2882</td>
</tr>
<tr>
<td>1246</td>
<td>Crest</td>
<td>-6</td>
<td>-7.5</td>
<td>0 0 0</td>
<td>2882</td>
</tr>
<tr>
<td>1183</td>
<td>Tangent</td>
<td>-8</td>
<td>-8</td>
<td>0 0 0</td>
<td>2882</td>
</tr>
<tr>
<td>1183</td>
<td>Tangent</td>
<td>-8</td>
<td>-8</td>
<td>0 0 0</td>
<td>2882</td>
</tr>
</tbody>
</table>

The roadway surface friction was measured using a GripTester, a continual friction measuring device. A locked-wheel friction tester was also used to collect friction at 0.5-mile intervals for comparison purposes. The correlation of the GripTester with the locked-wheel friction tester for all route categories combined is found in Eq. 11. This was done to relate the results to state’s previous experience using the locked-wheel tester.

\[
SN40 = 58*GN + 27
\]  
\(SN40 = \text{Skid Number value from the locked-wheel friction tester at 40 mph.}\)
The roadway horizontal and vertical geometry data were obtained from the Maintenance Division. This data was produced by a contractor hired to collect condition assessments using an automated vehicle.

**Data Analysis and Safety Performance Function Development**

The data was processed as discussed in the previous section and used to define the Investigatory Level of friction for each type of route. As an example, the graphical representation of the modified AASHTO GPF Method 3 for the United States Routes in District Ten is presented in Fig. 17 (Musick and Flintsch, 2019a). In this case, the results seem to indicate that the normalized crash rate is higher and more variable for the bins with friction values below 0.28-0.30, and thus, an investigatory level of GN = 0.3 was selected for this road category. Given the mean and standard deviation for the friction are 0.43 and 0.09, respectively, the level corresponds to the mean minus 1.5 standard deviations. Similar results were obtained for the West Virginia routes. Although no relationship was found between friction and crashes for the interstate routes, the same IL was used for all types of routes in the example.
Fig. 17 – Friction Histogram and Normalized Crash Rate Trend for United States Routes.

The SPF's were determined as discussed in Musick and Flintsch (2019b). The functions estimate the average number of crashes over a three-year period per each 0.1-mile segment for each roadway category, considering the variables that influence crashes along the network. The natural logarithm of the annual average daily traffic (LNADT), the roadway surface friction value from the GripTester (GRIP), the horizontal radius of curvature for the roadway (CURVERAD), and the superelevation or cross slope of the roadway (XFALL) were considered. The best-fit Negative Binomial Distribution (lowest AIC) for each of the roadway categories and the following equations were developed as shown in Table 12. Since friction was not found significant on the Interstates, this type of roadway was not analyzed.
Table 12 – Safety Performance Functions from District Ten Data (Musick, 2018).

<table>
<thead>
<tr>
<th>Roadway Category</th>
<th>Safety Performance Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstate</td>
<td>SPF = ADT^{1.68} e^{(-16 - 4.24 \times 10^{-10} \text{CURVERAD})}</td>
</tr>
<tr>
<td>United States</td>
<td>SPF = ADT^{1.01} e^{(-6.99 - 3.42 \times \text{GRIP})}</td>
</tr>
<tr>
<td>West Virginia</td>
<td>SPF = ADT^{1.07} e^{(-9.17 - 1.92 \times \text{GRIP} - 0.0922 \times \text{XFALL})}</td>
</tr>
</tbody>
</table>

Since the methodology proposed aims to enhance how projects are selected for the WVHSIP in the Federal Statewide Transportation Improvement Program (STIP), it was necessary to define how much HSIP funding each year will be appropriated to address roadway surface friction needs in the network. After consultation with the ITS, Traffic Mobility & Safety Engineer, an appropriation of $2 million statewide, or $200,000 per District, was adopted.

Then, the analysis determined which 0.1-mile segments in each roadway category are below the Investigatory Level of 0.3 and computed the potential reduction in the number of crashes by improving the roadway surface friction. The friction after the application of the HFST grip value of 0.9. The estimated before and after crash counts were determined using the SPF/EB methodology.

