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Continuous Friction Measurement Equipment As a Tool for Improving Crash Rate Prediction: A Pilot Study

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Abstract:

A comprehensive pavement management system includes a Pavement Friction Management Program (PFMP) to ensure pavement surfaces are designed, constructed, and maintained to minimize friction-related crashes in a cost-effective manner. The Federal Highway Administration's (FHWA) Technical Advisory 5040.38 on Pavement Friction Management supersedes a previous advisory that focused on skid crash reduction. In addition to traditional locked-wheel friction-testing devices, this new advisory recommends continuous friction measuring equipment (CFME) as an appropriate method for evaluating pavements.

The study described in this report developed a pavement friction inventory for a single construction district in Virginia using the Grip Tester, a low-cost CFME. The continuous friction data were then coupled with crash records to develop a strategy for network analysis that could use friction to improve the ability to predict crash rates.

The crash rate analysis applied the well-established methodology suggested by the FHWA for the identification of high crash risk areas using safety performance functions (SPFs), which include empirical Bayes rate estimation from observed crashes. The current Virginia Department of Transportation SPF models were modified to include skid resistance and radius of curvature (interstate and primary system only) to improve the predictive power of the models. A variation of the same methodology was also used to contrast the effect of two different friction repair treatments, i.e., conventional asphalt overlay and high friction surface treatments, to explore how their strategic use can impact network level crash rates. The result suggests significant crash reductions with comprehensive economic savings of $100 million or more when applied to a single relatively rural district.

These findings easily justify an aggressive state-level PFMP and further support continued research to quantify the influence of other pavement-related characteristics such as macrotexture, grade, and cross-slope.

FINAL REPORT

CONTINUOUS FRICTION MEASUREMENT EQUIPMENT AS A TOOL FOR IMPROVING CRASH RATE PREDICTION: A PILOT STUDY

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DISCLAIMER

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Each contract report is peer reviewed and accepted for publication by staff of Virginia Transportation Research Council with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

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INTRODUCTION

Background

In 1980, the Federal Highway Administration (FHWA) issued *Technical Advisory 5040.17: Skid Accident Reduction Program* as a general overview of factors that should be considered as part of the Highway Safety Program Standard 12 (HSPS-12) that required every state to have a program of highway design, construction, and maintenance to improve highway safety. HSPS-12 provided pavement friction directives and also emphasized the need for resurfacing or other surface treatment with emphasis on correction of locations or sections of streets and highways with low skid resistance and high or potentially high accident rates susceptible to reduction by providing improved surfaces. In particular, it stated that the purpose of a skid accident reduction program focused mainly on minimizing the wet weather skidding accidents. In Virginia, as in many other states, this program functioned under the name Wet Accident Reduction Program (WARP).

In 2005, The Safe, Accountable, Flexible, and Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) established the Highway Safety Improvement Program (HSIP) "to achieve a significant reduction in traffic fatalities and serious injuries on public roads" (FHWA, 2013a). To use the HSIP funds, states were required to develop Strategic Highway Safety Plans (SHSPs), establish a crash data system, and annually report locations with severe safety needs. In Virginia, the Surface Transportation Safety Executive Committee was formed in 2006 to integrate and coordinate all transportation safety programs, particularly those established to comply with the mandates outlined in SAFETEA-LU and the National Highway Safety Act of 1966. This committee created, implemented, and evaluated the 2006-2010 Commonwealth SHSP (Virginia Department of Transportation [VDOT], 2013).

The Moving Ahead for Progress in the 21st Century Act (MAP-21) continued the goals of the HSIP, nearly doubling the funds for FY13 and FY14. MAP-21 required a data-driven, strategic approach to improving highway safety on all public roads that focuses on performance (FHWA, 2013b). Virginia's 2012-2016 SHSP and update process has been approved by FHWA. The new SHSP should be an opportunity to revisit a statement made in the 2006-2010 SHSP regarding Virginia's transportation safety public policy. In the earlier document, it read: "Transportation safety public policy in the United States as well as in Virginia has focused on crash survivability and not crash prevention" (VDOT, 2013).

In 1997, the American Association of State Highway and Transportation Officials (AASHTO) first approved its SHSP by more than the required two-thirds majority vote; the plan was revised and updated in 2004. Since then, each state and many organizations have implemented their own SHSPs. However, AASHTO (with the help of many highway safety stakeholders) found in 2010 that there is no one strategy that united all SHSPs. The U.S. Department of Transportation (U.S. DOT), specifically through FHWA, and AASHTO have since initiated an effort to develop a national approach. This new strategy is called Toward Zero Deaths: A National Strategy on Highway Safety (U.S. DOT, 2013).

This strategy represents a nationwide effort to eliminate highway fatalities as a threat to public and personal health. The strategy will be developed with input from a range of highway safety stakeholders. The end result will comprise two key parts: a national safety plan and an associated outreach program. A process will be developed for implementing the plan. The holistic, data-driven plan will include key emphasis areas, projection of future needs, promising countermeasures, and expected improvements.

Pavement Friction Measurements in Virginia

Virginia has had a long history with measuring tire-pavement friction since its introduction in the United States and more recently under the state's WARP (Mahone and Sherwood, 1996). "ASTM Committee E-17 on Vehicle-Pavement Systems (originally the Committee on Skid Resistance) had its genesis after the First International Skid Prevention Conference, held in Charlottesville, Virginia in September 1958, through the efforts of the late Tilton E. Shelburne," Virginia Department of Highways first Head of Research (Whitehurst, 2011). Through the efforts of the Virginia Transportation Research Council (VTRC), Virginia helped establish national standards for skid resistance and, in 1976, "developed a procedure for systematically identifying and evaluating wet crash sites or low skid number sites and established the WARP. The program procedures are outlined in Virginia's Wet Accident Reduction Program: A User's Manual" (McGovern et al., 2011).

VTRC materials and engineering research continued, but with changes in scope. VDOT's Materials Division purchased the first ASTM E-274 Locked-wheel skid trailer in 1974, equipped with ribbed tires (VDOT, 2009). Since 1988 the Materials Division has grown the skid testing program in Virginia to include the following areas (Habib, 2012):

- Programmatic Testing
  —Inventory
  —WARP

- Needs-based Testing
  —Project specific
  —As needed.

The inventory program is set up to test all interstate and primary routes on a multiyear cycle, doing two to three districts/year, with a measurement every 0.2 mile. However, data from inventory testing were last uploaded in 2010 into VDOT's Highway Traffic Records Inventory System (HTRIS), a system that was abandoned around 2012. Any new data that might have been recorded were not transferred into the new Roadway Network System (RNS) program. Thus, VDOT's Traffic Engineering Division (TED) has experienced increasing difficulties using skid testing data to analyze crash locations for much of the last decade. Although testing resumed in 2014, the last published WARP report that contains any friction testing references data from 2007 (VDOT, 2009).

As with most state agencies in the United States, Virginia's program continues to use a locked-wheel testing device, having switched to a smooth tire (ASTME E-524) in the 1990s. This device measures friction very well on long pavement sections that are relatively homogeneous in nature.

The Virginia Strategic Highway Safety Plan (SHSP)

The 2012 update to the Virginia SHSP establishes seven emphasis areas to include: speeding, young drivers, occupant protection, alcohol-related incidents, roadway departure, intersections, and data collection, data management, and data analysis (VDOT, 2013).

The SHSP update also reported that from 2001 to 2010, roadway departure and intersection crashes accounted for 83% of all deaths and 68% of the severe injuries. Strategy 1 under Roadway Departure is to keep vehicles on the road and in their lanes, a goal made far more achievable with adequate adherence to the traveled surface. Action 1.7 for this strategy says to "continue to research advances in pavement designs to enhance pavement friction. Seek opportunities to install high-friction pavements where appropriate, cost effective and practical."

Although the actions for the intersection-related crash strategies do not specifically mention tire-pavement friction, intersections are where braking, turning, and other extreme maneuvering is most common and by definition where sufficient tire-pavement friction is most essential. Finally, Strategy 4 under the Data Emphasis Area Plan specifically addresses improved tools for highway safety analysis that uses highway inventory and condition data; tire-pavement friction is among the more fundamental and relevant properties of traveled surfaces.

Pavement Friction Management Programs

In June 2010, FHWA issued the new *Technical Advisory 5040.38: Pavement Friction Management* (FHWA, 2010), superseding the previous *Technical Advisory 5040.17: Skid Accident Reduction Program.* This new advisory provides guidance to highway agencies towards developing or improving pavement friction management programs (PFMPs) to ensure pavement surfaces are designed, constructed, and maintained to provide adequate and durable friction properties that reduce friction-related crashes in a cost-effective manner. The advisory lists four types of full-scale friction test equipment:

> . . . locked wheel, fixed slip, side force, and variable slip. The locked wheel method (ASTM E-274) is used widely on US highways and simulates emergency braking without anti-lock brakes. Many agencies monitor friction on an annual basis or on a 2 or 3 year cycle. The spatial interval for friction tests is typically 1-2 tests per mile with some US highway agencies performing 3-5 friction tests per mile (FHWA, 2010).

The three remaining methods can be characterized as continuous friction measurement equipment (CFME) because they collect friction measurements continuously, greatly enhancing the ability to detect isolated low friction areas on pavements. The side force method evaluates the ability to maintain control in curves, and similar to the fixed slip and variable slip methods, relate better to braking with anti-lock brakes. When this advisory was published, side force friction, fixed and variable slip measurement systems were not readily available or used on U.S. highways. However, the advantage of these methods over the locked wheel method is the ability to operate continuously over a test section, especially on curves, and the better relationship to braking with anti-lock brakes. Because all friction test methods can be insensitive to macrotexture under specific circumstances, it is recommended that friction testing be complemented by macrotexture measurement (FHWA, 2010).

In 2010, in support of that directive, the Center for Sustainable Transportation Infrastructure of the Virginia Tech Transportation Institute (VTTI) initiated the FHWA-funded research project "Development and Demonstration of Pavement Friction Management Programs." The three objectives of this project are (1) to establish investigatory (desirable) and intervention (minimum) levels for friction and macrotexture for different friction demand categories or classes of highways; (2) assist at least four states in developing PFMPs; and (3) demonstrate state-of-the-art friction measurement equipment.

An essential early-project task of the VTTI research was to prepare a written report to FHWA that recommended the most technically sound type of continuous friction measurement equipment to manage proactively a network-level pavement friction program (Flintsch et al., 2011). The overriding criterion used was the ability of the recommended equipment to discern pavement properties that can be addressed to reduce crashes on as much of the network as possible. The final recommendations called for a sideway force coefficient (SFC) continuous measuring system with a 2,000-gallon tank able to measure friction between 30 and 60 mph, with a fixed slip ratio between 30% and 45%, dynamic load measurement capability along both the vertical and horizontal axes, macrotexture and temperature sensors, and an inertial differential GPS system capable of providing grade, cross-slope, and radius of curvature at 10-m intervals. This device is marketed as the SCRIM (Side-Force Coefficient Routine Investigation Machine) manufactured by W.D.M. Limited in Bristol, England, under license to the UK Transport Research Laboratory (TRL).

A Recent Review of Virginia's WARP

In June 2010, when FHWA launched the new PFMP technical advisory, which emphasizes a network-level approach, the amount of friction testing suggested was significantly increased. In response to this and other changes in the highway legislation, in October 2012, the Highway Safety Engineer's Officer from VDOT's TED started a review of the WARP and approached the VTRC Pavement Research Advisory Committee to present their findings on the limitations to the WARP. As a result of this meeting, VTRC was asked to review the WARP and "one of WARP's critical components, the Potential Wet Accident Hotspot (PWAH) procedure, which identifies locations with elevated wet-weather crash rates relative to comparable locations" (Cottrell and Kweon, 2013). Among the outcomes from that review were recommendations to include multiple years of crash data, and to develop safety performance functions (SPFs) that incorporate predictors such as wet-weather and traffic exposure. Although not mentioned specifically, friction is another likely predictor of safety performance for pavements.

