HFST Before and After Safety Analysis

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16. Abstract

Due to its high potential for safety improvement, MoDOT deployed High Friction Surface Treatments (HFST) at several areas experiencing high crash rates since 2013. To determine if the HFSTs are providing the expected results and if MoDOT's HFST program is effective, this study was conducted with the primary objective of evaluating MoDOT's existing HFST sections with regard to their overall effectiveness (i.e., reduction in crashes) and benefit (i.e., return on investment).

Statistical modeling of before/after crashes from MoDOT's HFST sections showed that the HFST reduced crashes, with the reduction ranging from 13.7 percent to 79.5 percent and an overall reduction of 53.3 percent. The Benefit-Cost Analysis (BCA) carried out subsequently showed that MoDOT may expect a benefit-cost ratio (B/C) ranging from 2.3 to 409.1, with an overall average of 60.8. Based on these results, it is concluded that MoDOT's HFST program is effective in reducing crashes with a high rate of return.

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HFST BEFORE AND AFTER SAFETY ANALYSIS

Final Report

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ABSTRACT

Due to its high potential for safety improvement, MoDOT had deployed High Friction Surface Treatments (HFST) since 2013, at several areas experiencing high crash rates. To determine if the HFSTs are providing the expected results and if MoDOT's HFST program is effective, this study was conducted with the primary objective of evaluating MoDOT's existing HFST sections with regard to their overall effectiveness (i.e., reduction in crashes) and benefit (i.e., return on investment).

Statistical modeling of before/after crashes from MoDOT's HFST sections showed that the HFST reduced crashes, with the reduction ranging from 13.7 percent to 79.5 percent and an overall reduction of 53.3 percent. The Benefit-Cost Analysis (BCA) carried out subsequently showed that MoDOT may expect a benefit-cost ratio (B/C) ranging from 2.3 to 409.1, with an overall average of 52.6. Based on these results, it is concluded that MoDOT's HFST program is effective in reducing crashes with a high rate of return.

EXECUTIVE SUMMARY

Due to its high potential for safety improvement, MoDOT deployed High Friction Surface Treatments (HFST) since 2013, at several areas experiencing high crash rates. The expectation was that the HFSTs will generally reduce the number of crashes. To determine if the HFSTs are providing the expected results and if MoDOT's HFST program is effective, this study was conducted with the primary objective of evaluating MoDOT's existing HFST sections with regard to their overall effectiveness (i.e., reduction in crashes) and benefit (i.e., return on investment). A secondary objective of this study was to determine the factors that significantly affected the crash rates before and after HFST treatment.

A preliminary analysis of Missouri's available crash data indicated that the majority of crashes before HFST installation occurred during daylight and on curved roadways. Correspondingly, these conditions exhibited higher crash reduction following the installation of HFSTs. Furthermore, while both wet and dry crashes were reduced after HFST installation, by far the greater reduction was in the category of wet crashes. These results generally indicated that HFSTs have potential for significantly reducing crashes on both wet (approx. 86 percent reduction) and dry (approx. 50 percent reduction) pavement surfaces, with the benefit more pronounced for wet pavement surfaces.

Past studies indicated that while pavement friction gained by HFST is a crucial factor for improving highway safety and for reducing traffic crashes, it is not the only factor affecting crashes. In fact, crashes are complicated events involving not only vehicles and/or roadway features but also human factors (e.g., drinking and driving) and environmental factors (e.g., rain, snow, etc.) as well as other factors that are impossible to predict. For these reasons, crashes are often considered to be "random events" with its count statistic fluctuating naturally. Due to such random nature of crashes and crash counts, simple comparison of crash counts before/after a treatment is generally not recommended.

Due to the limitations of the simple, observational comparison of crash counts before and after HFST, Safety Performance Functions (SPF) were developed based on the available data. The purpose of the SPF was (1) to estimate the expected number of crash reduction after HFST, (2) to identify the factors significantly affecting crashes, and (3) to allow for an Empirical Bayes (EB) estimate of crash counts.

The initial SPFs were developed separately for wet and dry pavement surfaces, and for different conditions (total crashes as well as crashes on curves vs. tangent segments), while incorporating Friction Number (FN) as an independent variable. These results generally indicated that FN had a more pronounced effect on wet weather crashes and on curved roadways. A practical example of such SPF indicated that if an HFST treatment improved the FN from 35 to 75 for a given section, MoDOT may expect an average crash reduction of 24 percent and 73 percent under dry and wet weather conditions, respectively.

Although the initial, generalized SPFs described above may provide useful information, these models could not be used for all HFST sections, due to the lack of friction data. To account for the crashes from all HFST sections and for different crash severities (leading to EB estimates and

BCA), a set of more simple and basic SPFs were also developed. These SPFs were developed using a limited set of independent variables. Note that for these simplified SPFs, the FN was not used as an independent variable, and the crashes were simply categorized as before or after HFST installation. The results of the basic SPFs indicated that the expected number of crashes increase from high-severity to low-severity crashes, and HFSTs are expected to decrease the crashes of all severities.

Using the basic SPFs, the EB estimates of crash counts were calculated for all HFST Job Numbers. The EB results pointed out that all HFST sections are expected to reduce crashes, with the reduction ranging from 13.7 percent to 79.5 percent. In addition, the EB method did not result in any HFST sections with negative crash reduction (i.e., increase in crashes after HFST installation). It is believed that such a consistent reduction in crash counts is a consequence of the EB method more effectively eliminating the bias caused by the random nature of crashes (compared to the simple, direct comparison of before/after crash counts).

Since the EB estimates resulted in a consistent reduction in crashes (i.e., less crashes after HFST in all sections), the BCA was conducted again using the EB-based crash counts (as opposed to the observed, simple crash counts). Assuming 7 years of effective HFST life, the B/C ratio calculated from each Job Number ranged from 2.3 to 409.1, with an overall average of 60.8, indicating a high rate of return for MoDOT's HFST.

It should be noted, that MoDOT has the foundation necessary to perform an analysis to identify locations that would benefit from the application of HFSTs or other safety improvements. Currently, ARAN collects curve and superelevation data for the entire State highway system annually (with the exception of ramps), that may provide invaluable information for identifying the cause of high crash rates at any location. Coupled with the ability to locate crashes and filter them by type, condition, severity, etc. makes very detailed analysis possible.

While the methodology developed here is not for identifying location where high crash rates exist, the equations can be used to determine how much reduction could be expected from the application of HFST, if installed.

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1. INTRODUCTION

1.1. BACKGROUND

Safety is one of the major priorities of State Highway Agencies (SHA) including the Missouri DOT (MoDOT). Since 2005, MoDOT has implemented several innovative technologies intended to improve safety on its more than 33,700 mile system. Many, such as median guard cable and rumble strips, have become standard improvements applied across the State. Other programs that have contributed to improved safety include the replacement of 802 bridges that were either structurally deficient or functionally obsolete through the Safe and Sound Bridge Program, as well as the increased use of diverging diamond interchanges, J-turns, and roundabouts.

Figure 1.1 shows the locations of fatalities that occurred on straight and curved roads under MoDOT's jurisdiction over the 12-year period from 2005 to 2017, based on data that were made available by National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS). Figure 1.2 shows a summary of this data in terms of the number of fatalities. The figure also shows the percentage of fatalities that occurred on curved roadways. Clearly, MoDOT achieved a significant reduction in the number of total fatalities as well as those that occurred on curves from 2005 to 2013. Although the number of fatalities showed a slight growth between 2015 and 2017, this still reflects over 26 percent reduction in fatalities over a 12-year period and demonstrates a commitment to improving the safety of Missouri's highways.

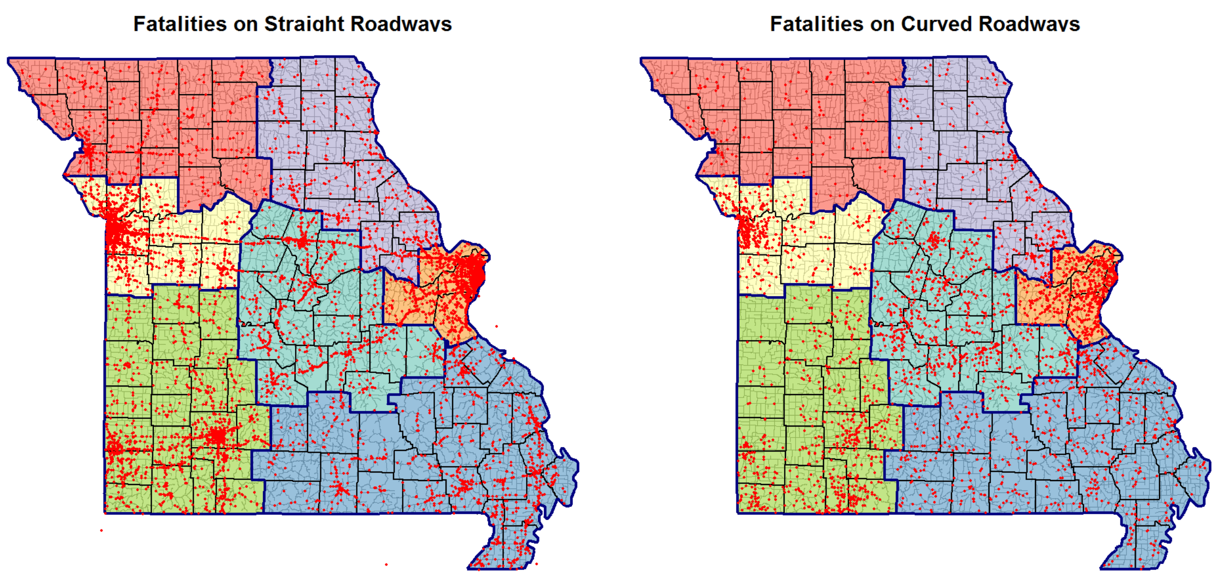

Figure 1.1. Mapping of fatalities on Missouri's highways (Left: Straight Roadways, Right: Curved Roadways)

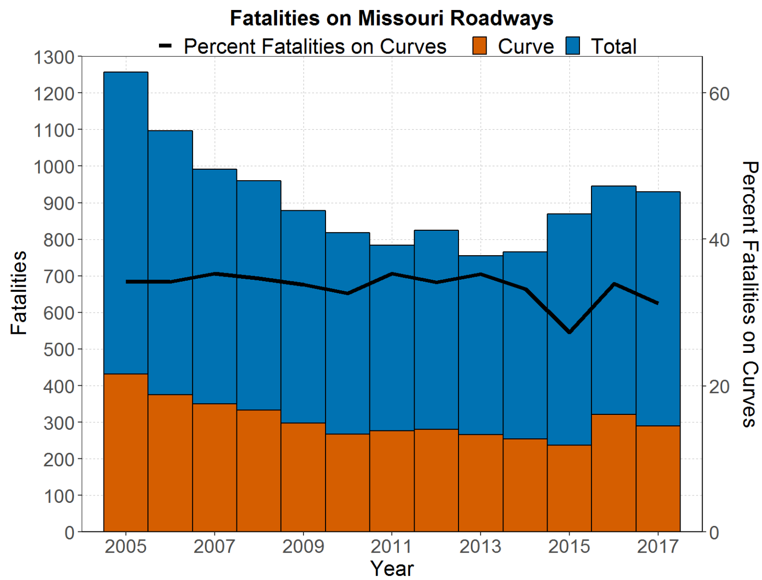

Figure 1.2. Number of fatalities on Missouri's highways

Figure 1.2 also indicates that the fatalities on curved roadways make up a significant portion (i.e., approximately 30 to 35 percent) of all fatalities that occur on MoDOT's roadway network. As an effort to improve safety on these curved roadways, MoDOT had adopted another innovative technology known as a High Friction Surface Treatment (HFST), which is proposed as a cost-effective pavement treatment to increase friction and drastically reduce vehicle crashes and resulting motorist injuries and fatalities. In general, HFSTs involves the application of a resin or polymer type binder and high-quality durable aggregates on shorter pavement sections where friction demand is deemed critical. HFSTs, often used at horizontal curves, intersection approaches, loop ramps, upgrades and downgrades, help reduce stopping distance and provide better driving control to motorists.