The cost of the HFSTs was computed using the $20 per square yard unit price previously mentioned, as $28,160 and $56,320, for a 0.1-mile section of two and four-lane roadway, respectively (WVDOH, 2019). The benefit/cost ratio was computed for each treated segment and the project were ranked as shown in Table 13. The table shows the sections selected for the HFST application and the estimated potential crash reductions. It can be observed that treating the 4 more critical sections at a cost of approximately $200,000, could potential eliminate 128 crashes, with a societal economic benefit of more than 10 million dollars. This results in an average cost/benefit ratio of approximately 50. These results show that a relatively modest investment in friction improvement treatments can result in a reduction of 20% of the crashes.

It is important to note that several other factors can be included when considering roadway selections to treat. For example, there is the consideration of remaining pavement life. To place a high friction surface treatment on a pavement with a short remaining service life would not be responsible. These expensive treatments should be applied on pavements that are still in good condition.
Table 13 – Selected Segments in District Ten.

<table>
<thead>
<tr>
<th>Route and County</th>
<th>Milepost</th>
<th>Friction (GN)</th>
<th>Crash Count</th>
<th>Potential Crash Reduction</th>
<th>Treatment Cost</th>
<th>Societal Benefit</th>
<th>Benefit/Cost Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>US 19 - Raleigh</td>
<td>8.7</td>
<td>0.21</td>
<td>32</td>
<td>28.5</td>
<td>$42,240</td>
<td>$2,852,700</td>
<td>67.5</td>
</tr>
<tr>
<td>US 19 - Raleigh</td>
<td>18.6</td>
<td>0.25</td>
<td>31</td>
<td>27.7</td>
<td>$70,400</td>
<td>$2,770,100</td>
<td>39.3</td>
</tr>
<tr>
<td>US 52 - Mercer</td>
<td>12.7</td>
<td>0.17</td>
<td>25</td>
<td>22.9</td>
<td>$28,160</td>
<td>$2,295,000</td>
<td>81.5</td>
</tr>
<tr>
<td>WV 16 - Raleigh</td>
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<td>0.29</td>
<td>40</td>
<td>27.1</td>
<td>$70,400</td>
<td>$2,716,300</td>
<td>38.6</td>
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</table>

In addition, the methodology could be expanded to consider more friction demand categories. It would be probably worth establishing higher investigate levels for sections with higher fiction demand, such as intersection, sharp curves, and vehicle-railroad crossings.

DISCUSSION

One interesting point that came to light in the study is that the District Ten roadway network contains three times as much frictionally deficient roadway mileage in the WV Route category versus the US Route category. If we combine this with the fact that total crashes are similar for the two route categories, while the average ADT on US Routes is nearly four times that of the WV Routes, this highlights a potentially severe problem in the WV routes. These statistics in themselves show the critical value of roadway surface friction on the United States route category.

Furthermore, it is recommended that given to the friction needs shown within the District Ten network, other types of friction-enhancing techniques should be explored and considered to help correct deficiencies that are more cost-effective. Techniques such as fine milling for asphalt pavements and diamond grinding for concrete pavements can be researched and applicable friction levels for each technique be established. This will provide more “tools in the toolbox” for the WVDOH so that HSIP funds may be utilized in even a more efficient manner.

Lastly, even with the suggested practical allocation of $2 million of HSIP funding for roadway surface friction improvement by the WVDOH Safety Engineer, funding does not go that far. The funding does, however, have a high benefit/cost ratio, making these improvements very worthwhile investments.
CONCLUSIONS

The paper proposed a method to enhance the decision-making process for selecting High Friction Surface Treatment projects. The proposed methodology uses network roadway surface friction testing and benefit cost analysis based on Safety Performance Functions and Empirical Bayes Method best crash estimates to recommend projects to include in the Highway Safety Improvement Program. The application of the methodology in a case study in the District Ten area, showed that the method is indeed effective in identifying areas with potentially deficient friction and highlighting the locations with the highest potential societal benefits per dollar invested when treated with a High Friction Surface Treatment.. Furthermore, the statewide application of the proposed methodology to identify and treat the most critical friction-related problems could results in significant reduction in crashes and associated facilities if method is can help optimize the investments.
REFERENCES


De Leon Izeppi, E. D., Katicha, S. W., Flintsch, G.W., McCarthy, R., and McGhee, K. K., 2016. Continuous Friction Measurement Equipment As a Tool for Improving Crash Rate Prediction: A Pilot Study. Available at


CHAPTER 5 - FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

This dissertation presented the implementation of a network-level roadway surface friction management program and how to use it to define friction investigatory levels, develop Safety Performance Functions, and determine optimum locations to place High Friction Surface Treatment.