PURPOSE AND SCOPE

The purpose of this research was to explore the use of CFME as a principal tool for pavement friction management. This was accomplished through a district-level pilot that included collection of an inventory of CFME-based data, reduction of that data to link with other pavement- and crash-related records, analysis to relate friction (and other) data to crash rates, and an exercise to demonstrate the economic ramifications of a proactive PFMP.

The researchers initially agreed to make a complete assessment of the pavement friction program to include CFME testing and comparisons to the locked-wheel skid tester used by Virginia. Because the locked-wheel tester was not operational during the data collection phase of the study, the comparisons were limited to operational characteristics. The analysis of the friction measurements and their relationship to crash data were accomplished and delivered through enhanced SPFs.

METHODS

Friction Data

Collection

VDOT's Salem District, which contains Virginia Tech, was selected for the pilot. The first step was to select the roads within the Salem District to survey. A starting point was the same roads that the Pavement Maintenance System (PMS) surveys each year as part of their road condition inventory. Every year PMS collects pavement condition data in one lane in each direction of travel for all divided roads and one lane in only one direction for undivided roads. These lanes are called directional lane-miles, and PMS collects data along the directional miles for the three major systems of highways in Virginia: interstate (100%), primary (100%), and secondary systems (20%, or equivalent to a 5-year cycle).

To understand the scope of this work, Table 1 details the number of highway miles, the actual number of lane-miles, and the directional miles for all VDOT roads and for the Salem District. Interstate highways have at least four lanes; thus the total number of interstate lane-miles (5,403) is about four times the total number of highway miles (1,118 x 4 = 4,472). This does not apply to the primary system, because some roads have two, others have three, and others have four lanes; the average is actually 2.68 lane-miles/highway miles. Finally, the secondary system is composed of two-lane undivided roads, which essentially equates to 2 lane-miles per mile of secondary highway. Friction measurements were made at 3-ft intervals, or 1,760 per mile, and processed for every site, or 0.1-mile segment, to match the crash database used in Virginia.

Table 1. Miles of Roads per Road System for Virginia

Highway Classification	Virginia			Salem District			
	Highway Miles[1]	Lane-miles[2]	PMS Directional Miles[3] (Approx.)	Lane-miles[2]	PMS Directional Miles[3] (Approx.)	Miles Tested	0.1-mile Sites
Interstate	1,118	5,403	2,200	493	235	220	2,322
Primary	8,111	21,794	10,500	2,667	1,288	1,133	11,204
Secondary	48,305	98,863	7,700*	14,702	1,092*	640	6,408
Frontage	333	655		105			
TOTAL	57,867	126,715	20,400	17,967	2,615	1,993	19,934

* (~ 20% of secondary system).
1 = (VDOT, 2015).
2 = (VDOT, 2014).
3 = (Chowdhury, 2015).

The reason to use only one representative lane in each direction of a divided pavement is that it is assumed that the pavement will have the same condition in all lanes of the pavement because all the lanes are usually constructed at the same time. For undivided pavements, it is also assumed that both lanes will be in the same condition. This also reduces the amount of lane-miles that need to be surveyed each year.

The Salem District is composed of 12 counties: Giles, Craig, Montgomery, Botetourt, Pulaski, Roanoke, Bedford, Franklin, Floyd, Carroll, Patrick, and Henry. The miles surveyed in the Salem District and the number of lane-miles collected by the PMS surveys is almost equal for the interstate (IS) and the primary system (PS) but vary significantly in the secondary system. This is due to the fact that for PMS purposes, the 20% sample is randomly made to reflect network-level condition. However, this random sampling includes some secondary sites that have little or no traffic, are dead-end streets, are unpaved, etc. This approach was not considered appropriate for the study, so a list of the most heavily traveled secondary roads for each county in the district was obtained from the staff of the Regional Traffic Engineering Department (RTE) and is provided in Appendix A.

Because the FHWA-recommended device for implementation of a statewide PFMP (Flintsch et al., 2011) was not available in the United States, the Grip Tester (GT) device (Figure 1) was used to collect friction data on the IS, PS, and highest priority secondary system as identified. These data were then compiled into a format suitable for input into PMS at 0.1-mile intervals, including divided IS and PS roads in both directions and all non-divided roads in only one direction. This was done from south to north and from west to east on all routes, as that is the way the mileage system is numbered for all of the state routes.

Figure 1. VTTI's Grip Tester, CFME Available in Virginia.

Before the GT testing started, researchers learned that VDOT's locked-wheel skid tester would not be available. In lieu of field-level comparison runs, results from tests made on the Virginia Smart Road are used to help relate CFME to locked-wheel test results.

Pre-Processing

On open roadways, it is very difficult to maintain a constant speed as required by friction specifications, normally 40 mph. A speed modification factor (0.007/per mph) found in a previous study was used to convert the results to the 40 mph standard (Flintsch et al., 2010).

Additional analysis was necessary to group all of the friction data (collected every 3 feet) into a meaningful average for each of the 0.1-mile sites that corresponded with available crash data. This was accomplished using a moving-average filter of 60 feet for the entire 0.1 mile. The filter length was selected to align with the locked wheel tester, which reports friction from an average of 1 second of measurement at 40 mph (59 feet). The analysis then selected the lowest point in that 0.1-mile moving-average data, which then represents the lowest measurement that any locked-wheel skid tester could find if it knew exactly where the worst 1-second average would happen in every 0.1 mile. There are 157 possible 60-feet sections in a 0.1-mile (528 ft) site, so the chances of a locked-wheel device "finding" that same location are 1/157.

Crash Records

Annual Virginia Data

A breakdown of the 10-year crash data from 2003 to 2012 in Virginia is shown in Table 2 to show that on average every year 82% of crashes occur under dry (clear or cloudy) conditions compared to only 15% that are considered wet crashes with the remaining (~3%) happening during snow, ice or hail events. Because the great majority of crashes happen under dry conditions, it is important that comprehensive crash analysis (to include friction, etc.) considering all crashes, not just the wet ones. It is also worth noting that on average, the percentage of fatal crashes, injury, and personal property crashes is 1%, 35%, and 64% of the total crashes, respectively.

Table 2. Average Crashes in Virginia: 1999-2012 (Commonwealth of Virginia, 2013)

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	Average
Fatal	860	837	875	865	940	760	694	689	707	714	794
Personal Injury	55,041	55,194	53,727	52,083	49,138	48,887	44,285	43,149	43,993	44,924	49,042
Property Damage	98,947	97,876	99,247	98,744	95,327	85,635	71,765	72,548	75,813	77,941	87,384
Total Crashes	154,848	153,907	153,849	151,692	145,405	135,282	116,744	116,386	120,513	123,579	137,220
Crash Conditions											
Dry*	119,444	123,999	126,824	126,756	123,972	110,539	89,433	97,422	100,642	103,702	112,273
Snow	4,703	2,740	4,238	1,445	2,753	1,482	2,656	5,102	1,420	1,612	2,815
Ice (Sleet/Hail)	1,332	771	1,187	56	894	503	758	339	527	386	675
Wet and other**	29,369	26,397	21,600	23,435	17,786	22,758	23,897	13,523	17,924	17,879	21,457
% Dry	77%	81%	82%	84%	85%	82%	77%	84%	84%	84%	82%
% Wet	19%	17%	14%	15%	12%	17%	20%	12%	15%	14%	15%

* Dry (No adverse condition: clear or cloudy and ** Wet and other (rain, fog, mist, etc.).

Salem District

Snow and ice (and sleet/hail) represent conditions in which the tire and pavement are often at least partially separated by a "contaminant." Therefore, crashes that happen under these conditions cannot be attributed to lack of friction on the road, and have been eliminated from the analysis. When these crashes are not taken into account, the proportion of wet to dry crashes in the Salem District is 17% to 83%, as can be seen in Table 3. The crash data and average annual daily traffic (AADT) were obtained from the VDOT Traffic Monitoring System records for each corresponding 0.1-mile site of pavement where friction was measured. The data for curvature (radius of curvature on curves sites) were also obtained, only for the interstate and primary systems, from the PMS database, but it does not include the secondary system.

Table 3. Crashes Analyzed in the Salem District (2010-2012)[1] by Highway System

Highway System	Wet and Other*			Dry**			Analyzed (Wet + Dry)			Total Crashes	Found in 0.1-mile Sites	Total 0.1-mile Sites
	Fatalities	Injury	Property Damage	Fatalities	Injury	Property Damage	Fatalities	Injury	Property Damage			
Interstate	6	123	324	22	485	1,181	28	608	1,505	2,141	1,189	2,322
Primary	11	242	396	72	1,526	2,597	83	1,768	2,993	4,844	3,072	11,204
Secondary	0	126	209	17	510	783	17	636	992	1,645	1,217	6,408
Total Crashes	17	491	929	111	2,521	4,561	128	3,012	5,490	8,630	5,478	19,934
Interstate %	0.1%	1.4%	3.8%	0.3%	5.6%	13.7%	0.3%	7.0%	17.4%	24.8%		
Primary %	0.1%	2.8%	4.6%	0.8%	17.7%	30.1%	1.0%	20.5%	34.7%	56.1%		
Secondary%	0.0%	1.5%	2.4%	0.2%	5.9%	9.1%	0.2%	7.4%	11.5%	19.1%		
TOTAL %	0.2%	5.7%	10.8%	1.3%	29.2%	52.9%	1.5%	34.9%	63.6%	100.0%		

1 = (Commonwealth of Virginia, 2013).

* Dry (No adverse condition: clear or cloudy and ** Wet and other (rain, fog, mist, etc.).

The crash counts are divided into three types of crashes: fatalities, injuries, property damage. The proportion of the three types of crashes for the Salem District (1.5%, 34.9%, and 63.6%) matches the statewide averages in Table 2 (1%, 35%, and 64%). The 3-year series is used to average out the result of any uncommon effect from a single year. The results for the crash rates will also be presented as a 3-year total, from which a yearly average can be estimated. Figure 2 shows a histogram of the number of 0.1-mile sites surveyed in the Salem District with the same number of crashes.

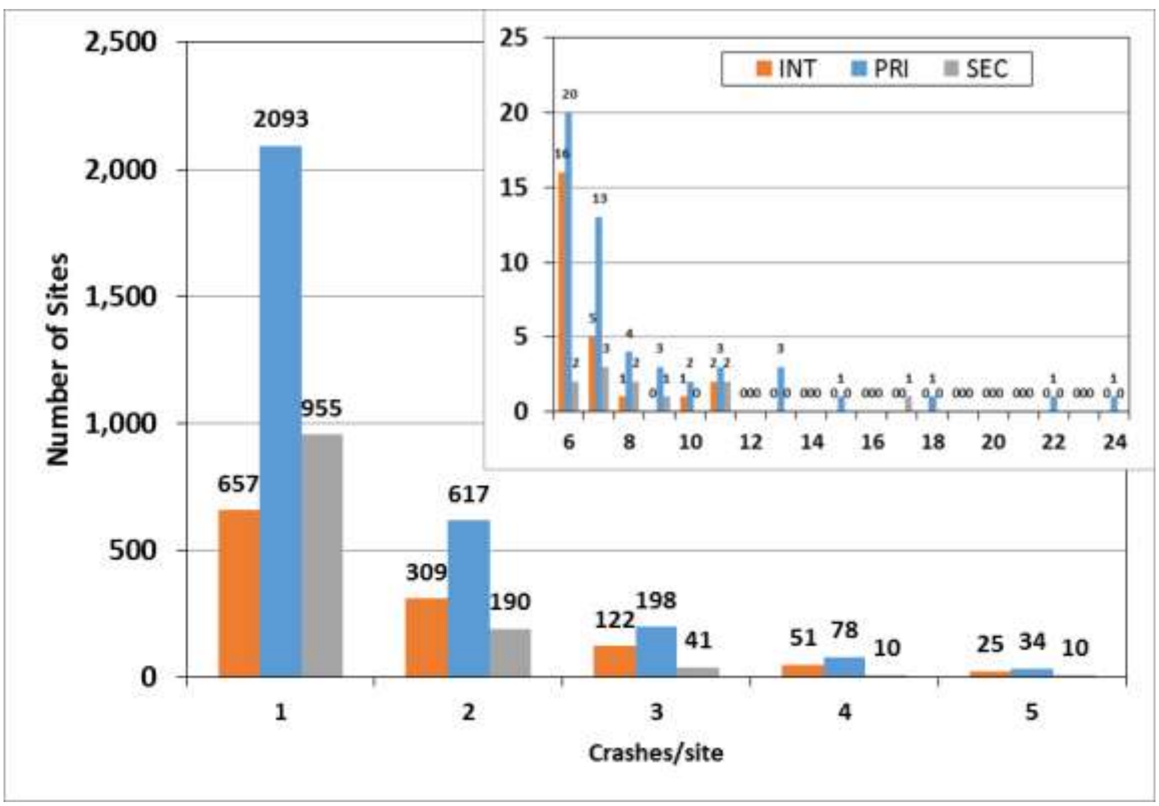

Figure 2. Sites With Increasing Number of Crashes

The number of sites with high crashes is very low. However, the two sites that have the maximum number of crashes observed on a site (22 and 24 crashes) are on the primary highway system.