Since its first HFST project on US 54 in Jefferson City in October 2013, Missouri Department of Transportation (MoDOT) has successfully deployed HFST techniques at several locations. Figure 1.3 shows the location of high friction surface treatments applied to date, statewide.

It is anticipated that HFSTs will generally reduce crash rates in Missouri by improving surface friction. However, while pavement friction is a crucial factor for improving highway safety and for reducing traffic crashes, it is not the only factor that should be considered. In fact, traffic accidents are complicated events resulting from a combination of pavement friction and various other factors that are driver-related (e.g., distraction), vehicle-related (e.g., tires, brake system), pavement-related (e.g., structural and functional distresses, pavement marking issues), roadway-related (e.g., geometry, visibility), and weather-related (e.g., rainfall intensity, fog, ice). As such, there is a need to assess and justify the effectiveness of the HFSTs installed on Missouri's highways in terms of safety and friction improvements, pavement performance, and cost.

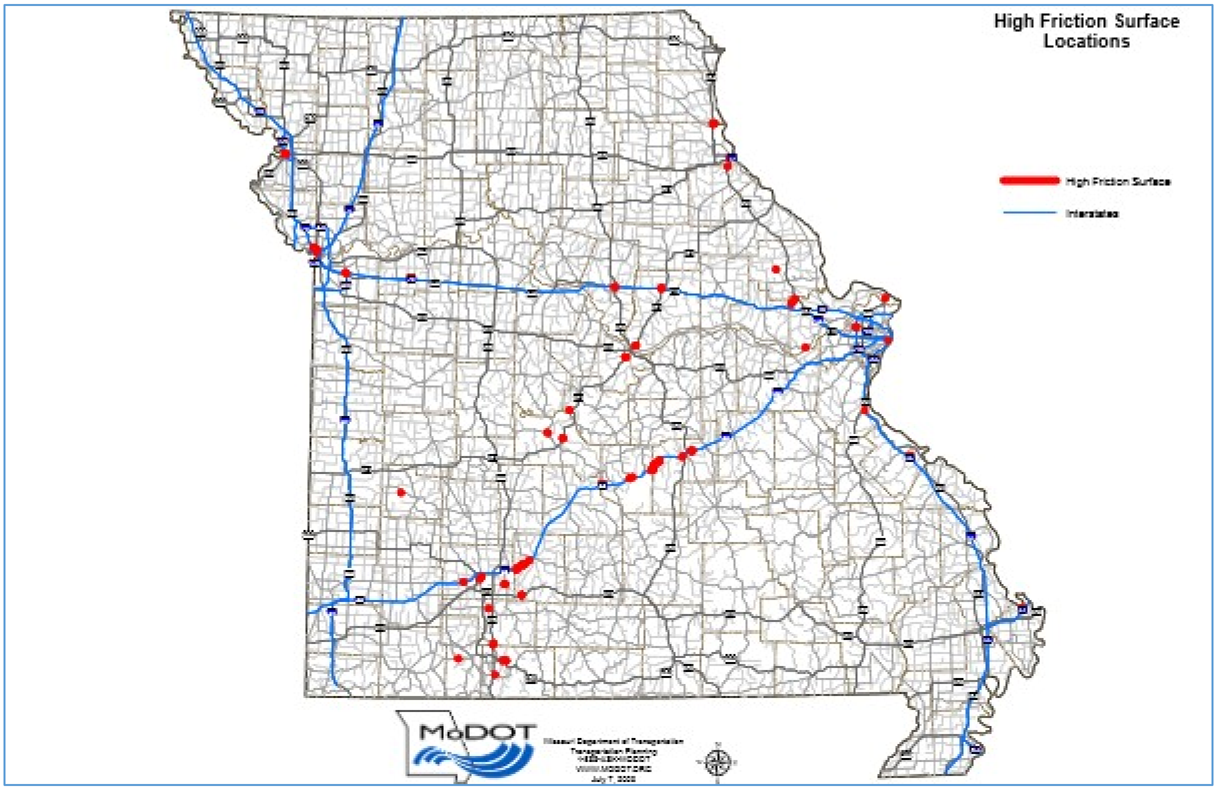

Figure 1.3. Location of HFST projects completed since 2013. (MoDOT)

1.2. PROJECT OBJECTIVE

In recognition of the above research need, the objective of this study is to evaluate MoDOT's existing HFST sections with regard to the following.

- Effectiveness of HFST: Before/after crash analysis for different crash types (wet vs. dry, fatality vs. property damage, curved vs. tangent segments, etc.) and reduction in crashes over time.
- Return on Investment: Financial benefit gained by crash reduction compared to the cost of HFST installation (Benefit-Cost analysis).
- Pavement and Roadway Characteristics: Type and condition of pavement surface before HFST application as well as roadway characteristics such as curve, ramp, sag, etc.
- Performance of HSFT: Current condition of HFST in terms of friction, cracking, etc.

2. REVIEW OF HIGH FRICTION SURFACE TREATMENTS

2.1. GENERAL

As implied by its name, High Friction Surface Treatment (HFST) is intended to drastically improve the frictional characteristics of roadway surface. It is also a relatively new technology, first applied in Missouri in 2013. The technology has been used at many locations around the nation and the globe, where friction demand (i.e., need for friction) is greater than the level of friction achieved by existing paving materials (i.e., available friction). Areas with increased friction demand include, but not limited to, curved roadways (horizontal and/or vertical), intersections, ramps, interchanges, etc. (Von Quintus and Mergenmeier, 2015; Cheung, 2014).

HFSTs are primarily composed of two materials, namely the high-friction aggregates and polymer resin binder. The high-friction aggregates are typically very hard, durable, polish- and abrasion-resistant, and are capable of enhancing the frictional characteristics of a roadway surface significantly. The most common high-friction aggregate used for this purpose is calcined bauxite which is produced to a fine gradation (i.e., typical maximum size of 3 mm to 4 mm). The high-friction aggregates are locked in place using a thermosetting polymer resin binder (usually epoxy, modified polyester, or urethane). The resin binder is typically much tougher and stiffer than conventional asphalt binders to prevent loss of high-friction aggregates under extreme shear forces frequently experienced in curved roadways.

2.2. APPLICATION OF HFST

Application of HFST can take several forms. The epoxy (i.e., resin binder) can be applied using a hand wand (Figure 2.1) and then spread using a notched squeegee (Figure 2.2), or can be sprayed directly from an application vehicle. High-friction aggregates can be dropped from a spreader (Figure 2.3), blown onto the surface using a device that resembles an insulation blower (Figure 2.4), or applied by hand for smaller areas. The amount of material applied is to be more than needed, and any excess material not absorbed into the epoxy binder is swept up and removed before opening to traffic.

Historically, studies indicate that the typical HFST can be expected to last from 7 to 12 years, depending on the amount of traffic, condition of the underlying pavement, and other external factors such as the frequency of snowplowing (Von Quintus and Mergenmeier, 2015; Cheung, 2014; Holzschuher, 2017). Because of the expense, HFST should only be placed on pavements in good structural condition and should not be viewed as a maintenance treatment. Typically, HFST provides friction far above what normal overlays or surface treatments can. For example, HFSTs typically result in friction numbers ranging from 65 to 90, while conventional pavement surfaces typically range from 35 to 45.

Figure 2.1. Example of application of epoxy to road surface using sprayer wand.

Figure 2.2. Example of notched squeegee used to distribute epoxy to pavement surface.

Figure 2.3. Example of machine used to place aggregate onto fresh epoxy for HFST surface.

Figure 2.4. Example of blower used to place aggregate onto fresh epoxy for HFST surface.

2.3. HFST CASE STUDIES

As discussed previously, HFSTs are rapidly becoming more popular among SHAs for areas that require increased friction demand. Therefore, it is also of interest to summarize the experience and success stories gained from different agencies, as presented below.

Based on a simple before/after crash analysis of 43 sections in Kentucky, Von Quintus and Mergenmeier (2015) reported a significant reduction in both wet and dry weather crashes after HFST installation. More specifically, they reported that on horizontal curves, 86 percent and 47 percent reduction in wet and dry weather crashes were observed, respectively. These numbers translated to a total crash reduction of 73 percent on horizontal curves. Similarly, the HFSTs installed on ramps also showed a significant reduction in crashes equivalent to 85 percent and 66 percent reduction for wet and dry weather crashes respectively (for a total crash reduction of 78 percent per year). Based on these findings, it was concluded that Kentucky's HFST program is effective in reducing roadway crashes (especially, roadway departure and fatalities). Furthermore, it was recommended that the HFSTs be used where the friction demand is the greatest, including ramps, horizontal curves, areas of steep grades, as well as intersections.

The City of Bellevue in Washington State experienced a significant number of crashes on one of their downgrade intersections (Cheung, 2014). With approximately 35,000 vehicles entering the intersection weekly, the number of crashes were further increased during icy weather conditions. The city had tried several countermeasures such as a large flashing warning sign at the bottom of the grade, additional road markers, new streetlights, and raised pavement markers, but failed to reduce the number of crashes. Upon installation of a HFST, the city experienced a 78 percent reduction in crashes and a corresponding crash cost reduction of 83 percent. Furthermore, it was pointed out that HFSTs are significantly less expensive and more effective than alternative geometry corrections (e.g., realignment, superelevation, etc.).

The Iowa Department of Transportation (IDOT) experienced excessive number of crashes on an I-380 bridge over Cedar River, which carries 85,000 vehicles (including 7,800 heavy trucks) per day (Cheung and Julian, 2016). More specifically, a total of more than 54 crashes were reported between 2008 and 2012, including 28 injury crashes and 8 crashes that involved a semi-trailer. The field review indicated that the existing friction numbers ranged from 30s to 40s. To mitigate the high crash potential on this bridge, IDOT installed a single layer of HFST in 2012. The HFST effectively increased the friction numbers to high 90s and low 100s which reduced to high 80s to low 100s after 1 year of service. Within a year after HFST installation, only 4 crashes occurred including one injury crash. The cost of HFST was $494,000 (for 1.8 lane-miles of roadway, or 0.3 miles over six lanes). Assuming the HFST provides a lifespan of 8 to 10 years, IDOT estimated an approximate benefit-cost ratio of 3.8.

In 2013, the Pennsylvania Department of Transportation (PennDOT) identified 50 locations requiring high friction demand (Cheung et. al. 2016). Of these 50 locations, 19 received HFSTs and a simple before/after crash analysis was conducted based on 5-years of crash data before HFST and 3-years of crash data after HFST. Prior to HFST installation, a total of 234 crashes (including 164 wet weather crashes and 8 fatalities) occurred on these 19 HFST sites. The same sections only experienced 17 total crashes (and no fatalities) after HFST installation, indicating a significant reduction in crash rates due to HFST.

A 1-mile section of US 25 in South Carolina had experienced an excessive number of crashes for many years and had always been a concern to South Carolina Department of Transportation (SCDOT). The main problem of the section was that the concrete barriers installed along the roadway did not allow for proper drainage and the water accumulated at the driving lane and shoulder (Cheung et. al. 2015). The roadway being located in a mountainous terrain with horizontal curve and a vertical grade of 6 percent worsened the crash rates, especially during inclement weather such as rain, snow, and fog. SCDOT estimated that a major reconstruction of this roadway (including superelevation and drainage improvements with new barrier walls) would cost approximately $5.0 million. Instead of conducting such an expensive corrective action, SCDOT installed HFST on this section for a total cost of $1.0 million (i.e., 80 percent less cost). Since the HFST installation, SCDOT experienced a 68 percent reduction in wet weather crashes and 56 percent reduction in total crashes.