The first manuscript examined the network roadway surface friction across the State of West Virginia in the Division of Highways’ District Ten jurisdiction and defined illustrative Investigatory Level, or minimum level of roadway surface friction, for different roadway categories.

The second manuscript discussed the derivation of sample safety performance functions (SPF) that consider roadway surface and geometric properties as explanatory variables. It also showed how to use these functions to compute best crash estimates using the Empirical Bayes (EB) method and illustrate their potential use for identifying areas in need of friction-improvement treatments.

The third and last manuscript integrates the network-level friction data collecting and SPB/EB methodology to propose a systemic approach to select the optimum locations for application of High Friction Surface Treatments. The approach is illustrated in a case study using the District Ten network data to determine the optimum locations to place High Friction Surface Treatment on roadway segments with roadway surface friction values under the Investigatory Level.

FINDINGS

The main findings of the dissertation are the following:

1. A network-level investigation of the friction levels across a highway maintenance district in West Virginia confirmed that increased roadway surface friction reduces the risk of having a crash. The analysis showed lower crash rates as the roadway surface friction increases on the United States Routes and the West Virginia routes, allowing to determine investigatory friction levels. However, the same relationship is not evident for the Interstate Routes; this could be because of the better geometric standards and higher overall friction values on this type of routes, or because of the small sample of Interstate segments available for the analysis.
2. A statistical analysis of the relationship between friction and crashes showed that it was possible to determine SPFs that incorporate friction for both the United States Routes and the West Virginia Routes. The analysis also suggested that roadway surface friction seems to be more important in preventing crashes on roadways without proper or optimum roadway geometric design.

3. The combination of the network roadway surface friction testing and benefit cost analysis based on Safety Performance Functions and Empirical Bayes best crash estimates can be used effectively to select and prioritize High Friction Surface Treatment projects to include in the Highway Safety Improvement Program. The application of the methodology in a case study showed that the method is indeed effective in identifying areas with potentially deficient friction and highlighting the locations with the highest potential societal benefits per dollar invested.

**CONCLUSIONS**

The main conclusion of the study is that it is possible to enhance the decision-making process for selecting High Friction Surface Treatment projects to include in the Highway Safety Improvement Program. The dissertation proposed a methodology that combines network roadway surface friction testing and benefit cost analysis based on Safety Performance Functions and Empirical Bayes best crash estimates to identify location with the highest potential crash reduction when treated with friction improvement treatments. The practicality and effectiveness of the methodology summarized in Fig. 18 is illustrated with a case study. The results suggest that the expansion of the methodology to the statewide network could results in significant reductions in crashes and associated fatalities.
RECOMMENDATIONS FOR FUTURE RESEARCH

Although this dissertation has the potential to make a major impact on the West Virginia Division of Highways’ roadway network, there are multiple possibilities for future research in this area of study:

- Additional research may be warranted in the area of Safety Performance Functions. Beyond the sample Safety Performance Functions generated during this research for Interstate Routes, United States Routes, and West Virginia Routes, Safety Performance Functions should be developed for other friction demand categories, such as multi-lane facilities, intersections, and interchanges based on different factors. Potential factors could include vehicle classes and types of crashes.
- Additional research to determine additional relationships or correlations between various roadway and traffic factors known to contribute to vehicle crashes could also be beneficial. This may shed some additional light on why or how routes such as the Interstate Routes are not greatly affected by roadway surface friction values.
Further research could be performed on how pavement preservation techniques other than High Friction Surface Treatment can be used effectively from a benefit-cost perspective. Due to the high cost of High Friction Surface Treatment, only a few sections can be treated every section; other lower-cost treatments, such as diamond grinding and milling, may be more effective when considering pavements with limited life remaining or lower volume roads.