Modeling of Crash Rates for Individual Pavement Sections

Vehicle crash analysis for network screening is typically analyzed using Poisson or Poisson-Gamma (Negative Binomial) models, and empirical Bayes (EB) crash rate estimation from observed crashes and SPFs, as described in the Highway Safety Manual (HSM) predictive methods (AASHTO, 2008). These terms are mostly unfamiliar to pavement engineers and, in this section, an intuitive explanation of crash rate modeling and estimation is provided.

Empirical Bayes and Safety Performance Functions

The data obtained from crash records are essentially count data; that is, the data are given in terms of the number of crashes observed at a specific pavement section (the same 0.1-mile pavement sections). Crash occurrence is a rare event with an associated very low probability of occurrence, a probability that will be named p. As such, for every vehicle traversing a 0.1-mile pavement section (the analysis can be done for other section lengths), there is a (very low) probability (chance) p that this vehicle will be involved in a crash on that specific section.

Because there are only two possible outcomes, crash or no crash, the observed outcomes will follow a binomial distribution (e.g., tossing a coin, but with the probability of heads very small, similar to the chance of winning the lottery). With a very large number of vehicles traversing the pavement section and a very small p, the binomial distribution converges to the Poisson distribution. Therefore, the use of the Poisson distribution to model crash rates can be explained through a logical physical process (that involves chances of occurrence). The Poisson distribution is parametrized by a rate (average) which represents the rate of crash occurrence. *Parametrized* means that it is completely defined by the rate (as a side note, the normal distribution is parametrized by two parameters, its average and standard deviation).

Highway safety analyses have determined that the crash rate depends on factors such as traffic, driver behavior, road geometry, pavement characteristics, and others. To find how these factors affect the rate (Poisson), a regression analysis is performed. In this study, traffic (expressed as Annual Average Daily Traffic or AADT), pavement friction, and curvature (when present) were considered as affecting the crash rate. Under the Poisson model assumption, given the AADT, pavement friction, and pavement curvature, the crash rate at a specific section can be determined.

In practice, the Poisson model does not fully represent the observed crash count. For the Poisson model, the variability (variance) of the observations is restricted to be equal to the rate. Researchers have long observed that the variability (variance) of actual crash data is much larger than the rate, referring to this phenomenon as over-dispersion (i.e., more variability than what would be predicted by the Poisson model). The physical explanation for this over-dispersion is that there are factors other than the ones considered in the regression model that affect the crash rate. In this study, AADT, friction, and curvature were considered and it should be expected that there are many more factors involved in a crash occurring.

The most common approach that has been used to account for the over-dispersion is to consider that the crash rate of sites having similar recorded characteristics (AADT, friction, and, if available, curvature) will vary according to a Gamma distribution (hence the term Poisson-Gamma, also called Negative Binomial [NB]) which provides significant flexibility in representing this variation. NB regression can be used to estimate the parameters of the regression. In general, the parameters will be close to the ones obtained from the Poisson regression. The advantage of the NB regression is that it also estimates the over-dispersion.

The estimated over-dispersion parameter is what essentially differentiates between the Poisson model and the NB model. The Poisson model considers that all relevant parameters that affect the crash rate have been considered in the model. As such the actual crash count on a pavement section does not provide any additional information about the crash rate as the rate can be (according to the Poisson model, exactly) calculated from the measured variables (AADT, friction, and curvature). In the NB model, the calculated rate is not the final estimated rate for a specific section. It represents the average of similar sections but the actual rate of each of these sections vary according to the over-dispersion parameter. Therefore, the actual crash count at a specific section provides additional valuable information about the crash rate at that specific section. A sensible approach to follow is to somehow combine the information from the model with the site specific crash count to come up with a better estimate of the true crash rate than what can be obtained from either the model or crash count alone.

This estimation approach is similar to the engineering method of problem solving that combines experience with site specific information, commonly known as the Observational Method (Peck, 1969). The model summarizes the information from all available sites and can be seen as compiling the engineering experience while the actual crash count is the site specific information. An experienced engineer knows to combine accumulated knowledge with the site specific information to come up with a good solution, in contrast with an inexperienced engineer that only uses site specific information to come up with "erroneous" solutions. If site specific information is relatively accurate, the experienced engineer will put more weight on this information and less weight on previous experience. In contrast, if site specific information is relatively inaccurate, an experienced engineer will place more importance on past experience.

In the modeling approach, the information is combined using Bayes' theorem. For the NB model, the Bayes solution turns out to be a simple weighted average of the model prediction and the actual site specific crash count, the relative weights of each depending on the over-dispersion. The empirical part of the EB approach refers to the fact that the parameters of the Gamma distribution, which is the prior, parameters are estimated from the data (using the NB regression).

For a more in-depth discussion of the models used here, their origins and applications, as well as more figures related to the different models, thesis work done as part of this research explains them in more detail than is necessary here (McCarthy, 2015).

Regression Analysis With Safety Performance Functions

As explained before, in the United States, the identification of high crash risk areas is assessed using SPFs, a procedure that is well established by the FHWA and AASHTO. The SPF used in Equation 1 employs the NB model, requiring the evaluation of AADT as the mandatory variable, while other factors (i.e., roadway geometry, traffic control features, etc.) are left to the discretion of the state DOT (Srinivasan and Bauer, 2013).

$$P = L \times e^{\beta_o + \ln(AADT)\beta_1 + X_{1+i}\beta_{1+j}} \quad \text{[Eq. 1]}$$

where

P = Expected number of crashes (also referred to as λ or the crash rate)
AADT = Annual Average Daily Traffic (natural logarithm)
X_{ij} = Independent variables
β_j = Regression coefficients
L = Road segment length.

In Virginia, the current network screening structure for Equation 1 considers only the AADT (Kweon and Lim, 2014). Equation 2 shows the variation from Equation 1 as the model form used for this study. In this model, two additional variables are included in the SPF model, radius of curvature, *CV* (interstate and primary routes only) and skid resistance, represented as *GN*, or Grip Number. The coefficient β_o is the intercept term. Since the sectional length is defined as 0.1 mile (all data adjusted accordingly), the *L* term is not included here.

$$\mu = e^{\beta_o + \ln(AADT)\beta_1 + GN\beta_2 + CV^{-1}\beta_3} \quad \text{[Eq. 2]}$$

The decision to use the inverse of the radius of curvature is based on the relationship of minimum radius of curvature to the maximum allowable side friction established by the equation for designing horizontal curves (AASHTO, 2011).

Negative Binomial Model (NB)

As explained before, to resolve the problem of over-dispersion, the NB distribution was used. The simplest way to describe what the NB modification does to Equation 1 is by including an extra "error" variable it now accounts for factors outside the model's direct consideration (i.e., traffic, friction, curvature, etc.), potentially resulting in a more precise theoretical estimations of the mean, as is shown here (Lord and Park, 2010).

$$\lambda_i = \mu_i \upsilon = e^{X_{ij}\beta_j e^{\varepsilon}} = e^{X_{ij}\beta_j + \beta_o} \quad \text{[Eq. 3]}$$

where

λ = Crash rate
μ = Poisson mean
υ = Random error term.

In Equation 3, the Poisson mean, μ, is treated as a random continuous variable, whose variability is dependent on the error term υ. The error term, υ, has a gamma distribution with a mean of 1 and a variance equal to an over-dispersion parameter α. With α and μ, the probability of a random crash variable, Y, equaling a crash event y_i can be computed using a probability density function as illustrated in Equation 4 (Cameron and Trivedi, 2010). The coefficient α is defined as the response to the mean rate caused by the over-dispersion parameter

$$P(Y = y_i|\mu_i, \alpha) = \frac{\Gamma(\alpha^{-1} + y_i)}{\Gamma(\alpha^{-1})\Gamma(y_i + 1)} \left(\frac{\alpha^{-1}}{\alpha^{-1} + \mu_i}\right)^{\alpha^{-1}} \left(\frac{\mu_i}{\alpha^{-1} + \mu_i}\right)^{y_i} \qquad \text{[Eq. 4]}$$

with a variance of

$$VAR[y_i|\mu_i, \alpha] = \mu_i + \alpha\mu_i^2 \qquad \text{[Eq. 5]}$$

Goodness-of-Fit

In the process of setting up the models for each highway classification system (interstate, primary and secondary), several models were created, each employing a different array of variables to determine which model had the best combination of variables, as follows:

Intercept
Intercept + AADT
Intercept + AADT + GN
Intercept + AADT + GN + CV.

The determination of which model to use (how many variables) was done with the Akaike Information Criterion (*AIC*) evaluation technique, which uses its log-likelihood value (*LLV*).

Akaike Information Criterion (AIC)

AIC assesses the fitness of a model based on the log-likelihood value of the model, *LLV*, and a penalty term related to the number of estimated parameters, *p* (Lord and Park, 2010). First, a value of *AIC* must be computed for each model i as shown in Equation 6.

$$AIC_i = -2\ln(LLV) + 2p \qquad \text{[Eq. 6]}$$

After computing the *AIC* for each model, the model with the lowest *AIC* becomes $AIC_{\min}$ with which all other model *AIC*'s are compared. The term ΔAIC_i is computed with Equation 7, by taking the difference between the *AIC* for each model and $\Delta AIC_{\min}$ among all the models used (Mazerolle, 2004).

$$\Delta AIC_i = AIC_i - AIC_{\min} \quad \text{[Eq. 7]}$$

Using ΔAIC_i the probability of each model being the best model is determined by computing the Akaike Weight (W_i) as shown in Equation 8.

$$W_i = \frac{e^{\frac{-\Delta AIC_i}{2}}}{\sum_{i=1}^{n} e^{\frac{-\Delta AIC_i}{2}}} \quad \text{[Eq. 8]}$$

After computing (W_i), the model with the highest value is taken as the best model. The best model is then compared to the other models using an evidence ratio (ER_i) calculation as shown in Equation 9. The value of ER_i expresses how likely it is that the best model will perform better than the other models (Mazerolle, 2004).

$$ER_i = W_{Best} / W_i \quad \text{[Eq. 9]}$$

Risk Assessment: Empirical Bayes Method

Finally, the solution used to predict the number of crashes at each site is derived from the empirical Bayes (EB) estimation. In EB estimation, the observed crash counts O_i for $site_i$ are combined with the NB estimate λ_i from Equation 3, to produce a more precise crash estimate γ_i as described by Equation 10. The weighted EB estimate in Equation 10 is established using a weighted measure W_i from Equation 9, which accounts for the variability in both the model and the observed amounts (Hauer, 2001).

$$W_i = \frac{1}{1+\mu_i \alpha} \quad \text{[Eq. 9]}$$

$$\gamma_i = W_i \times \lambda_i + (1 - W_i) \times O_i \quad \text{[Eq.10]}$$

where

γ_i = Weighted empirical Bayes crash estimate for $site_i$

O_i = Observed crash count for road $site_i$

RESULTS

Friction Data

Site Characterization

Figure 3 illustrates the process used to characterize the friction for 0.1-mile sites.