It should also be noted that Missouri was a part of a Highways for Life (HfL) Project in 2013 involving the use of HFST (Bledsoe, 2015). Based on a 3- crash history before HFST placement, the US 54 location placed as part of this HfL project exhibited 32 crashes per year. The crashes were composed of 0.0 percent fatal, 32.3 percent injury, and 67.7 percent property damage crashes, with an average estimated crash cost of $35,790. In the first year after construction of the HFST, there were only 5 crashes reported. Based on this limited initial data from one of the projects, MODOT's goal of 20 percent reduction in accident rates was easily achieved. Furthermore, the reduction of 27 crashes during the first year at just this one location resulted in an estimated savings of $966,300, or nearly twice the additional cost of HFST placement of all four HFST locations placed as part of the HfL study.

In summary, the above case studies indicate that HFST may be a cheaper and at the same time, an effective alternative to some of the major roadway corrections (e.g., realignment, cross-slope and/or grade correction, drainage improvement, etc). While the initial cost of HFSTs may be more expensive than many of the more traditional alternatives (e.g., micro surfacing, surface texturing, etc.), the additional reduction in crashes may still make HFST a cost effective alternative, as evidenced by the case studies reviewed herein, all of which reported a significant crash reduction (up to 87 percent reduction) over a variety of conditions (wet vs. dry, curve vs. tangent, ramp vs. mainline, etc).

3. REVIEW OF HIGHWAY SAFETY ANALYSIS PROCESS

3.1. BACKGROUND

As discussed in the previous chapter, many agencies have observed and have reported the effectiveness of HFSTs by a simple, direct comparison of the crash rates before and after HFST. While the improved level of friction provided by HFST does have a significant effect on improved safety, it should be noted again that friction is not the only factor affecting crashes (i.e., installing a HFST does not guarantee a result of zero crashes). Examples of other roadway and pavement related variables that have a significant effect on crashes include pavement surface distresses such as cracking and rutting (Li and Huang, 2014; Tehrani et. al., 2017; Lee et. al., 2015), roughness (Li and Huang, 2014; Tehrani et. al., 2017), horizontal and vertical alignment (Tehrani et. al., 2017; Musey et. al., 2016), and retroreflectivity of pavement markings (Bektas et. al., 2016).

As seen above, there are many factors that may potentially have a significant effect on number of crashes or crash severities. However, it is important to note that these factors do not always show significant correlation with the number of crashes or crash rates. Furthermore, crashes are complicated events involving not only the vehicle and/or roadway features but also human factors (e.g., drinking and driving) and other factors that are close to impossible to predict. For these reasons, crashes are often considered to be “random events” with its count statistic fluctuating naturally.

Due to such random nature of crashes and crash counts, the Federal Highway Administration’s (FHWA) Highway Safety Improvement Program (HSIP) generally does not recommend the simple comparison of crash counts before/after a treatment (Herbal et. al., 2010). Such a simple evaluation of before/after crash statistics (used in all HFST case studies presented previously) is referred to as a naïve method because it fails to address the randomness of crash counts that occur naturally. Instead, FHWA recommends a more statistical approach for before/after evaluation of a treatment.

The remainder of this chapter provides a summary review of relevant literature and procedures regarding the statistical relationship between crash and various influencing factors.

3.2. STATISTICAL RELATIONSHIP BETWEEN CRASH, FRICTION, AND OTHER FACTORS

3.2.1. <u>Equation Forms for Predicting Crash</u>

FHWA and AASHTO recommends the use of Safety Performance Functions (SPF) for estimating the crash counts (Srinivasan and Bauer, 2013). The primary purpose of the SPF is to identify roadway sites that may benefit from a safety treatment by estimating the number of crashes for a given roadway with a specified length. The SPF is defined in terms of an exponential function. More specifically, the SPF in its most basic form is given as the following equation.

$$\mu = L \cdot e^{\beta_0} \cdot AADT^{\beta_1}$$
$$= L \cdot e^{\beta_0 + \beta_1 \cdot \ln(AADT)} \quad (1)$$

where μ is the expected number of crashes, L is the segment length, $AADT$ is the annual average daily traffic, and β_0 and β_1 are regression coefficients.

As seen from Equation (1), the only mandated variable in SPF is the traffic ($AADT$). However, FHWA Office of Safety further recommends that the above equation be generalized to include additional site factors such as the lane width, shoulder width, horizontal curvature, and the presence of turn lanes, intersections, and traffic control (Srinivasan and Bauer, 2013). The generalized form of the equation, with these variables included, can be written as:

$$\mu = L \cdot e^{\beta_0 + \beta_1 \cdot \ln(AADT) + \sum \beta_i \cdot X_i} \quad (2)$$

where X_i is the additional site factors to be included and β_i is the corresponding regression coefficient. It is also noted that while FHWA's SPF document does not mention pavement friction (or texture) as potential site factors, these terms can easily be included in the generalized SPF. As an example, shows the U.K. crash model as a function of pavement friction and texture (Viner et. al., 2004). In fact, this crash model takes the form of the generalized SPF, as shown in Table 3-1 along with additional equations found in literature for relating the crash count (or crash rate) to the pavement and roadway related site factors. Note that with the exception of the equation form proposed for intersection crashes by Larson et. al. (2008), most of the equations involve nonlinear functions such as the exponential or the logarithmic functions.

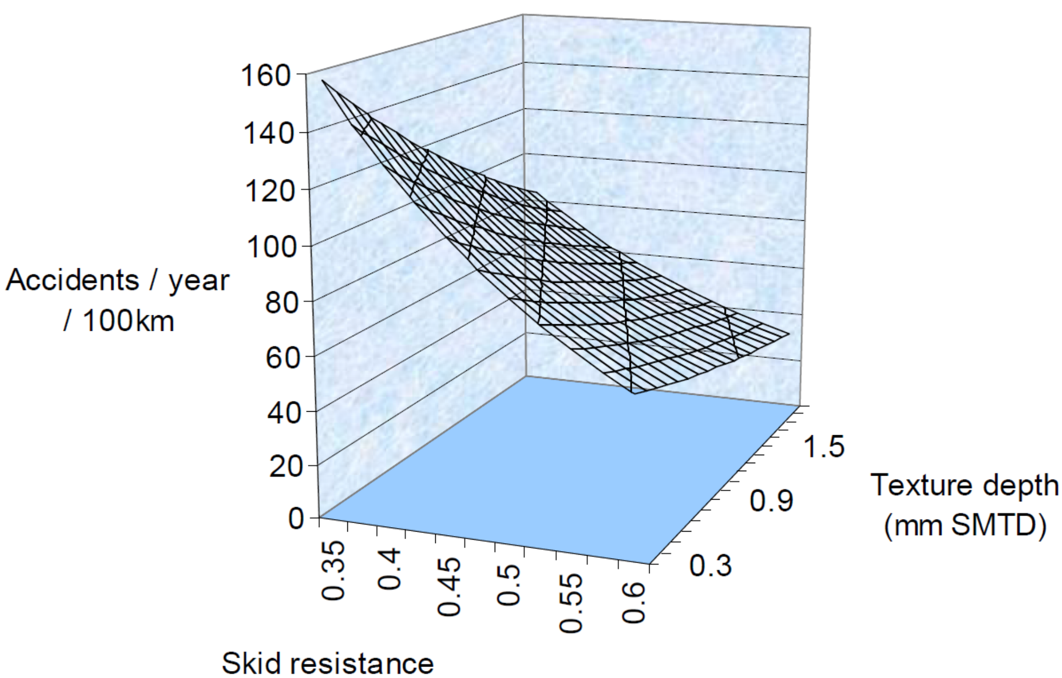

Figure 3.1. U.K. crash model for friction and texture (Viner et. al., 2004)

Table 3-1. Example Equations in literature relating crash, friction, and other variables.

Reference	Equation Form	Comments
Kuttesch (2004)	$CR = e^{2.54-0.01492\cdot \mathrm{FN40S}-0.000026\cdot AADT}$	CR = Crash Rate
Long et. al. (2014)	$CRR = 3.894\cdot e^{-0.04605\cdot \mathrm{FN50S}}+0.9205$ (for total crashes) $CRR = 5.023\cdot e^{-0.05292\cdot \mathrm{FN50S}}+0.9264$ (for wet crashes, FN50S < 39) $CRR = 3.894\cdot e^{-0.04605\cdot \mathrm{FN50S}}+0.9205$ (for wet crashes, FN50S ≥ 39)	CRR is the Crash Rate Ratio defined as: $CRR = \frac{P_{CR}}{P_{LM}}$ where P_{CR} and P_{LM} are cumulative percentage of total crashes and lane miles below a specific friction number, respectively.
De Leon Izzepi et. al. (2016a, 2016b) McCarthy et. al. (2016)	$\mu = e^{-0.35+1.25\ln(AADT)-1.19GN}$ (for Interstate Routes) $\mu = e^{-0.25+0.37\ln(AADT)-1.00GN+0.04/CV}$ (for Primary Routes) $\mu = e^{-0.55+0.75\ln(AADT)-0.56GN}$ (for Secondary Routes)	μ = mean crash count per 0.1 mile segment GN = Grip Number from Grip-Tester CV = Roadway Horizontal Curvature
Ivan et. al., (2010, 2014)	$\mu = e^{\beta_0+\beta_1\cdot \mathrm{FN40R}+\beta_3\log(AADT)}$	μ = mean crash count per 0.5 mile segment $\beta_1 - \beta_3$ = regression coefficients
Viner et. al. (2004)	$\mu = k\cdot Q^{\alpha} L^{\beta} e^{a_1 x_1 + a_2 x_2 + \cdots + a_i x_i}$	Q = Traffic L = Segment length α, β, a_i = regression parameters x_i = independent variables (friction, texture, etc.)
Musey et. al. (2016)	$\mu = -24.91\ln(\mathrm{FN40R})+109.59$	μ = Mean crash count
Larson et. al. (2008)	$\mu = a\cdot \mathrm{FN20R} + b\cdot MTD$ for intersection pavement sections	μ = Total crash count

3.2.2. Statistical Approach for Predicting Crash

The SPF described above or the closed-form regression models shown in Table 3-1 do not allow for the parameters to vary across different observations. In other words, the effect of the explanatory variable (e.g., friction) on the frequency of crashes is constrained to be the same for all segments within the predefined friction demand category. However, because of the factors that influence a crash but cannot be measured or are not measurable, the crash statistics typically show large variations from one roadway segment to another.

In order to address such variability in crash counts, it is necessary to model the statistical distribution of the crash counts and the associated probabilities.

Lord and Mannering (2010) also pointed out that because crash counts are discrete, non-negative integers, application of ordinary least-squares or ordinary normal distribution should not be used for modelling the distribution of crash-frequency data. Instead, FHWA's recommendation is to use the Poisson or Negative Binomial (NB) distribution for modelling the crash statistics. The Poisson model is given by the following equation.

$$P(y_i) = \frac{e^{-\mu_i} \mu_i^{y_i}}{y_i!} \tag{3}$$

where $P(y_i)$ is the probability of section i having y_i crashes per year and μ_i is the mean or expected number of crashes determined from the SPF shown in Equation (2). However, the drawback of the Poisson model is that the variance of the distribution is equal to its mean, and does not allow for modelling the over-dispersion of the data (variance being greater than the mean) which is frequently encountered in crash data (Lord and Mannering, 2010; Srinivasan and Bauer, 2013; Herbal et. al., 2010; Cameron and Trivedi, 2005).

Due to the above limitation of the Poisson model, FHWA recommends the use of the NB model for Highway Safety Improvement Program (HSIP) purposes (Herbel et. al., 2010). The NB model is derived by rewriting the SPF in Equation (2) as:

$$\lambda = \mu\upsilon = L \cdot e^{\beta_0 + \beta_1 \cdot \ln(AADT) + \sum \beta_i \cdot X_i} \cdot e^{\varepsilon} \tag{4}$$

where υ is the gamma-distributed, random error term with a mean of 1.0 and a variance of α. Given λ and υ, the NB model is written as the following (Cameron and Trivedi, 2005).

$$P(y_i) = \frac{\Gamma(\alpha^{-1} + y_i)}{\Gamma(\alpha^{-1})\Gamma(1 + y_i)} \left\{ \frac{\alpha^{-1}}{\alpha^{-1} + \lambda} \right\}^{\alpha^{-1}} \left\{ \frac{\lambda}{\alpha^{-1} + \lambda} \right\}^{y_i} \tag{5}$$

The mean of the above distribution is equal to λ as given by Equation (4) and the variance is equal to $\lambda(1+\alpha\lambda)$.

In addition to the NB model shown above, FHWA's HSIP manual recommends the use of Empirical Bayes (EB) method for combining the observed crash counts with the predicted counts from the SPF to calculate the statistically expected crash count for a given section (Herbal et. al., 2010). The EB method is based on the assumption that crash counts from a given pavement section are not the only evidence of the safety of that pavement. Other evidence or clues that should be considered is the information given for other pavements with similar characteristics. Hauer et. al. (2002) provides simple examples behind the concept of EB method as the following:

"For example, consider Mr. Smith, a novice driver in Ontario who had no accidents during his first year of driving. Let it also be known that an average novice driver in Ontario has 0.08 accident/year. It would be absurd to claim that Smith is expected to have zero accidents/year (based on his record only). It would also be peculiar to estimate his safety to be 0.08 accident/year (by disregarding his accident record). A sensible estimate must be a mixture of the two clues. Similarly, to estimate the safety of a specific segment of, say, a rural two-lane road, one should use not only the accident counts for this segment, but also the knowledge of the typical accident frequency of such roads in the same jurisdiction."

Mathematically, the EB method is written as the following:

$$EB_i = W_i \lambda_i + (1 - W_i) y_i \tag{6}$$

where EB_i is the crash count for section i estimated from the EB method and W_i is the weight factor given as:

$$W_i = \frac{1}{1 + \lambda_i \alpha} \tag{7}$$

The primary purpose of the EB method is to eliminate the Regression to Mean (RTM) bias and to improve the precision of the estimated crash counts. As an example, to explain the RTM phenomenon which often causes erroneous conclusions in highway safety analysis, consider the crash counts shown in Figure 3.2. Given the random fluctuations in crash counts shown in this figure, FHWA's HSIP manual illustrates the RTM bias as the following:

"(Figure 3.2) shows an example to demonstrate this concept. It shows the history of crashes at an intersection, which might have been identified as a high-hazard location in 2003 based upon the rise in crashes in 2002. Even though a treatment may have been introduced early in 2003, any difference between the frequencies of crashes in 2002 and those in 2003 and 2004 would, to some unknown degree, not be attributed to the treatment, but to the RTM phenomenon. The RTM phenomenon may cause the perceived effectiveness of a treatment to be overestimated. Thus, there would be a "threat to validity" of any conclusions drawn from a simple comparison of conditions before and after a change at a site."

Essentially, the RTM bias is caused by not incorporating the random fluctuation of the crash counts in the analysis. In order to eliminate the RTM bias, the EB method pulls the observed crash count from a given pavement towards the mean by combining the observed crash count with the predicted SPF predicted crash count, as shown in Figure 3.3. Therefore, the expected or corrected crash count based on the EB method is always between the observed value and the predicted value from the SPF.

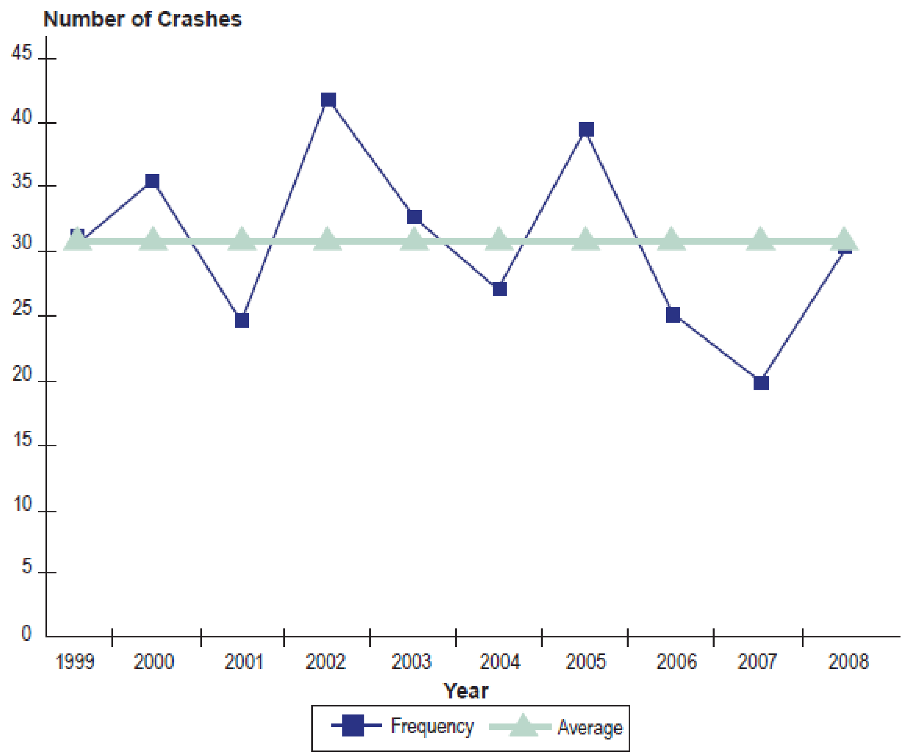

Figure 3.2. Description of Regression to Mean bias (Herbal et. al., 2010)

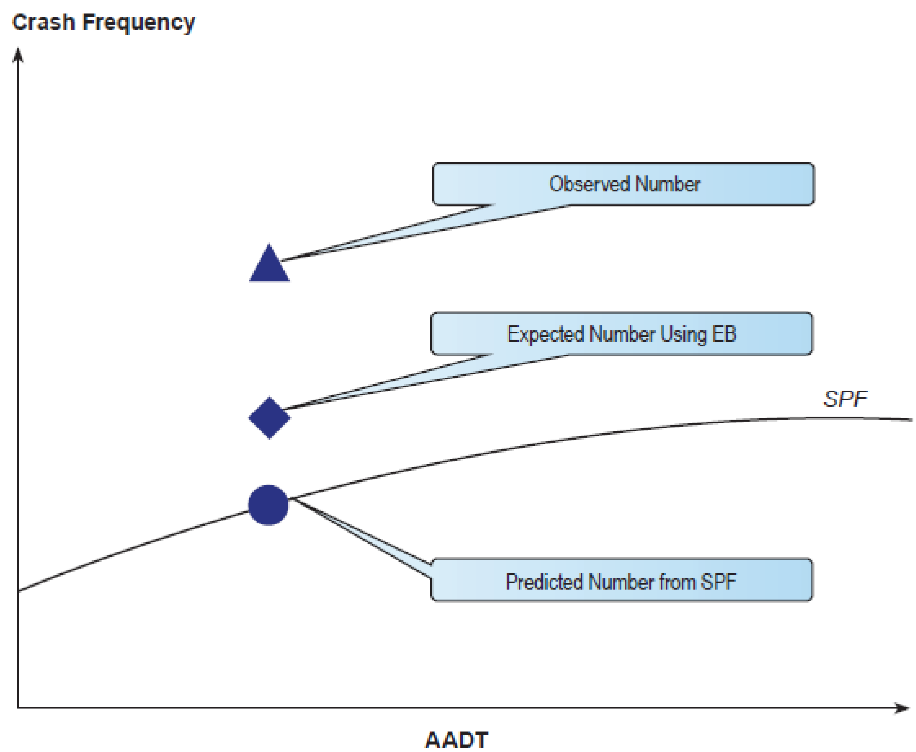

Figure 3.3. Illustration of Empirical Bayes method (Herbal et. al., 2010)

The application of the NB and EB methods have been illustrated in great detail by de Leon Izeppi et. al. (2016a, 2016b) and McCarthy et. al. (2016) as part of a pilot effort for incorporating the Continuous Friction Measuring Equipment (CFME) into roadway safety decision process. The researchers used the negative binomial SPF for modelling the crash versus friction relation relationship, and the EB method for predicting the crashes that occurred on a segment of I-81 in Virginia. Their results are as shown in Figure 3.4.

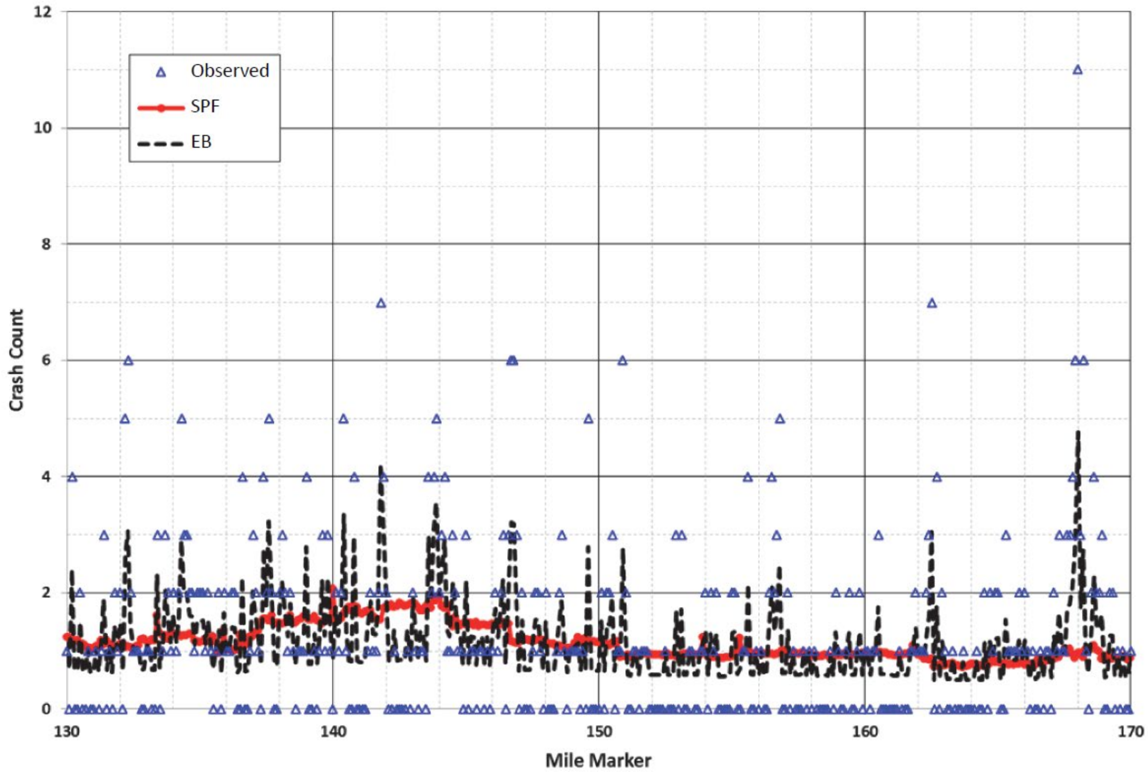

FIGURE 3 Observed crashes, rate (SPF), and predicted (EB) crashes on I-81, MM 130 to MM 170, Salem District.

Figure 3.4. Observed crash count from I-81 in Virginia along with SPF and EB predictions (de Leon Izeppi et. al., 2016)

4. DATA GATHERING AND PRELIMINARY ANALYSIS

4.1. BACKGROUND

Prior to developing the statistical models between crash counts and roadway related features, a preliminary analysis was conducted using the available data to understand the trends in friction, traffic, and crash. This chapter documents the data gathering process as well as the results and findings of the preliminary analyses.

4.2. DATA GATHERING

For this study, MoDOT provided a spreadsheet containing the HFST Job Numbers and their locations. In total, 33 distinct Job Numbers were identified containing 76 individual mainline location and 19 ramp locations. Three of these Job Numbers contained both mainline and ramps as part of the work, with two Job Numbers where only ramps were treated.