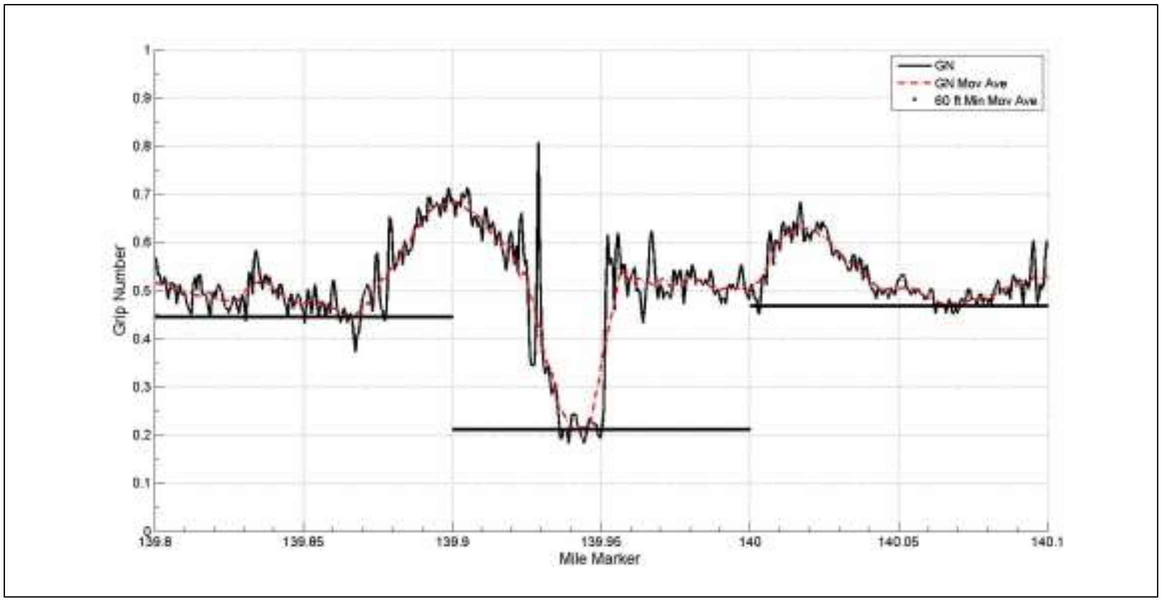

Figure 3. Grip Tester Measurements Mile Marker 139.8 to 140.1

The plot shows the results of the Grip Tester measurements made every 3 feet in the continuous line marked GN (Grip Number). The dotted line represents the 60-foot moving average at every point (an average of 20 measurements along the road). The moving average filters the high and the low peaks. Finally, the lowest 60 foot moving average is selected for the 0.1-mile site (528 feet), representing the lowest possible friction measurement that a non-continuous (e.g., locked-wheel) skid tester would measure as the lowest friction spot along that 528-foot section. For this particular example, the Grip Numbers associated with each of the three 0.1-mile sites are MM 139.8 – GN = 0.45; MM 139.9 – GN = 0.21; and MM 140.0 – GN = 0.47.

The representative value for each site can be obtained if a different criterion is used. The important thing is that the resulting Grip Number adequately relates to the risk that a site's friction could contribute to a crash.

All Highway Systems

Figure 4 shows the histogram of the Grip Tester Grip Numbers for all the 0.1-mile highway sites of interstate, primary, and secondary roads measured in the Salem District.

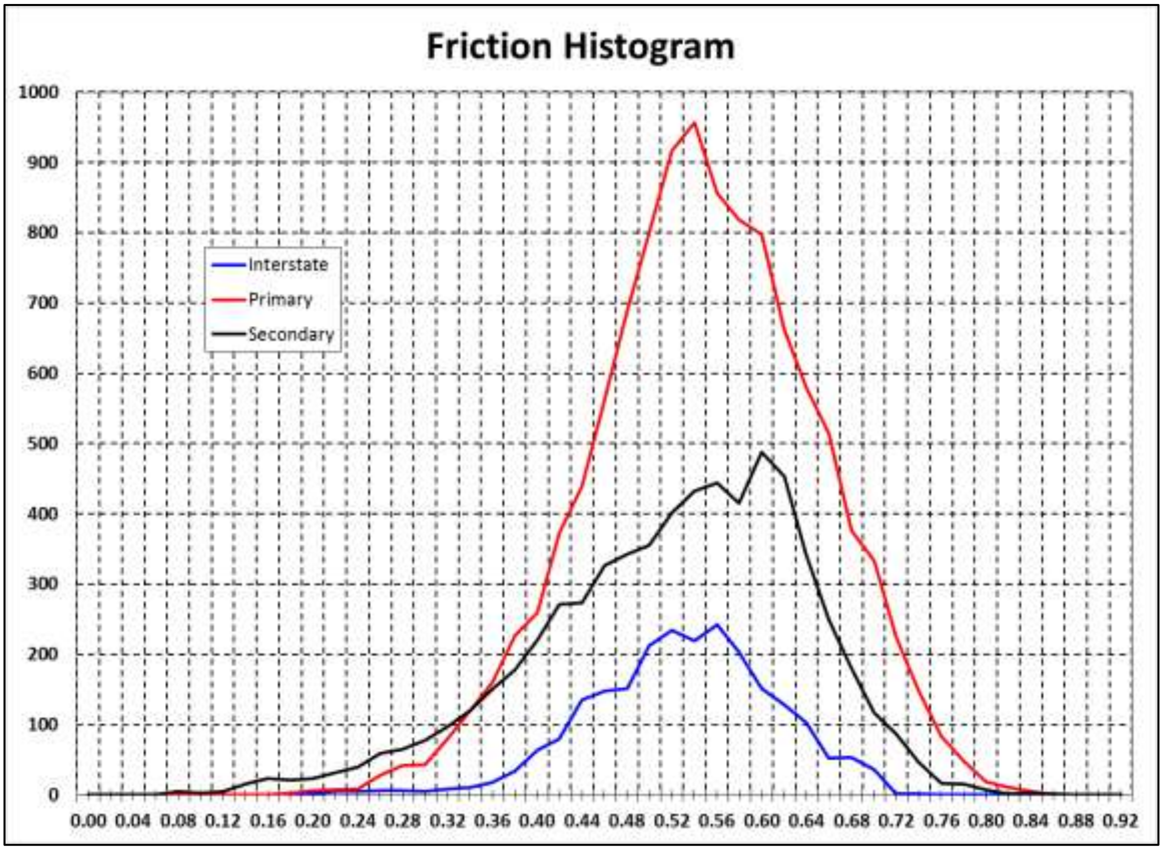

Figure 4. Histogram of Grip Numbers for Highway Systems in the Salem District

The three highway systems had the following average values and standard deviations:

1. Interstate: 0.52 average and 0.08 standard deviation
2. Primary: 0.54 average and 0.10 standard deviation
3. Secondary: 0.51 average and 0.12 standard deviation.

It can be observed in Figure 4 that because of the larger standard deviations at lower road classifications, there are more road sites with lower Grip Numbers in the primary system than in the interstate, and even more in the secondary system than in the other two.

Comparison of Pavement Friction: Locked-wheel Skid Testers vs. Grip Tester

In tests done at the Virginia Smart Road in May 2013, testing at 40 mph resulted in average differences between measurements with several locked-wheel skid testers and a Grip Tester of 22 and 15, when equipped with a smooth and ribbed tire, respectively. In another set of tests done in October 2013 at the AASHTO National Transportation Product Evaluation Program (NTPEP) with High Friction Surface Treatments in Lexington, Kentucky, the average difference at 40 mph was 19 and 9, but that difference increased to 21 and 12, when comparing only the HFST tested, both respectively with a smooth and a ribbed tire. For this project, the researchers deemed it appropriate to use a difference of 20 and 10 for comparing measurements done with a Grip Tester and a locked-wheel skid tester, with a smooth and a ribbed tire, respectively. All Grip Numbers equal or less than 0.40 are assumed equivalent or less than a locked-wheel test

[SN40(S)] of 20 with a smooth tire, which is the current threshold used in Virginia. This is provided just as a reference comparison that does not affect the results of the analysis because it is based entirely on the Grip Numbers obtained for all the sections measured.

Crash Data Results

Using the total 8,630 crashes found in each of the three highway systems analyzed in the Salem District, the following models were developed to predict the cumulative crashes for the next 3 years.

Regression Model Results

Regression analysis was performed using 3 years of crash data for the three highway systems. Modification of the negative binomial rates, the intercept term, and the over-dispersion parameter was performed to generate the regression models, and their goodness-of-fit data are shown in Tables 4, 5, and 7 that determined the number of significant variables for each model.

Interstate Highway System

$$\mu = e^{-0.35+1.25\times\ln(AADT)-1.19\times GN} \quad \text{[Eq.11]}$$

Table 4. Regression Analysis and Akaike Information Criterion for Interstate Routes

	Parameter Estimates				Goodness-of-fit					
	Intercept	AADT	GN	CV	α	ln(L)	AIC	ΔAIC	W_i	ER_i
1	-0.08	-	-	-	0.71	-3,081.20	6,164.40	107.17	0.0%	1.87E+23
2	-0.99	1.29	-	-	0.63	-3,032.52	6,069.04	11.81	0.2%	367.39
3	**-0.35**	**1.25**	**-1.19**	**-**	**0.62**	**-3,025.61**	**6,057.23**	**0.00**	**68.0%**	**1.00**
4	-0.37	1.25	-1.18	0.02	0.62	-3,025.38	6058.75	1.52	31.7%	2.14

Model 3 has a 68% chance of being the best model, Model 4 only a 32% chance. Model 3 is the chosen model for the interstate system, which does not include the curvature parameter as a significant contributor to the predictions (ramps were not included).

Primary Highway System

$$\mu = e^{-0.25+0.37\times\ln(AADT)-1.00\times GN+0.04\times CV^{-1}} \quad \text{[Eq.12]}$$

Table 5. Regression Analysis and Akaike Information Criterion for Primary Routes

	Parameter Estimates				Goodness-of-fit					
	Intercept	AADT	GN	CV	α	ln(L)	AIC	ΔAIC	W_i	ER_i
1	-0.84	-	-	-	1.91	-9,731.92	19,465.84	437.04	0.0%	7.96E+94
2	-0.69	0.37	-	-	1.66	-9,538.47	19,080.95	52.15	0.0%	2.11E+11
3	-0.17	0.34	-1.01	-	1.64	-9,527.07	19,060.14	31.34	0.0%	6.39E+06
4	**-0.25**	**0.37**	**-1.00**	**0.04**	**1.62**	**-9,510.40**	**19,028.80**	**0.00**	**100.0%**	**1.00**

The calculations of W_i indicate that *Model 4* has a 100% chance of being the best model. This model chosen for the primary system does include the curvature parameter as a very significant contributor to the predictions. This highlights the importance of acquiring the curvature data for the secondary system. As can be seen in Table 6, the curves of the interstate and the primary systems seem to indicate the possibility that the number of sites with very low radius of curvature in the secondary system is greater, thus making driving more critical to having adequate friction. This reinforces the fact that when the PFMP is implemented in Virginia, it is highly recommended it should obtain curvature data for the secondary roads.