A quick review of MoDOT's data revealed that for some ramp locations, the entire ramp was treated with HFST, but in several other ramps, only the beginning and end (entrance and exit) were treated. The corresponding crash data includes those from the entire ramp, not to specific locations along the length. It should also be noted that MoDOT does not survey ramps so no data on pavement condition or roadway geometry is available.

There were two turn lanes included in the data, which do not have crash data located specifically to that lane. In general, they are logged to the intersection they serve. However, there was no accurate way of specifying which leg of the intersection a crash occurred on (or in the intersection itself) without reviewing individual crash reports. Considering the small number of such locations and the lack of sufficient crash before and after application HFSTs, it was decided to eliminate these locations from the study.

As part of the initial data screening effort, the individual HFST locations were verified against MoDOT's relational database (TMS) which contained information on specified locations where a HFST treatment had been applied. All locations were visually verified from the ARAN Viewer and corrections or additions to the TMS database were made. The TMS data was used as a starting point to assign log miles to the HFST locations so that further data (crashes, AADT, curve data, speed limit, etc.) could be obtained. An example of the ARAN viewer used for verifying the HFST locations is shown in Figure 4.1.

Figure 4.1. Example of ARAN viewer used to confirm HFST locations and log miles for use in analysis. (Phelps County I-44, near Powellville)

4.2.1. <u>Friction Data before and after HFST</u>

After all locations have been verified, they were reviewed for the availability of Friction Numbers (FN) for inclusion in the study. Some of the FN data was included in the spreadsheet supplied by MoDOT. However, as mentioned previously, not all locations had both before and after FNs available, in fact only about 14 HFST sections had both.

It is also noted that ARA had previously provided much of the friction testing for locations included in this study. As such, ARA's friction data files and internal records were reviewed for any additional FN data that can be brought into the analysis. As part of friction testing, GPS coordinates were available for the individual tests conducted. To ensure that the friction testing locations corresponded to the HFST locations, the GPS coordinates from friction testing was visually reviewed in Google Earth. An example of the GPS coordinates from ARA's friction testing unit is shown in Figure 4.2.

Figure 4.2. Example of ARA friction data overlayed on Google Earth map. (MO 364 and I-270 interchange).

4.2.2. Crash Data

Once the beginning and ending log miles of each HFST location had been reviewed and verified, MoDOT was asked to supply additional data. In many cases, a single Job Number contained several different locations where HFSTs were applied, and the crash data was requested for every available HFST location.

A total of 1,846 crashes were identified and provided by MoDOT for this study. The crash data included various attributes including the severity (e.g., fatal, minor injury, etc.) as well as the roadway condition (e.g., wet vs. dry roadway surface) and the environmental condition (e.g., daylight vs. dark) at the time of crash.

4.2.3. Roadway Data

Similar to the crash data, the roadway data was requested for each of HFST location. The roadway data included information on surface distresses (rut depth, ride quality, cracking) as well as the roadway curvature. Roadway curvature and superelevation data is now routinely collected by MoDOT as part of annual ARAN survey. It should be noted that many of the HFSTs were applied continuously over multiple curves in differing directions (e.g., over the entire "S" curve). In this case the entire curve was subdivided into multiple segments (e.g., curve 1, curve, 2 and tangent portion) for the subsequent analysis.

4.3. DATA INTEGRATION

Figure 4.3 shows the schematics of merging all of the individual data attributes into a single database. Essentially, all of the individual data attributes (i.e., roadway, pavement, friction, and cost data tables) were all merged back to the crash data. The merging of the data was primarily carried out based on location information (i.e., County, Route, Log Mile, Direction, and Lane Number) and MoDOT's Job Number. During the merging process, it was found that 17 crashes did not match to any of the other tables. Therefore, these 17 crashes were eliminated from further analysis, leaving a total of 1,829 crashes in the merged database.

Furthermore, several Job Numbers were not matched to any of the crash data provided by MoDOT. These Job Numbers were subsequently removed from this study, leaving a total of 27 unique Job Numbers over 67 distinct HFST locations for this study. The location, year of HFST installation, and the cost associated with these HFST sections are summarized in terms of MoDOT's Job Number in Table 4-1, while their geographic locations are depicted in Figure 4.4. It is noted again that in Table 4-1, a single Job number may correspond to one or more HFST locations including ramps (designated with "RP" under the Route column). In addition, it is emphasized that the HFSTs sections in Table 4-1 were installed in different years, ranging from 2014 to 2019. As such, the number of years for which the before and after crash data was available is not consistent from one Job number to another.

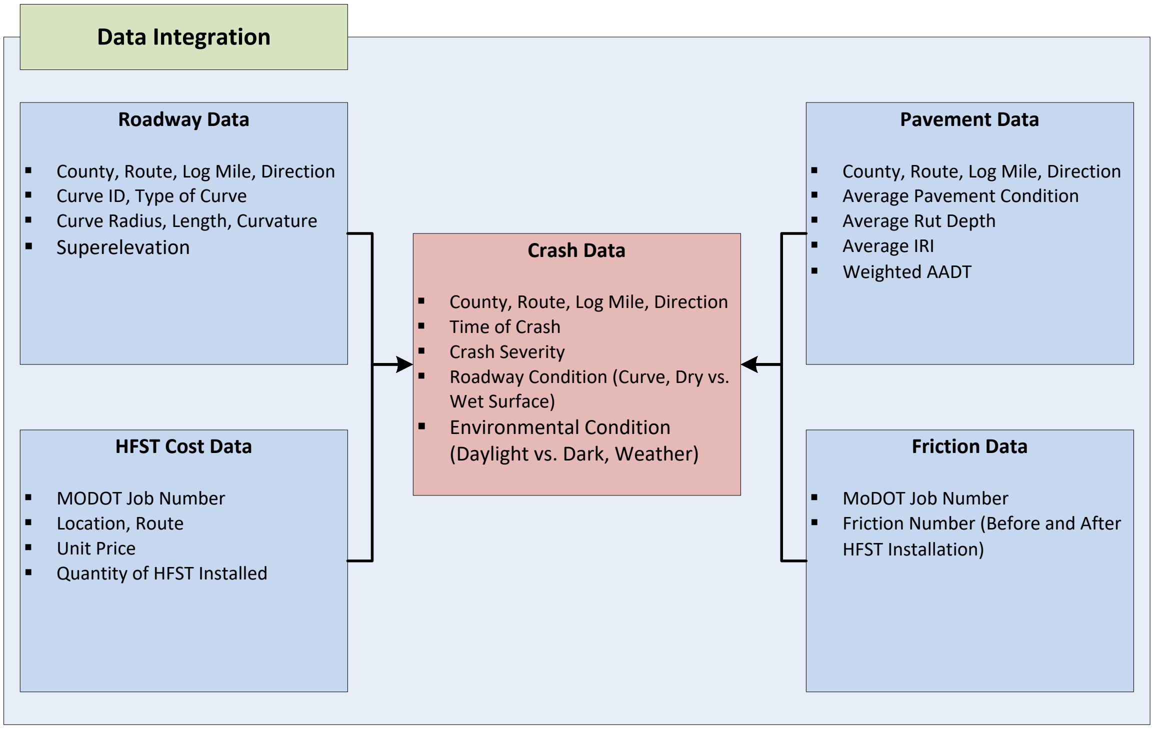

Figure 4.3. Schematics of Data Integration

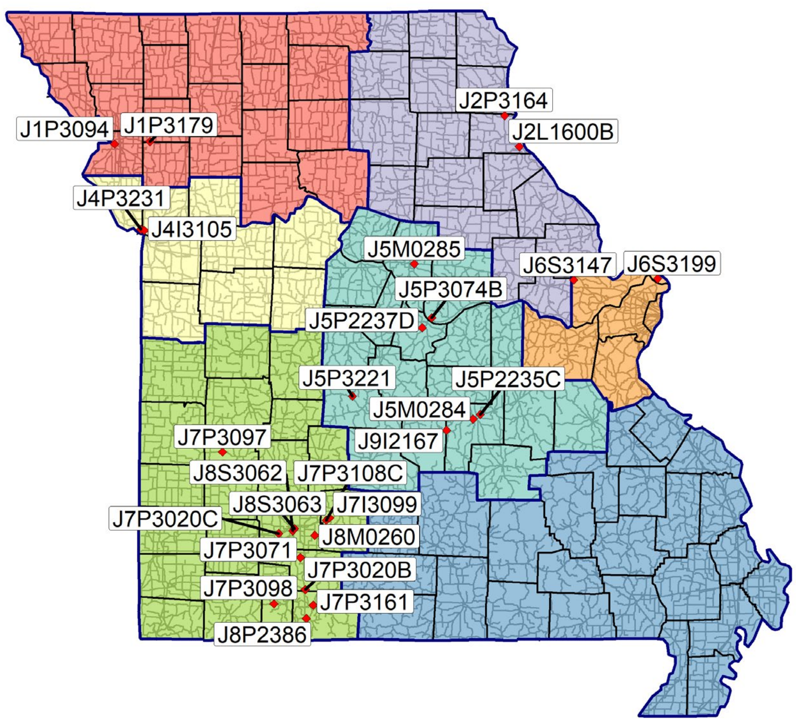

Figure 4.4. Mapping of MoDOT HFST Sections

Table 4-1. MoDOT's HFST Job Numbers and Locations Identified for this Study.

<table>
<tr><th>HFST Job Number</th><th>County</th><th>Route</th><th>Begin Log</th><th>End Log</th><th>Year HFST Installed</th><th>Price/yd^2</th><th>Sq. Yards</th><th>Total Cost ($)</th></tr>
<tr><td>J1P3094</td><td>Buchanan</td><td>US 36 W</td><td>191.680</td><td>192.061</td><td>2015</td><td>18</td><td>5,921</td><td>106,578</td></tr>
<tr><td rowspan="2">J1P3179</td><td>Dekalb</td><td>US 36 W</td><td>175.290</td><td>175.342</td><td rowspan="2">2017</td><td rowspan="2">19.5</td><td rowspan="2">6,723</td><td rowspan="2">131,098.5</td></tr>
<tr><td>Buchanan</td><td>US 36 W</td><td>192.061</td><td>192.318</td></tr>
<tr><td>J2L1600B</td><td>Marion</td><td>US 61 S</td><td>59.415</td><td>59.526</td><td>2016</td><td>21</td><td>2,667</td><td>56,007</td></tr>
<tr><td rowspan="3">J2P3164</td><td>Marion</td><td>RP US61S TO US24E</td><td>0.000</td><td>0.175</td><td rowspan="3">2017</td><td rowspan="3">17.5</td><td rowspan="3">10,681</td><td rowspan="3">186,917.5</td></tr>
<tr><td>Marion</td><td>US 24 E</td><td>215.843</td><td>216.677</td></tr>
<tr><td>Marion</td><td>US 61 N</td><td>354.255</td><td>354.471</td></tr>
<tr><td rowspan="5">J4I3105</td><td>Platte</td><td>RP IS29N TO IS635S</td><td>0.034</td><td>0.161</td><td rowspan="5">2017</td><td rowspan="5">17.5</td><td rowspan="5">5,911</td><td rowspan="5">103,443</td></tr>
<tr><td>Clay</td><td>RP IS29S TO US169N</td><td>0.000</td><td>0.063</td></tr>
<tr><td>Clay</td><td>RP IS29S TO US169N</td><td>0.267</td><td>0.289</td></tr>
<tr><td>Clay</td><td>RP IS29S TO US169N</td><td>0.289</td><td>0.345</td></tr>
<tr><td>Platte</td><td>RP IS635N TO IS29S</td><td>0.273</td><td>0.388</td></tr>
<tr><td rowspan="7">J4P3231</td><td>Platte</td><td>IS 635 N</td><td>3.378</td><td>3.766</td><td rowspan="7">2017</td><td rowspan="7">18</td><td rowspan="7">8,760</td><td rowspan="7">157,680</td></tr>
<tr><td>Jackson</td><td>RP IS470E TO IS70W</td><td>0.296</td><td>0.35</td></tr>
<tr><td>Jackson</td><td>RP IS470W TO IS70E</td><td>0.297</td><td>0.357</td></tr>
<tr><td>Jackson</td><td>RP IS70E TO IS470E</td><td>0.284</td><td>0.342</td></tr>
<tr><td>Jackson</td><td>RP IS70E TO IS470W</td><td>0.000</td><td>0.084</td></tr>
<tr><td>Jackson</td><td>RP IS70E TO IS470W</td><td>0.375</td><td>0.52</td></tr>
<tr><td>Jackson</td><td>RP IS70W TO IS470W</td><td>0.259</td><td>0.326</td></tr>
<tr><td>J5M0284</td><td>Phelps</td><td>IS 44 W</td><td>108.340</td><td>108.800</td><td>2019</td><td>NA</td><td>NA</td><td>NA</td></tr>
<tr><td>J5M0285</td><td>Boone</td><td>IS 70 W</td><td>121.109</td><td>121.595</td><td>2019</td><td>NA</td><td>NA</td><td>NA</td></tr>
<tr><td>J5P2235C</td><td>Phelps</td><td>IS 44 E</td><td>189.097</td><td>189.930</td><td>2014</td><td>21.5</td><td>21,675</td><td>466,012.5</td></tr>
<tr><td rowspan="2">J5P2237D</td><td>Cole</td><td>MO 179 S</td><td>42.014</td><td>42.326</td><td rowspan="2">2014</td><td rowspan="2">18</td><td rowspan="2">9,106</td><td rowspan="2">163,908</td></tr>
<tr><td>Cole</td><td>MO 179 S</td><td>42.773</td><td>42.844</td></tr>
<tr><td rowspan="2">J5P3074B</td><td>Callaway</td><td>US 54 E</td><td>171.558</td><td>171.908</td><td rowspan="2">2017</td><td rowspan="2">NA</td><td rowspan="2">NA</td><td rowspan="2">NA</td></tr>
<tr><td>Callaway</td><td>US 54 W</td><td>99.840</td><td>100.160</td></tr>
</table>

HFST Job Number	County	Route	Begin Log	End Log	Year HFST Installed	Price/yd^2	Sq. Yards	Total Cost ($)
J5P3221	Camden	MO 5 S	218.453	218.964	2017	17	13,905	236,385
	Miller	RT W S	21.696	21.789				
	Camden	US 54 E	114.749	114.961				
	Camden	US 54 W	156.876	157.091				
J6S3147	St. Charles	RT W S	2.458	2.530	2019	17.85	7,056	125,950
	St. Charles	RT W S	3.718	3.810				
	St. Charles	RT W S	0.160	0.298				
J6S3199	St. Charles	MO 94 E	85.117	85.306	2017	17.5	37,627	658,472.5
	St. Louis	RP IS270W TO MO364E	0.000	0.269				
	St. Louis City	RP IS55N TO IS44W	0.132	0.262				
	St. Louis	RP MO364E TO IS270E	0.000	0.308				
	St. Louis	RP MO364E TO IS270W	0.000	0.136				
	St. Louis	RP MO364W TO IS270W	0.000	0.287				
	St. Charles	US 67 S	2.406	2.557				
J7I3099	Webster	IS 44 E	95.312	96.645	2017	17.5	18,769	328,457.5
J7P3020B	Christian	US 65 N	23.674	23.992	2015	19.5	8,392	163,644
	Christian	US 65 S	288.547	288.825				
J7P3020C	Greene	MO 360 W	3.849	4.132	2015	19.5	4,589	89,485.5
J7P3071	Christian	MO 14 E	26.941	27.105	2016	21	4,252	89,292
	Webster	US 60 W	240.165	240.467				
J7P3097	Cedar	MO 32 E	13.124	13.253	2017	23	1,438	33,074
J7P3098	Stone	MO 76 E	81.641	81.869	2017	18	2,943	52,974
J7P3108C	Webster	IS 44 E	92.497	93.363	2019	16	32,120	513,920
	Webster	IS 44 W	199.853	200.887				
	Webster	IS 44 W	193.964	194.254				
J7P3161	Taney	US 160 E	141.532	141.87	2017	18	7,072	127,296
	Taney	US 160 E	142.981	143.116				

HFST Job Number	County	Route	Begin Log	End Log	Year HFST Installed	Price/yd^2	Sq. Yards	Total Cost ($)
	Taney	US 160 E	143.179	143.249				
J8M0260	Greene	RT D E	6.988	7.352	2019	16.5	6,570	108,405
	Greene	RT D E	6.617	6.762				
J8P2386	Taney	MO 76 E	110.275	110.402	2017	18	2,286	41,148
J8S3062	Greene	LP 44 W	6.146	6.286	2017	23	1,971	45,333
J8S3063	Greene	MO 13 S	232.577	232.659	2017	23	1,029	23,667
J9I2167	Phelps	IS 44 E	170.289	170.689	2019	17.34	32,413	562,041.4
	Phelps	IS 44 E	168.959	169.519				
	Pulaski	IS 44 E	158.088	159.649				
	Phelps	IS 44 E	172.700	172.974				
	Phelps	IS 44 E	173.570	174.438				
	Phelps	IS 44 W	123.800	124.980				
	Phelps	IS 44 W	122.050	122.230				
	Phelps	IS 44 W	121.250	121.400				

4.4. PRELIMINARY ANALYSIS

Prior to developing the SPF based on MoDOT's crash data and HFST related features, a preliminary analysis was conducted to understand the trends in friction and crash data. The results and findings of the preliminary analyses are summarized in this section of the report.

4.4.1. <u>Friction Numbers Before and After HFST</u>

Figure 4.5 shows the FN values (before and after HFST) available from the 27 HFST Job Numbers. As seen from the figure, the FN values were not available for all HFST sites. Nonetheless, the figure also shows that the FN values increased significantly upon installation of the HFST. More specifically, the average FN before HFST installation was found to be 35 (based on 8 projects) whereas the average FN on HFST surfaces was 78.

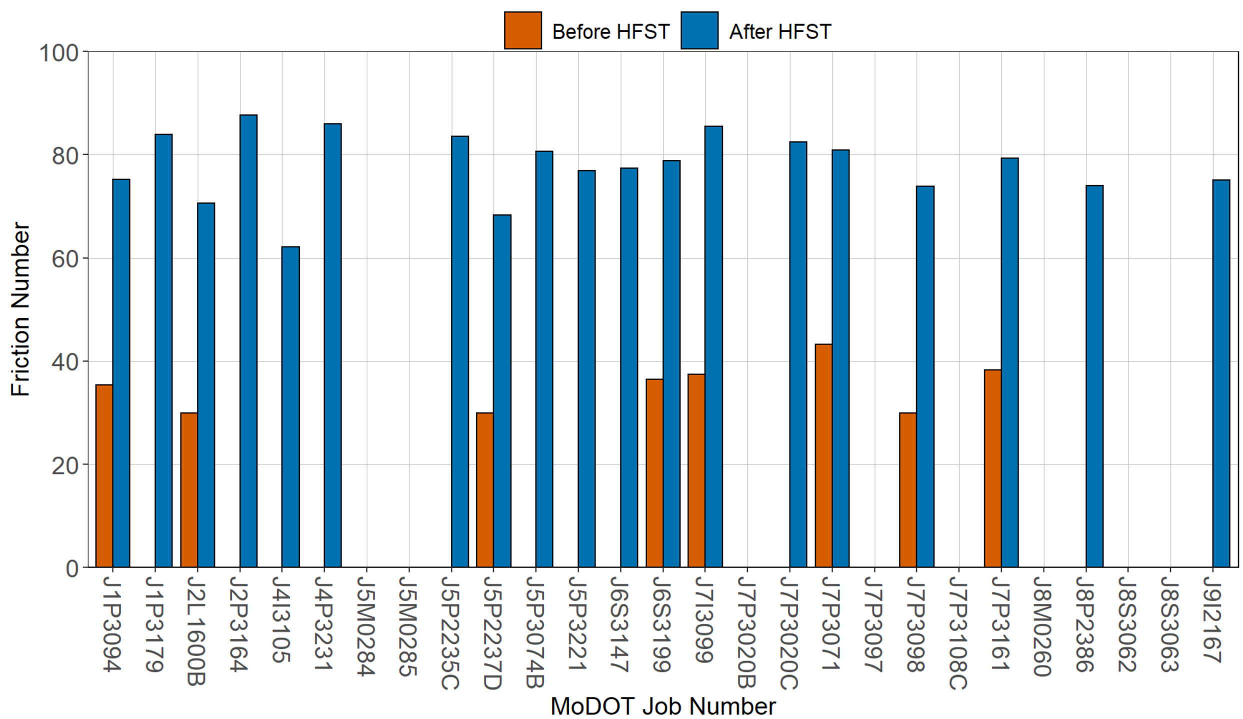

Figure 4.5. Available Friction Numbers Before and After HFST

The above figure clearly indicates that MoDOT's HFST projects were effective in improving the friction of roadway surfaces. However, it is acknowledged that (1) the FN values on HFST projects do degrade over time and (2) the service life of an HFST is typically shorter than the conventional pavement surfaces (i.e., asphalt or concrete). As such, it is also of interest to study how fast the FN values decrease over time and to estimate the effective service life of MoDOT's HFSTs.

Figure 4.6 shows the trend between FN and HFST age from two HFST sections in Missouri, both of which were tested for friction at different HFST ages. It is noted that the HFST on MO 94 showed an unexpected trend, i.e., the FN values showed a sudden increase approximately from 79 (at 3 years of age) to 88 (at 5 years of age). While it is possible that such a jump in FN can be caused by some other surface distresses (e.g., cracking and ravelling that may increase surface texture and thereby allowing the water at the pavement surface drain faster), this clearly contradicts the anticipated trend of FN decreasing over time. As such, the FN values of MO 94 at 5 years of age (highlighted in oval) were excluded from the analysis.

Linear trend lines were constructed using the remaining data points and are shown in Figure 4.6 for the respective HFST sections. The trend lines indicate that the FN value of HFSTs may decrease at a rate of 3.7 to 4.5 points per year (producing a rough average of 4 points per year). Consider an HFST having an FN value of 78 (equal to the average HFST FN in Figure 4.5) immediately after installation. If the FN of this HFST section decreases at a rate of 4 point/per year, then the FN of this section will fall below 60 in 5 years and below 40 in 10 years. In other words, the effective life of the HFST would roughly be between 5 and 10 years, depending on the FN threshold. This is consistent with the findings of Holzschuher (2017) who reported 5 to 10 years of service life for HFSTs in Florida. As such, a typical HFST life of 7 years was assumed for the subsequent benefit-cost analyses to be presented in the following chapters of this report.