Table 6. Radius of Curvature

Road System	Sections with Radius < 1,600 ft	Total No. of Sections	% < 1,600 ft
Interstate	125	2,322	5.4%
Primary	2,626	11,204	23.4%
Secondary	?	6,408	?

Secondary Highway System

$$\mu = e^{-0.55+0.75\times\ln(AADT)-0.56\times GN} \quad \text{[Eq.13]}$$

Table 7. Regression Analysis and Akaike Information Criterion for Secondary Routes

	Parameter Estimates			Goodness-of-fit					
	Intercept	**AADT**	**GN**	**α**	**ln(L)**	**AIC**	**ΔAIC**	**W_i**	**ER_i**
1	-1.36	-	-	1.99	-4,047.10	8,096.21	624.18	0.0%	3.45E+135
2	0.30	0.77	-	0.95	-3,735.68	7,475.37	3.34	15.9%	5.31
3	**0.55**	**0.75**	**-0.56**	**0.95**	**-3,733.02**	**7,472.03**	**0.00**	**84.1%**	**1.00**

The secondary system inventory does not include the curvature data.

Empirical Bayes Method Crash Prediction

Using the models developed in the previous section, an EB prediction of the number of expected crashes can be made for all three highway systems. An example of this is shown in Figure 5 for a portion of I-81 in the Salem District (MM 130-170). The figure shows the data in 0.1-mile sections. The individual observed crashes in each section is marked with a triangle. The continuous (red) line represents the expected crashes for each section using the SPF model.

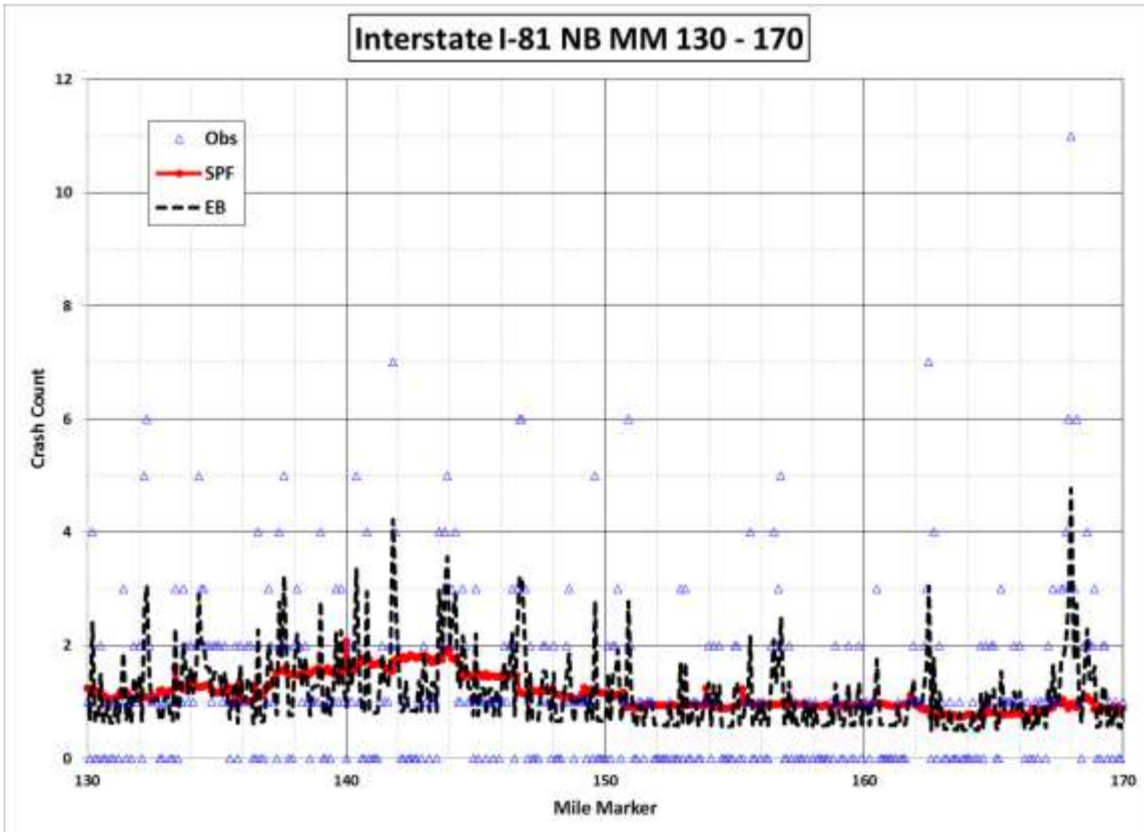

Figure 5. Observed Crashes, Rate (SPF), and Predicted (EB) Crashes on I-81 MM 130-170, Salem District

It is interesting that this estimation is higher than observed on sections with zero crashes and lower on those sections that have more than two crashes. The overall average and total number of crashes of the observed data and the SPF crash rate is identical. Thus, what has happened is a redistribution of the expected crash rate assigning a non-zero value to all sections accordingly with the data used by each individual model (AADT, GN, and where applicable, CV). The last series of data points in Figure 5 (dotted black line) is the SPF crash rate as improved by the EB method, which applies a weighted average of the observed number of crashes to provide a more realistic (and conservative) prediction of crashes per section.

DISCUSSION

Crash Reduction and Pavement Friction

A demonstrated relationship between predicted crashes and an "influence-able" characteristic of the pavement surface (like skid resistance) creates an opportunity to explore scenarios that could lead to measureable safety improvements. With that in mind two alternatives were developed, one in which pavement sections were "improved" to a friction level consistent with a well-performing hot-mix asphalt (HMA) overlay (OL) and the second in which the sections received a high friction surface (HFS) treatment.

Average skid resistance for the two surfaces used in this exercise was based on test results for different pavements at the Virginia Smart Road, the NTPEP tests mentioned earlier, and recent measurements made on Virginia interstate pavements in the Salem District. The average Grip Number (GN) values assumed were 0.70 for OL and 0.95 for HFS. Substituting these values to represent friction level for a given pavement section, the analysis generates a new predicted SPF rate (when the observed GN for that specific section is lower than the proposed GN_{OL} or GN_{HFS}), which we will call λ_{OL} or λ_{HFS}, respectively. These rates are then used to make a new EB estimate by applying a multiplier that is proportionally related to the original λ_i, as shown in Equations 14 and 15.

$$\gamma_{OLi} = \frac{\lambda_{OL}}{\lambda_i} \times \gamma_i \qquad \text{[Eq.14]}$$

$$\gamma_{HFSi} = \frac{\lambda_{HFS}}{\lambda_i} \times \gamma_i \qquad \text{[Eq.15]}$$

This approach can then be used to generate new crash rates for any segment in the network. This is illustrated in Figure 6, which represents a small part of the stretch of interstate shown in Figure 4, but without the observed crash counts. Again, the original EB estimate for crash rate is the dotted line. Below it, for every 0.1-mile site, are the rates as estimated with the two alternative friction-enhancement treatments. The circles represent overlays and the triangles are HFS treatments. The predicted crashes for the HFS sites are always lower than those for the OL, due to the lower friction of the OL with respect to the HFS.

Evaluating Treatment Strategies

This process can be used to explore the user-safety ramifications of any treatment strategy that might impact pavement skid resistance. Projected crash rates are first calculated using three variables: AADT, GN, and when available, CV. Modified crash rates can then be computed using the average friction increase achieved with the new treatment, in this case either the OL or HFS. After this is done, the difference between the original EB crash rate produced by the model and the new crash rates achieved by increasing the pavement friction can be computed. The reduction in the number of crashes can be computed as an economic, or societal, benefit by estimating the cost of an average crash in any system.

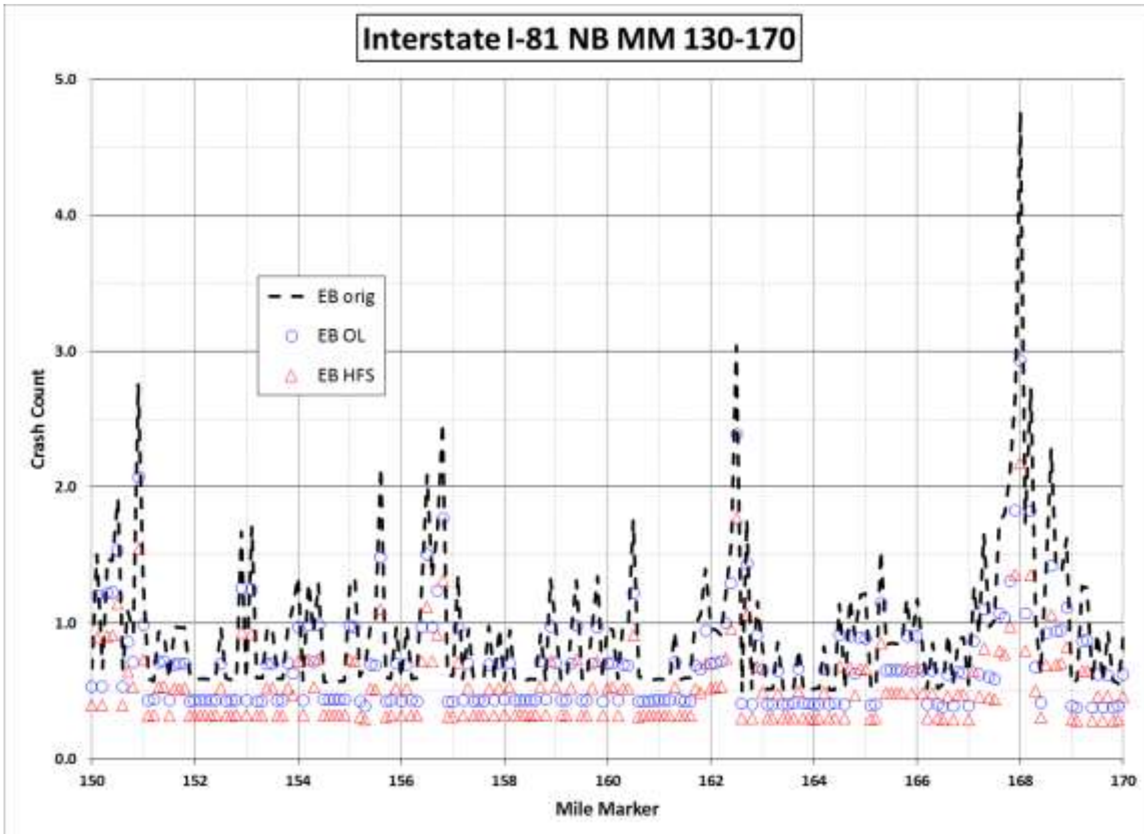

Figure 6. Original EB, EB_{OL}, and EB_{HFS} Crash Rates on I-81 MM 130-170, Salem District

Crash Costs

The average cost of a crash can be complicated to estimate and requires several sources. The first one is the Guidance on Treatment of the Economic Value of a Statistical Life (VSL) in the U.S. Department of Transportation Analyses. In its conclusion, the Under Secretary for Policy recommends "studies published in recent years indicate a VSL of $9.1 million in current dollars for analyses using a base year of 2012" (U.S. DOT, 2015). This same document also provides a breakdown of the injury severity level with the Abbreviated Injury Scale (AIS) for all types of injuries, as seen in Table 8.