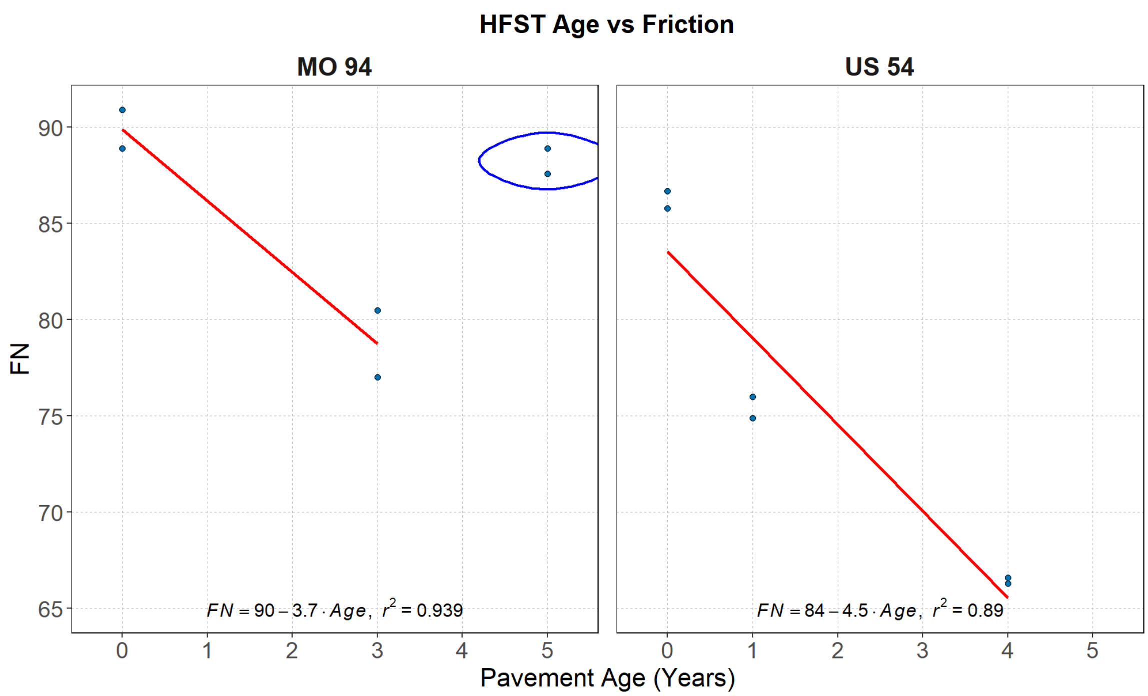

Figure 4.6. Friction Number vs. HFST Age

4.4.2. Crash Counts Before and After HFST

The 1,829 total crashes, including PDO crashes, made available for the analysis include those that occurred before HFST installation as well as those after HFST installation. More specifically, a total of 1,425 crashes occurred before HFST while the remaining 404 crashes occurred on HFST surfaces. These numbers translate to a total reduction of 1,021 crashes or 71.6

percent. Figure 4.7, Figure 4.8, and Figure 4.9 show the breakdown of these before/after HFST crash counts for different lighting conditions (daylight vs. dark), roadway curves (on curved vs. straight segment of roadway), and roadway surface condition (wet vs. dry surface), respectively.

Figure 4.7 and Figure 4.8 show that the majority of the before HFST crashes occurred during daylight and on curved roadways. Correspondingly, these conditions exhibited higher crash reduction following the installation of HFSTs. Figure 4.9 indicates that before the installation of HFSTs, more crashes occurred on wet pavement surfaces than on dry surfaces. Furthermore, it is shown that while both wet and dry crashes were reduced after HFST installation, by far the greater reduction was in the category of wet crashes. These preliminary results generally indicate that (1) HFSTs are more effective in reducing crashes on wet pavement surfaces and (2) there are other factors affecting crashes (e.g., visibility on curved roadways).

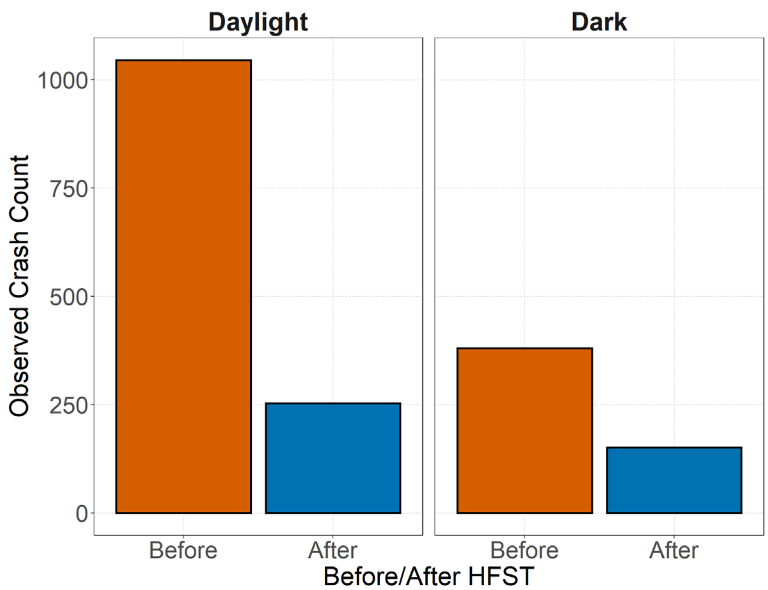

Figure 4.7. Before and After HFST Crash Counts for Daylight vs Dark

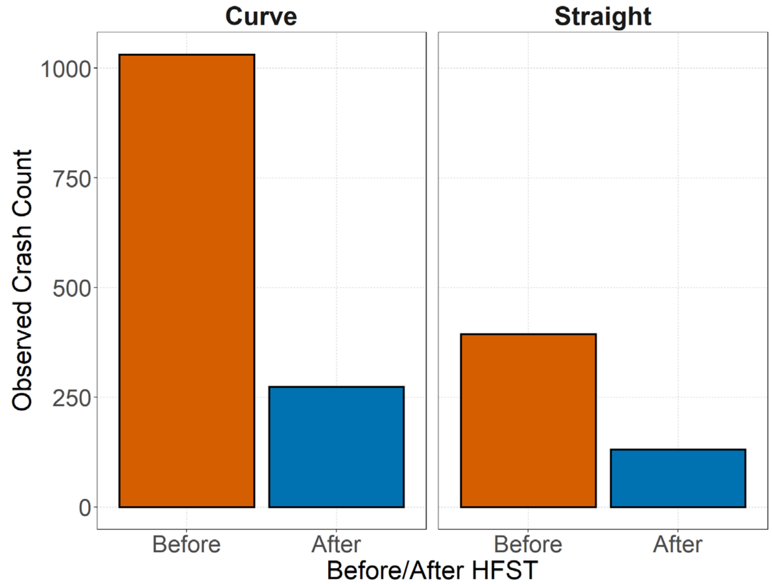

Figure 4.8. Before and After HFST Crash Counts on Curve vs Tangent Roadways

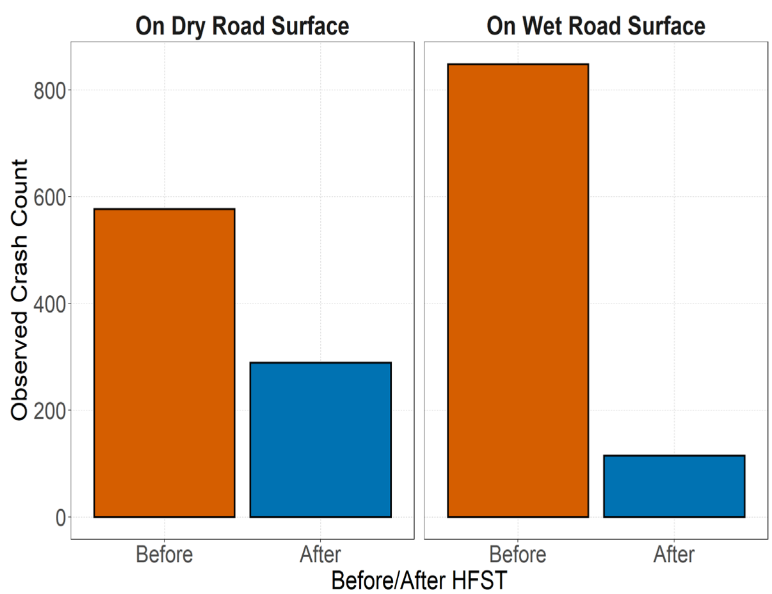

Figure 4.9. Before and After HFST Crash Counts for Wet vs Dry Roadway Surfaces

Table 4-2 shows a more detailed breakdown of the crash counts while Table 4-3 shows the crash reduction (both in terms of number of crashes and percent reduction) observed from the HFST sections. These tables clearly show that the HFSTs have potential for reducing crashes on both wet and dry pavement surfaces, with the benefit (i.e., crash reduction) more pronounced for wet pavement surfaces.

Table 4-2. Summary of Crash Counts Before and After HFST Installation.

Before/After	Surface Condition	On Curved Segments, During Daylight	On Straight Segments, During Daylight	On Curved Segments, During Dark	On Straight Segments, During Dark	Total
Before	Dry	261	157	110	49	577
Before	Wet	490	137	170	51	848
Before	**Before Total**	**751**	**294**	**280**	**100**	**1,425**
After	Dry	119	62	70	38	289
After	Wet	56	16	28	15	115
After	**After Total**	**175**	**78**	**98**	**53**	**404**

Table 4-3. Summary of Crash Reduction After HFST Installation.

Crash Reduction	Surface Condition	On Curved Segments, During Daylight	On Straight Segments, During Daylight	On Curved Segments, During Dark	On Straight Segments, During Dark	Total
Occurrence	Dry	142	95	40	11	288
Occurrence	Wet	434	121	142	36	733
Occurrence	**Before Total**	**576**	**216**	**182**	**47**	**1,021**
Percent Reduction	Dry	54.4	60.5	36.4	22.4	49.9
Percent Reduction	Wet	88.6	88.3	83.5	70.6	86.4
Percent Reduction	**After Total**	**76.7**	**73.5**	**65.0**	**47.0**	**71.6**

Figure 4.10 shows a breakdown of before and after HFST crash counts for each Job Number. As expected, the figure shows the number of crashes may have reduced after the installation of HFST. However, as previously shown in Table 4-1, these HFSTs were installed in different years, ranging from 2014 to 2019. As such, the number of years for which the before and after crash data was available is not consistent from one Job number to another. For example, the HFST in Buchanan County (i.e., Job Number J1P3094) was constructed in 2015, and the crash data was available for 4 years before HFST and 5 years after HFST. On the other hand, the Marion County HFST (i.e., Job Number J2L1600B) was constructed in 2016 but the crash data was available for only 1 year before HFST and 4 years after HFST. Further investigation showed that the crash data provided by MoDOT contained a 100 foot “cushion” to allow for variance in the locations provided on the crash reports. When looking specifically at the Marion County example, several crashes were identified outside the limits defined by the HFST logs by a matter

of a few feet. For very short segments, this accounts for crashes "missing" from previous years. However, there would be no way to accurately account for the location issues, and thus it was decided to include only those crashes where the data from both datasets matched.

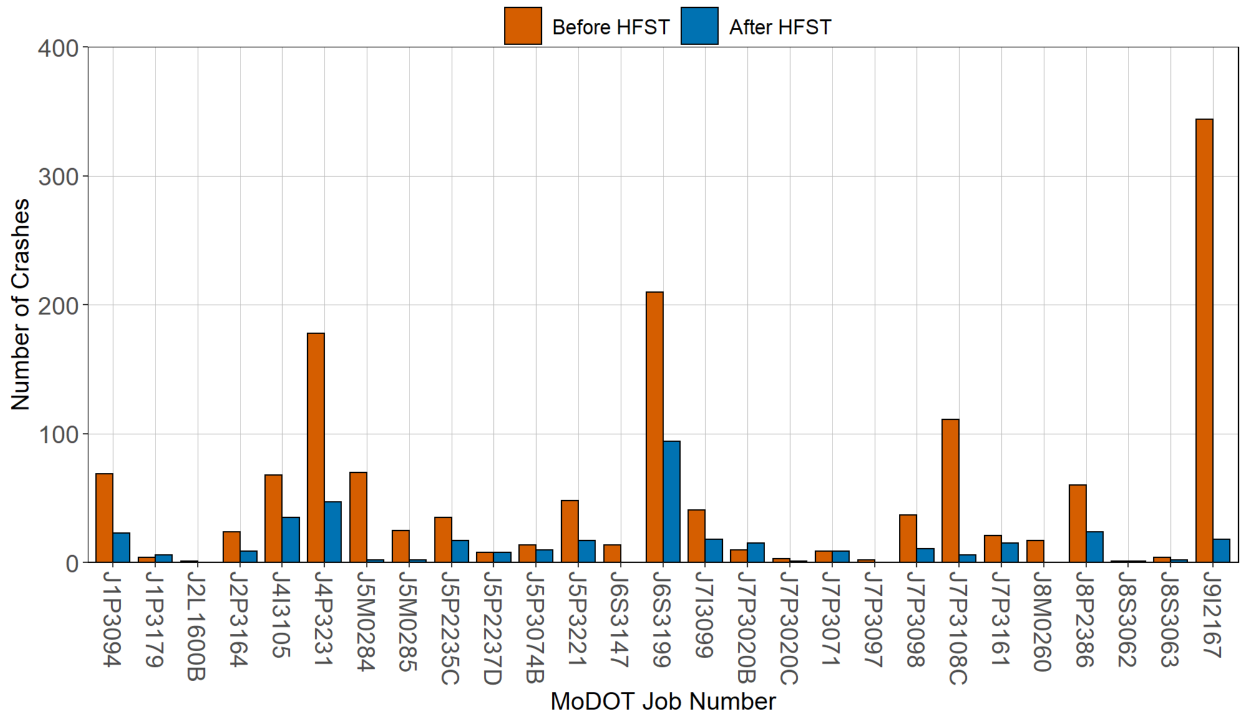

Figure 4.10. Total Number of Crashes Before and After HFST for Each Job Number

Due to the difference in number of years of crash data availability, it was necessary that the crash counts be normalized by the number of years (i.e., crashes per years) for a more balanced comparison. Figure 4.11 shows the annual crash rate of all severities broken down by Job Number. The figure also shows the percent crash reduction achieved by each HFST Job Number, which ranges from 10 percent to 100 percent excluding those with negative crash reduction (i.e., average number of crashes increased after HFST installation).