Table 8. Relative Disutility Factors by AIS Level

AIS Level	Severity	Fraction of VSL
AIS 1	Minor	0.003
AIS 2	Moderate	0.047
AIS 3	Serious	0.105
AIS 4	Severe	0.266
AIS 5	Critical	0.593
AIS 6	Un-survivable	1.000

Virginia still uses the KABCO classification (K is fatal; A, B, and C, are for personal injuries, and O is for property damage only). Therefore, it is difficult to make the conversion of the costs recommended by the U.S. DOT. Fortunately, a recent study by the National Highway

Traffic Safety Administration (NHTSA), the Economic and Societal Impact of Motor Vehicle Crashes in 2010, details the total economic costs of U.S. crashes (Blincoe et al., 2014). As explained in the report, economic cost components include "productivity losses, property damage, medical, rehabilitation, and legal costs, etc.," while comprehensive costs include "both economic cost components and quality-of-life valuations." A summary of the costs reported in this study can be seen in Table 9.

Table 9. Economic and Comprehensive Costs of 2010 Crashes (NHTSA)

Crash Type	Reported	Not Reported	Total Crashes	Economic Cost: Cost ($million)	Economic Cost: Cost/Crash	Comprehensive Cost: Cost ($million)	Comprehensive Cost: Cost/Crash
Fatal	30,296	-	30,296	$46,163	$1,523,733	$301,809	$9,962,008
Non-fatal injuries and				$146,347		$484,506	
Uninjured (MAISO)	1,791,572	1,178,391	2,969,963	$13,030	$53,663	$13,030	$167,523
Property damage only	4,255,495	6,310,019	10,565,514	$71,480	$6,765	$71,480	$6,765
Total	6,077,363	7,488,410	13,565,773	$277,020	-	$870,825	-

The fatality cost estimation from NHTSA is slightly higher than the recommendation from the U.S. DOT, $9.1 million vs. $9.962 million, so the lower value was used. Similarly, the NHTSA study reports a value for *reported crashes* with property-damage-only at only $6,076. Since this analysis is limited to reported crashes, $6,076 is used as the per-crash value rather than $6,675 as shown in the table. Finally, the average value of all non-fatal injuries from the NHTSA study ($167,523) is used to estimate injury-related crashes since Virginia does not scale injury crashes in accordance with the U.S. DOT.

Using these three average unit costs for fatal, injury, and property damage only, the total cost of the crashes that took place in the Salem District was obtained and then an average cost per crash was derived to be used in the benefit calculation. Table 10 summarizes these calculations.

Table 10. Economic and Comprehensive Costs of Crashes 2010-2012, Salem District

Crash Type	Crashes	Economic Cost/Crash ($1,000)	Total Economic Cost ($1,000)	Comprehensive Cost/Crash ($1,000)	Total Comprehensive Cost ($1,000)
Property Damage only	5,490	$3.9	$21,202	$6.1	$33,357
Personal Injury	3,012	$167.5	$161,633	$167.5	$504,579
Fatal	128	$1,398.9	$179,061	$9,146.0	$1,170,688
Total	8,630		$361,897		$1,708,624

If only economic costs are used for the analysis, an average crash would cost $41,935/crash ($361,897,000/8,630). However, the average comprehensive costs (recommended by the U.S. DOT memo), are estimated at $197,987/crash ($1,708,624,000/8,630). This average cost per accident has to be established by each agency according to what each states considerations are regarding the cost of each type of crash.

Treatment Costs

A recent report detailed average costs for HFS treatments at $27/yd^2 and the average cost of an HMA overlay for a longer section at $10/yd^2 (Sprinkel, et al., 2015). That means that these two treatments for 0.1 mile of road (528 ft), two 12-ft lanes, represent a cost of $14,080 and $38,016 for an overlay and an HFS treatment, respectively.

Benefit to Cost Analysis

When assessing the benefits from prevented crashes as predicted using the developed models, it becomes clear very quickly that regardless of the treatment selected ($14,080 or $38,016 per 0.1-mile section), increasing the friction has a net positive economic effect. A case study from the Salem District (discussed next) helps demonstrates how pavement friction data could be incorporated into existing pavement maintenance procedures to improve safety and reduce overall societal costs.

Case Study 1: I-81 Mile Markers 167-169

The section of I-81 between mile markers 167 and 169 incorporates characteristics that are conducive for studying measures for improving highway safety. This location, referred to as the Arcadia Exit, consists of a composite “S” curve with the first curve having a radius of 1,050 ft and the second one a radius of 1,200 ft. Figure 7 shows two plan views of the two curves at the site.

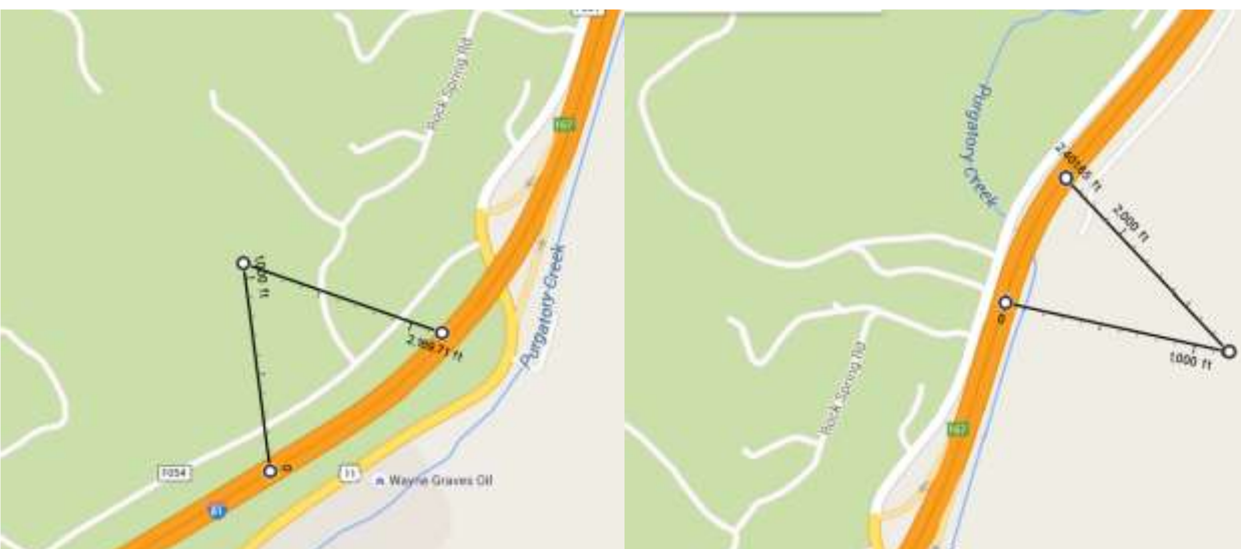

Figure 7. I-81 Northbound MM 167 to 169, Salem District (from Google maps)

These curves are also located at the bottom of a vertical sag curve, which probably causes vehicles to be going faster than normal in the entrance to the horizontal curves. The small radius, the increased speed, and a short tangent between both curves, likely challenge the effectiveness of the design cross-section, reducing the tolerance for driver error when negotiating the curves. This particular section of road experienced 58 crashes in 2 miles, and in the middle, from 167.6 to 168.6, there have been 43 crashes in 3 years.

Analysis that contrasts current friction against that which could be achieved using two possible alternative treatments (i.e., OL and HFS) show a great potential for improvement by increasing the available friction. This can be seen through the results presented in Table 11.

Table 11. EB Analysis Results for I-81 MM 167-169 With OL and HFS Alternatives

MP	Obs. Crashes	GN	AADT (10,000)	ln (AADT)	CV (mi)	Inv. CV	SPF Model (Eq. 11) Rate	Weight	EB	OL Rate	EB	OL Improve	HFS Rate	EB	HFS Improve
167.0	1	0.41	1.7	0.53	0.38	2.67	0.843	0.653	0.551	0.596	0.389	0.16	0.442	0.289	0.26
167.1	2	0.39	1.7	0.53	0.38	2.67	0.867	0.647	1.267	0.596	0.870	0.40	0.442	0.646	0.62
167.2	1	0.37	1.7	0.53	0.38	2.67	0.878	0.644	0.921	0.596	0.625	0.30	0.442	0.464	0.46
167.3	3	0.36	1.7	0.53	0.38	2.67	0.895	0.640	1.654	0.596	1.100	0.55	0.442	0.817	0.84
167.4	1	0.30	1.7	0.53	0.71	1.40	0.958	0.624	0.974	0.596	0.605	0.37	0.442	0.449	0.52
167.5	1	0.24	1.7	0.53	0.71	1.40	1.033	0.606	1.020	0.596	0.588	0.43	0.442	0.437	0.58
167.6	3	0.29	1.7	0.53	0.71	1.40	0.968	0.621	1.737	0.596	1.069	0.67	0.442	0.794	0.94
167.7	3	0.24	1.7	0.53	0.71	1.40	1.036	0.605	1.811	0.596	1.041	0.77	0.442	0.773	1.04
167.8	4	0.31	1.7	0.53	10.00	0.10	0.950	0.626	2.091	0.596	1.311	0.78	0.442	0.973	1.12
167.9	6	0.37	1.7	0.53	1.80	0.56	0.878	0.644	2.702	0.596	1.832	0.87	0.442	1.360	1.34
168.0	11	0.29	1.7	0.53	1.80	0.56	0.968	0.621	4.766	0.596	2.932	1.83	0.442	2.177	2.59
168.1	3	0.29	1.7	0.53	1.80	0.56	0.969	0.621	1.738	0.596	1.069	0.67	0.442	0.793	0.94
168.2	6	0.36	1.7	0.53	1.80	0.56	0.891	0.641	2.727	0.596	1.822	0.91	0.442	1.353	1.37
168.3	1	0.36	1.9	0.64	1.80	0.56	1.021	0.609	1.013	0.684	0.679	0.33	0.508	0.504	0.51
168.4	0	0.36	1.9	0.64	3.03	0.33	1.032	0.606	0.625	0.684	0.415	0.21	0.508	0.308	0.32
168.5	2	0.34	1.9	0.64	3.03	0.33	1.050	0.602	1.428	0.684	0.931	0.50	0.508	0.691	0.74
168.6	4	0.31	1.9	0.64	0.95	1.05	1.093	0.592	2.278	0.684	1.426	0.85	0.508	1.058	1.22
168.7	2	0.36	1.9	0.64	0.95	1.05	1.028	0.607	1.410	0.684	0.938	0.47	0.508	0.697	0.71
168.8	2	0.38	1.9	0.64	0.33	2.99	1.000	0.614	1.386	0.684	0.948	0.44	0.508	0.704	0.68
168.9	3	0.38	1.7	0.53	0.20	4.95	0.869	0.646	1.622	0.596	1.112	0.51	0.442	0.826	0.80
169.0	0	0.40	1.7	0.53	0.20	4.95	0.852	0.651	0.555	0.596	0.388	0.17	0.442	0.288	0.27

SPF Model "Eq. 11" = predicted crash rates (crashes every 3 years) with current friction.
OL EB = predicted crash rates with Overlay (OL).
HFS EB = predicted crash rates with high friction surface (HFS).
OL Improve = reduction in predicted crashes with OL.
HFS Improve = reduction in predicted crashes with HFS.

From this table, the EB model predicts that the total improvement in the "critical mile" (from MM 167.6 to MM 168.6, shaded) containing both curves and the short tangent in between could have an expected reduction of 8.4 crashes (every 3 years) if it is overlaid (OL) and 12.1 crashes should an HFS treatment be applied.

To calculate which treatment would be better, a benefit/cost (B/C) comparison or a total comprehensive economic savings can be made for each site, as shown in Table 12. This analysis reflects a cost for each 0.1 mile of $14,080 for an overlay (OL), $38,016 for the HFS treatment, and $197,987 for each crash avoided with the new treatment. It is interesting to note that although the B/C ratio for installing the conventional overlay (OL) is higher, the total comprehensive savings for the "critical mile" section is almost a half-million dollars more with the HFS treatment.

Table 12. EB Analysis Results for I-81 MM 167.6-168.6 With OL and HFS Alternatives

MP	Obs. Crashes	GN	OL Rate	OL EB	OL Improve	OL Savings	B/C OL	HFS Rate	HFS EB	HFS Improve	HFS Savings	B/C HFS
167.6	3	0.29	0.596	1.069	0.67	$117,365	8.3	0.442	0.794	0.94	$147,619	3.9
167.7	3	0.24	0.596	1.041	0.77	$137,589	9.8	0.442	0.773	1.04	$166,445	4.4
167.8	4	0.31	0.596	1.311	0.78	$139,170	9.9	0.442	0.973	1.12	$181,603	4.8
167.9	6	0.37	0.596	1.832	0.87	$156,461	11.1	0.442	1.360	1.34	$225,069	5.9
168.0	11	0.29	0.596	2.932	1.83	$345,012	24.5	0.442	2.177	2.59	$469,013	12.3
168.1	3	0.29	0.596	1.069	0.67	$117,660	8.4	0.442	0.793	0.94	$147,894	3.9
168.2	6	0.36	0.596	1.822	0.91	$163,445	11.6	0.442	1.353	1.37	$231,570	6.1
168.3	1	0.36	0.684	0.679	0.33	$52,146	3.7	0.508	0.504	0.51	$62,817	1.7
168.4	0	0.36	0.684	0.415	0.21	$27,983	2.0	0.508	0.308	0.32	$25,381	0.7
168.5	2	0.34	0.684	0.931	0.50	$84,050	6.0	0.508	0.691	0.74	$107,403	2.8
168.6	4	0.31	0.684	1.426	0.85	$153,555	10.9	0.508	1.058	1.22	$201,837	5.3
Total						$1,494,436					1,966,651	

It is also noteworthy that all of the sections in this segment of road are considered very low (at or below a GN of 0.40). As a matter of fact, this is true of almost every site in the whole two miles represented in Table 11, and even beyond this section, as can be seen in Figure 8, for mile markers 160 to 170. The dip in friction around mile marker 162 and the elevated number of crashes nearby should also be investigated further.

Finally, the reader should understand that the two example treatments used throughout this discussion are by no means the only options for managing pavement friction. Further, while an asphalt overlay is a feasible alternative for most modern high-speed roadways, HFS is a very specialized surface treatment designed to deliver extremely high levels of skid resistance, usually for very short distances (Sprinkel et al., 2015). The properties of an HFS make it effective for illustrative purposes, but the current costs alone make it an unlikely candidate for routine use beyond spot applications. Other relevant treatments that should be characterized (for friction) and considered include cold-mix seals such as slurries and micro-surfacing.

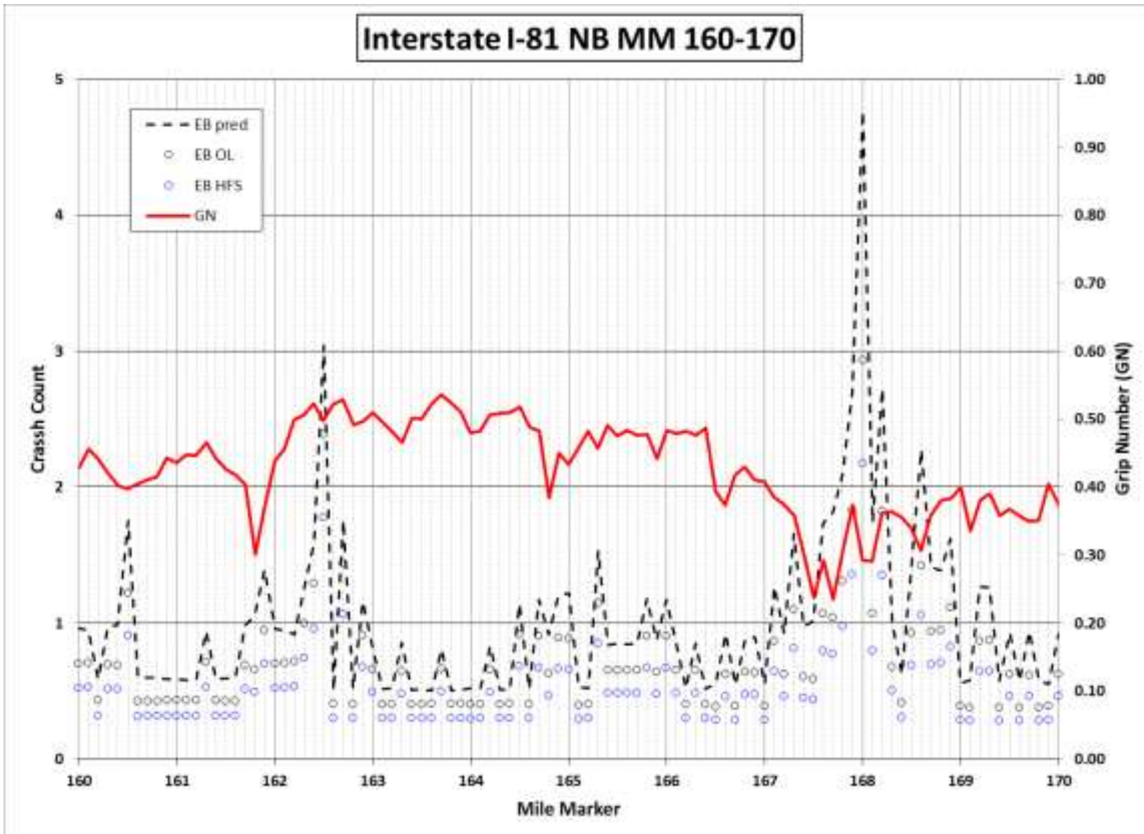

Figure 8. I-81 Northbound MM 160 to 170, Salem District

CONCLUSIONS

- *A network analysis of friction-related crashes can effectively incorporate all crash types, not just wet crashes.* The 10-year crash data from 2003 to 2012 in Virginia showed that on average, 82% of the crashes happen under dry (clear or cloudy) conditions compared to only 15% of what are considered wet crashes.

- *The granularity provided with a CFME accommodates coupling of crash data with pavement friction data, permitting for improved crash rate estimates and an ability to detect and mitigate negative conditions that might contribute to higher crash risks.* The locked-wheel system (Virginia's current method) is unable to effectively test in tight curves and its testing frequency will often fail to identify highly localized friction issues during network–level data collection.

- *Pavement friction can be incorporated into standard SPFs to improve the models' ability to estimate crash rates.*

- *Curvature data can further improve crash rate estimates for primary and secondary system analyses.*

- *Comprehensive crash costs can be used with improved SPFs to perform benefit/cost analyses that consider alternative friction repair treatments.*

- *The total economic savings from crash cost avoidance through friction enhancement can be considerable.* An example trade-off analysis resulted in high benefit-to-cost ratios when addressing low friction with two alternative treatments. The highest comprehensive crash cost savings were realized with an application of HFS treatments.

RECOMMENDATIONS

1. *VDOT's materials and traffic safety engineers should expand the use of continuous friction measurement equipment (CFME) to monitor pavement skid resistance.* Appendix B provides some logistical information and economic analysis that may help VDOT in considering options for equipment to manage pavement friction moving forward.

2. *VDOT's safety and maintenance engineers should seek to incorporate pavement friction in SPFs to improve network crash rate predictions.* This analysis should include all crash types (wet and non-wet) and, when available, should incorporate horizontal curvature.

3. *VTRC should work with VTTI to use pavement macrotexture, cross-section, grade, and horizontal curvature to improve crash rate estimates.* This research should attempt to take maximum advantage of VTTI's research with the FHWA to deploy pilot Pavement Friction Management Programs (PFPMs) using a Sideway-force Coefficient Routine Investigation Machine (SCRIM).

4. *VDOT's traffic safety and maintenance engineers should prepare to use improved SPFs (that incorporate friction and other pavement surface and geometric properties) to develop proactive and cost-effective friction repair treatment plans.* The demonstrated methodology uses estimated crash rates to predict comprehensive crash costs. Estimated crash costs for in-service conditions can be contrasted against "repaired" costs (when warranted) to maximize benefit-to-cost for treatments and/or minimize overall crash costs.

BENEFITS AND IMPLEMENTATION

Benefits

The added predictive power of friction in the current VDOT SPF model proved significant in estimating crash occurrences. To further illustrate the value of these modified SPF models, a benefit analysis was conducted for all sections of the three highway systems in the Salem District for which the B/C ratio for friction repair was greater than 1.0. The results are presented in Table 13.

Table 13. Results with OL and HFS Alternatives on Highway Systems in the Salem District

System	Crashes	%	Sections	%	Benefits ($1,000)	Costs ($1,000)	Savings ($1,000)
Interstate	2,141		2,322				
OL reduction	337	16%	1,202	52%	$66,712	$16,924	$49,788
HFS reduction	513	24%	836	36%	$101,634	$31,781	$69,853
Primary	4,844		11,204				
OL reduction	384	8%	1,443	13%	$76,124	$20,317	$55,807
HFS reduction	512	11%	820	7%	$101,439	$31,173	$70,266
Secondary	1,645		6,408				
OL reduction	40	2%	151	2%	$7,851	$2,126	$5,725
HFS reduction	40	2%	62	1%	$7,794	$2,356	$5,437
Total	8,630		19,934				
OL reduction	761	9%	2,796	14%	$150,689	$39,367	$111,322
HFS reduction	1,065	12%	1,718	9%	$210,869	$65,311	$145,557

Using these improved SPFs, the higher the friction, the fewer the expected crashes. When a conventional plant-mix overlay (OL) is used, the analysis predicts 761 fewer crashes. When an HFS is used, the analysis expects to reduce crashes by 1,065. The majority of the comprehensive savings is achieved on the interstate and primary systems, but regardless of the treatment chosen, the net economic benefit (societal savings) for one VDOT district could be in excess of $100 million every 3 years. Total economic savings of this magnitude would easily offset the costs of a comprehensive PFMP, the equipment necessary to administer it, the construction of the treatments on high volume roads, and even significant skid-crash mitigation on those sites for which traffic volumes would ordinarily be too low to meet strict economic criteria (such as low-volume high-risk rural roads, HRRR).

This research ultimately improves the ability of the district maintenance and regional traffic engineers to match user demands for pavement friction with the capability of common surface alternatives, both on a local and system-wide basis. An effective PFMP better positions VDOT to respond to its FY15-16 Business Plan, Section 3.2.3., which includes a focus on "lowering the number of deaths and severe crashes through engineered safety improvements."

Implementation

Implementation will next involve collecting continuous data on Virginia's Corridors of Statewide Significance (CSS), a joint activity with VDOT, FHWA, and VTTI. This effort will include about 3,700 centerline miles of highway; 1,100 miles of divided interstate; and approximately 2,600 miles of divided and four-lane undivided primary routes (see Figure 9). In addition to friction and curvature, the analysis of the CSS data will also incorporate texture, cross-slope, and grade. The preliminary cost is estimated to be around $200,000; and the effort is expected to consume about 1 year.

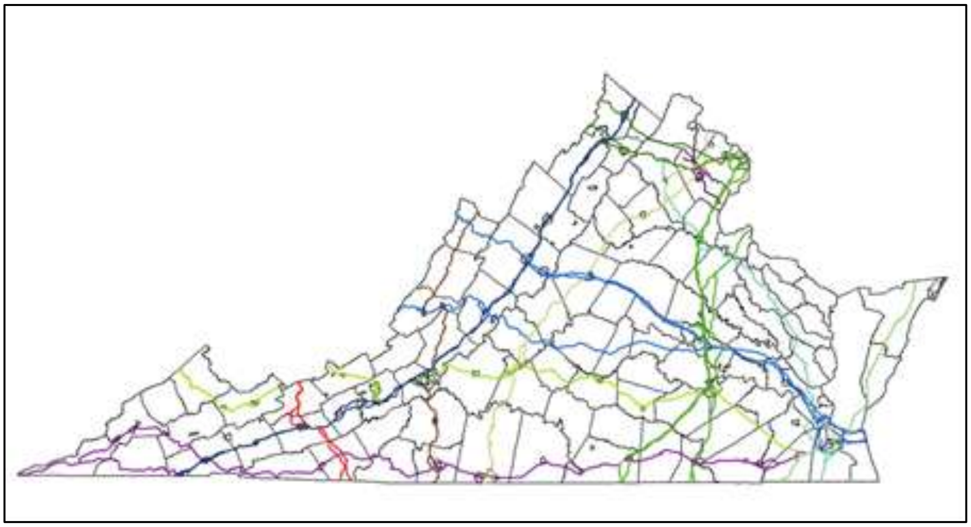

Figure 9. Corridors of Statewide Significance (VTrans 2035)

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APPENDIX A

LIST OF SECONDARY ROADS TESTED IN THE SALEM DISTRICT

Route	Name	County	AADT
619	Jordantown Road	**County**	3,090
622	Everett Road/Waterlick Road	Bedford County	8,999
626	Smith Mountain Lake Pkwy	Bedford County	1,570
663	Perrowville Road	Bedford County	8,563
695	Goose Creek Valley Road	Bedford County	924
746	Dickerson Mill Road	Bedford County	1,016
757	Goodview Road	Bedford County	4,893
811	Thomas Jefferson Road	Bedford County	14,849
715/671/803	Timber Ridge Road	Bedford County	1,341
634/676/636	Hardy Road	Bedford County	8,366
779	Catawba Road	Bedford & Franklin County	5,790
630	Main/Blacksburg/Springwoods Road	Botetourt County	2,913
640	Brughs Mill Road	Botetourt County	1,973
615	Craigs Creek Road	Botetourt County	4,315
620	Coulson Church Road	Botetourt & Craig County	2,591
638	Dugspur Road	Carroll County	341
670	Snake Creek Road	Carroll County	795
753	Double Cabin Road	Carroll County	792
669	Springwillow Drive	Carroll County	505
775	Chances Creek Road	Carroll County	3,821
620	Old Pipers Gap Road	Carroll County	1,395
607/721	Fries Road	Carroll County	4,923
615	Craigs Creek Road	Carroll County	4,315
615	Pilot/Old Pike/Christiansburg Pike Road	Craig County	3,303
637/653	Alleghany Springs Road/Shawsville Pike	Floyd County	2,211
610	Daniels Run Road	Floyd County	963
787	Indian Valley Road	Floyd County	819
619	Sontag Road	Floyd County	2,577
834	Brooks Mill Road	Franklin County	3,673
616	Scruggs Road	Franklin County	9,575
670	Burnt Chimney Road	Franklin County	3,219
890	Snow Creek Road	Franklin County	1,375
619	Sontag Road/Pleasant Hill Road	Franklin County	1,438
640	6 Mile Post Road	Franklin County	2,025
697	Wirtz Road	Franklin County	3,385
635	Bonbrook Mill Road	Franklin County	1,290
681	Coopers Cove Road	Franklin County	596
634/676/636	Hardy Road	Franklin County	8,366
605	Henry Road	Franklin County	1,212
718	Colonial Turnpike	Franklin County	1,994
739/643	Bethlehem Road	Franklin County	2,643
684	Boones Mill Road	Franklin County	1,873
613	Naff Road & Merriman Road	Franklin County	8,549
635	Big Stony Creek Road	Franklin & Roanoke County	1,167
730	Eggleston Road	Giles County	360
606/674	Oak Level Road	Giles County	1,969
609	Dillons Fork Road	Henry County	6,115
610	Axton Road	Henry County	1,678

620	Old Liberty Road	Henry County	2,015
650	Irisburg Road	Henry County	5,241
687	Preston Road/Stones Dairy Road	Henry County	4,095
698	Blackberry Road	Henry County	3,243
692	Horsepasture Price Road	Henry County	1,861
687	Soapstone Road	Henry County	1,241
605	Henry Road	Henry County	1,211
603	North Fork Road/Den Hill Road	Henry & Franklin County	2,362
685	Prices Fork Road	Montgomery County	9,890
615	Pilot/Old Pike/Christiansburg Pike Road	Montgomery County	3,303
637/653	Alleghany Springs Road/Shawsville Pike	Montgomery & Floyd County	2,211
622	Bradshaw Road	Montgomery & Floyd County	1,819
624	Mount Tabor Road/Newport Road	Montgomery & Roanoke County	972
785	Blacksburg Road	Montgomery & Roanoke County	554
614	Squirrel Spur Road	Montgomery & Roanoke County	413
626	Abram Penn Hwy	Patrick County	491
653	Ayers Church Road	Patrick County	1,071
773	Ararat Road	Patrick County	1,639
680	Spring Road	Patrick County	1,951
693	Lead Mine Road	Patrick County	1,084
738	Robinson Tract Road	Pulaski County	1,059
672	Lowmans Ferry Road	Pulaski County	2,320
613	Naff Road & Merriman Road	Pulaski County	8,549
622	Bradshaw Road	Roanoke County	1,819
624	Mount Tabor Road/Newport Road	Roanoke County	972
785	Blacksburg Road	Roanoke County	554
720	Colonial Ave	Roanoke County	11,117
904	Starkey Road	Roanoke County	10,835
679	Buck Mountain Road	Roanoke County	6,957

APPENDIX B

FRICTION INVENTORY COST CONSIDERATIONS

This appendix provides an economic analysis of three friction measurement devices that may be considered for friction inventory testing in Virginia. These devices are the locked-wheel skid tester (LWST), the Grip Tester (GT), and the Sideway-force Coefficient Routine Investigation Machine (SCRIM). The comparison includes the miles of road network that VDOT would monitor in 1 year, first considering only the interstate (IS) and the primary (PR) systems, and then including about 33% of the mileage in the secondary (SC) system, or 100% in a 3-year cycle. Note - the research team considers any friction measurement older than 3 years to not be useful for friction monitoring purposes.

The following are the total number of lane-miles that make up the statewide VDOT network if it was to be tested with the same criteria as was used for the Salem District work:

- Interstate (IS) 2,200
- Primary (PR) 10,500
- Secondary (SC) 38,500

Therefore, the two alternatives would be to monitor a) only IS+PR or 12,700 lane-miles (equal to 127,000 0.1-mile sites) and b) IS+PR+SC/3 or 25,500 lane-miles (equal to 255,000 0.1-mile sites).

The following are the operating assumptions regarding productivity of the three devices, mostly based on their water capacity, fuel consumption, personnel costs, etc.

1. The work schedule for one working year will be from April to October (± 150 workdays). Beyond these dates, data collection in Virginia is not reliable.
2. Daily Production:
    a. VDOT's E-274 unit can do about 120 tests per tank; assuming 4 tanks of water/day at 10 tests per mile (test every 0.1 mile) equals about 50 miles/day.
    b. The Grip Tester has a water tank that allows about 20 miles/tank of continuous testing. Assuming the same 4 tanks/day, it can measure about 75 miles/day.
    c. The SCRIM has a water tank that allows it to run for 150 miles; a conservative estimate would be to have at least 2 tanks/day for 300 miles/day.
3. Annual Production; down time for calibration, repairs, service, etc. is assumed to be about 20% of the total time for all units. Working with estimated daily production rates, the production for the total 150 days is estimated at:
    a. Locked-wheel (50*150)*0.8 = 6,000 miles
    b. Grip Tester (75*150)*0.8 = 9,000 miles
    c. SCRIM (300*150)*0.8 = 36,000 miles

4. Both the Locked-wheel and the Grip Tester will be operated by a single driver/operator, while the SCRIM requires both a driver and an operator.
5. Per diems and hotels expenses are estimated to be an average of $300/week and $400/week, respectively, for the operators and drivers.
6. The equipment costs for all three devices are estimated here. Caution is to be taken when comparing them because the prices for the locked-wheel and the Grip Tester do not represent a unit with a macrotexture laser and the inertial differential GPS system capable of measuring the cross-slope, grade, and curvature of the roads, and the price of the trucks that haul them is also not included.
   a. Locked-wheel $150,000 (Tow vehicle not included)
   b. Grip Tester $ 80,000 (Tow vehicle not included)
   c. SCRIM $800,000
7. All the devices are assumed to have a service life of 10 years for depreciation purposes and another 10% yearly maintenance cost is assumed during its life.
8. Fuel mileage is assumed to be 10 miles/gallon for the trucks towing both the locked-wheel and the Grip Tester and only 5 miles/gallon for the SCRIM truck.

With these estimations, an estimate of the overall direct costs, the cost per mile, and the necessary number of units for each type of device is presented in Table B1.

Table B1. Direct Costs, Cost per Mile and Number of Units Needed for Two Network Scenarios

Road Network	**Miles**	**ASTM E-274**	**GT**	**SCRIM**
Interstate and Primary	12,700	$200,942	$115,899	$110,725
Units needed		2.1	1.4	0.4
Interstate, Primary, and 33% of Secondary	25,500	$403,467	$232,711	$222,322
Units needed		4.3	2.8	0.7
Direct Costs/mile		$15.82	$9.13	$8.72
Estimated production/device/year		6,000	9,000	36,000

These numbers show that for the basic road network package of interstate and primary network, it would require the operation of 2.1 locked-wheel skid testers, 1.4 Grip Testers, or 0.4 SCRIM units. For the expanded network, including an additional 33% of the secondary roads, these requirements increase to 4.3 LWST, 2.8 GT, and 0.7 SCRIM. Although careful consideration should be given to all the assumptions and results, the evidence as presented appears to favor the SCRIM device, which is consistent with findings from the FHWA study (Flintsch and de León Izeppi, 2011). It should also be noted that, if desired, the additional cost for collecting the macrotexture, cross-slope, grade, and curvature data would have to be added to the total costs of each option for the LWST and the GT, respectively, as well as the consideration for the cost of the towing vehicle. It is also pertinent to point out that the GT is unproven as a tool for network testing on this scale.

This analysis (see Table B2) is relevant, regardless of whether VDOT would perform the services in-house or contract for them as is the case with the distress data that is collected for the PMS. It is very possible that with direct communication from VDOT, FHWA would be willing to include VDOT as the fifth state in its demonstration program to manage pavement friction using the SCRIM device.

Table B2. Detailed Cost Analysis Spreadsheet

						Miles a year per unit		
						6000	9000	36000
						Costs Per mile		
Costs		Direct/year	Plus Benefits	Apr-Oct (7)	x2	E274	GT	SCRIM
1	Operator	$50,000.00	$70,000.00	$40,833.33	$81,666.67	$6.81	$4.54	$2.27
	Per diem	$300/week	31 weeks	$9,300.00	$18,600.00	$1.55	$1.03	$0.52
	Hotel	$400/week	31 weeks	$12,400.00	$24,800.00	$2.07	$1.38	$0.69
			In 10 years					
2	Equipment	Cost	Depreciation	Plus 10% Maint				
50 miles	E-274	$150,000.00	$15,000.00	$30,000.00		$5.00		
75 miles	GT	$80,000.00	$8,000.00	$16,000.00			$1.78	
300 miles	SCRIM	$800,000.00	$80,000.00	$160,000.00				$4.44
3	Diesel fuel	$4.00	Mileage: 10mi/gal E274> 5mi/gal SCRIM			$0.40	$0.40	$0.80
4	Direct Costs/mile					$15.82	$9.13	$8.72
Two scenarios								
					Miles	Yearly Budget/Option		
A	Interstate and Primary				12,700	$200,942	$115,899	$110,725
	Units					2.1	1.4	0.4
B	Interstate, Primary and 20% of Secondary				25,500	$403,467	$232,711	$222,322
	Units					4.3	2.8	0.7
				%MI&E-expenses		23%	26%	14%