The Job Numbers with negative crash reduction correspond to J1P3179 (with 1.3 and 2.0 crashes/year before and after HFST, respectively, resulting in a crash increase of 50 percent) and J7P3161 (with 4.2 and 5.0 crashes/year before and after HFST, respectively, resulting in a crash increase of 19 percent). However, the number of crashes observed from these sections were relatively minimal (compared to some other sections) and it is likely that the increase in crash may be a result of the RTM bias (i.e., due to random fluctuations in crash counts as well as other factors that affect crash).

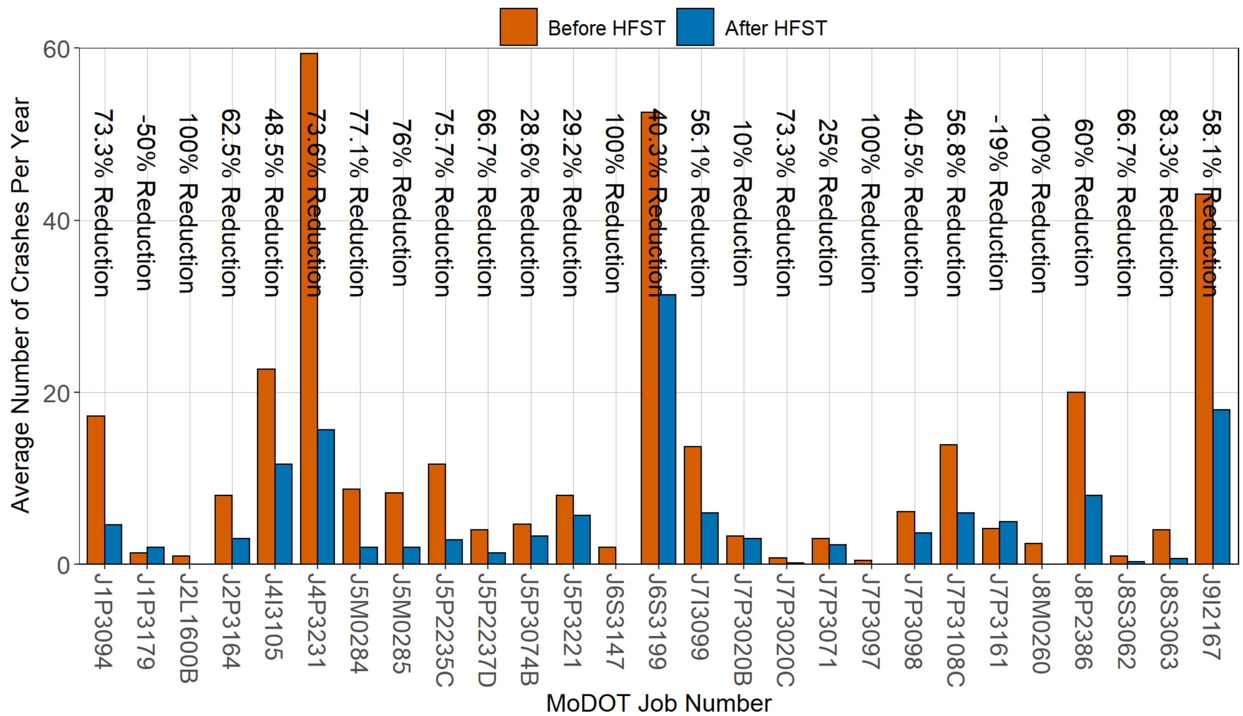

Figure 4.11. Average Number of Crashes Per Year Before and After HFST for Each Job Number

4.4.3. Benefit-Cost Analysis Based on Simple Before After Crash Counts

Based on the simple before and after HFST crash counts, it was shown previously that MoDOT's HFST sections are generally effective in reducing crashes. To justify the increased cost of HFST installation on these high-crash locations, it is also of interest to evaluate the benefit in terms of reduced crash costs. This section of the report documents the results and findings of such Benefit-Cost Analysis (BCA) based on the simple before & after average crash counts.

Table 4-4 shows the average crash cost used by MoDOT (2018) for 4 different crash severities namely fatality, serious injury, minor injury, and property damage only (PDO). As shown in the table, the crash cost increases by several orders of magnitude going from low-severity crash (i.e., PDO) to high-severity crash (i.e., fatality). While the use of an average crash cost over different severity levels was considered, it was decided not to use such an approach because the average crash cost (approximately $2.7 million per crash) was considered to be too high. As such, the yearly crash counts for different crash severity levels were calculated from the available crash data as shown in Figure 4.12 through Figure 4.15.

Table 4-4. Cost of Crash used by MoDOT.

Crash Severity	Crash Cost
Fatality	$ 9,962,900
Serious Injury	$ 577,700
Minor Injury	$ 150,300
Property Damage Only	$ 10,500

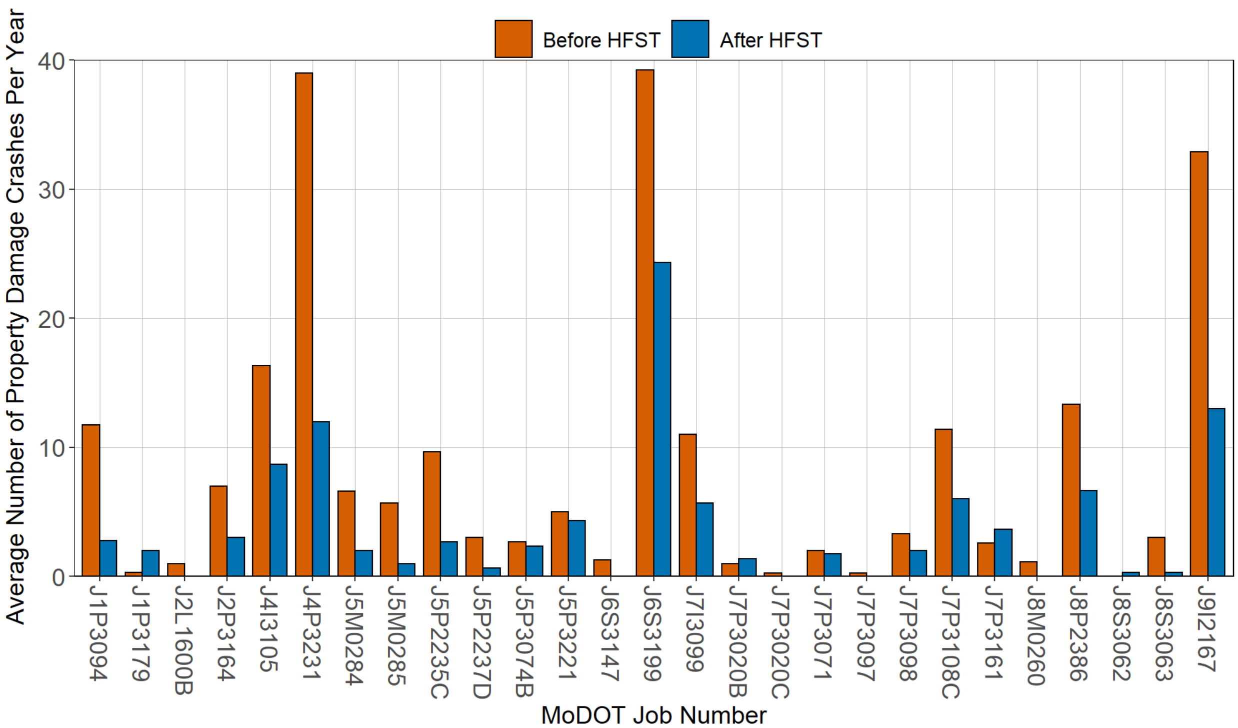

Figure 4.12. Average Number of Property Damage Crashes Per Year Before and After HFST for Each Job Number

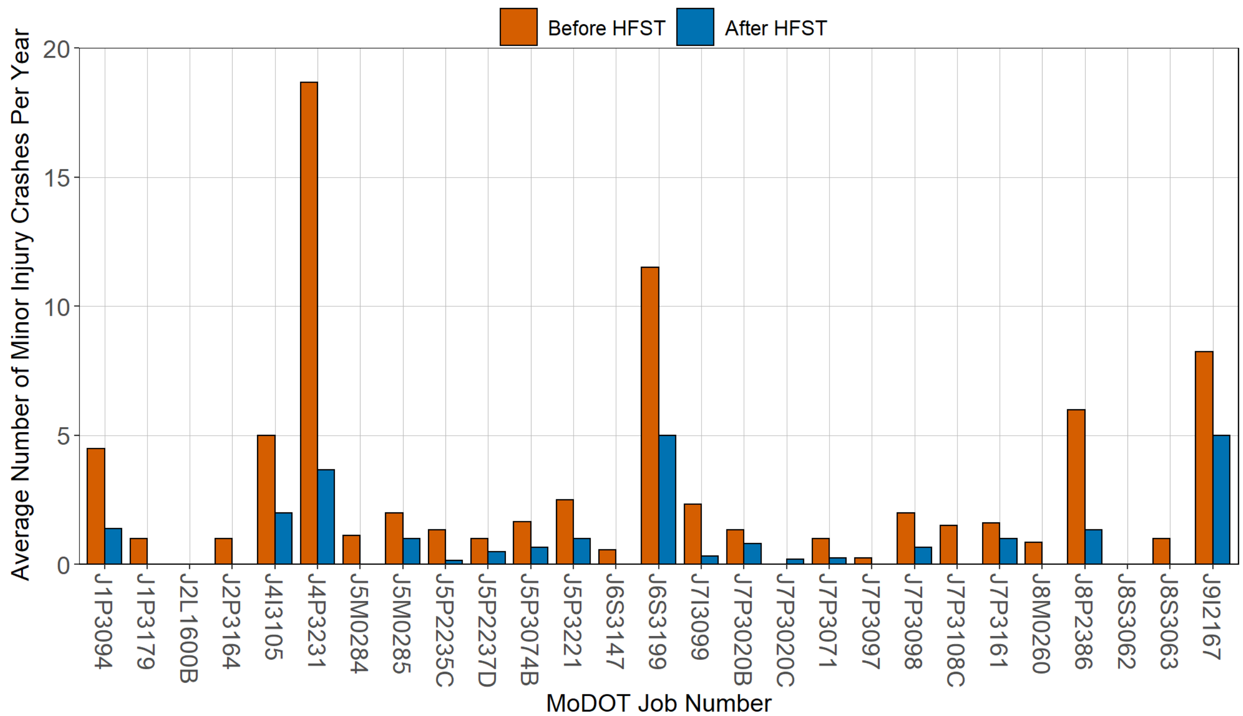

Figure 4.13. Average Number of Minor Injury Crashes Per Year Before and After HFST for Each Job Number

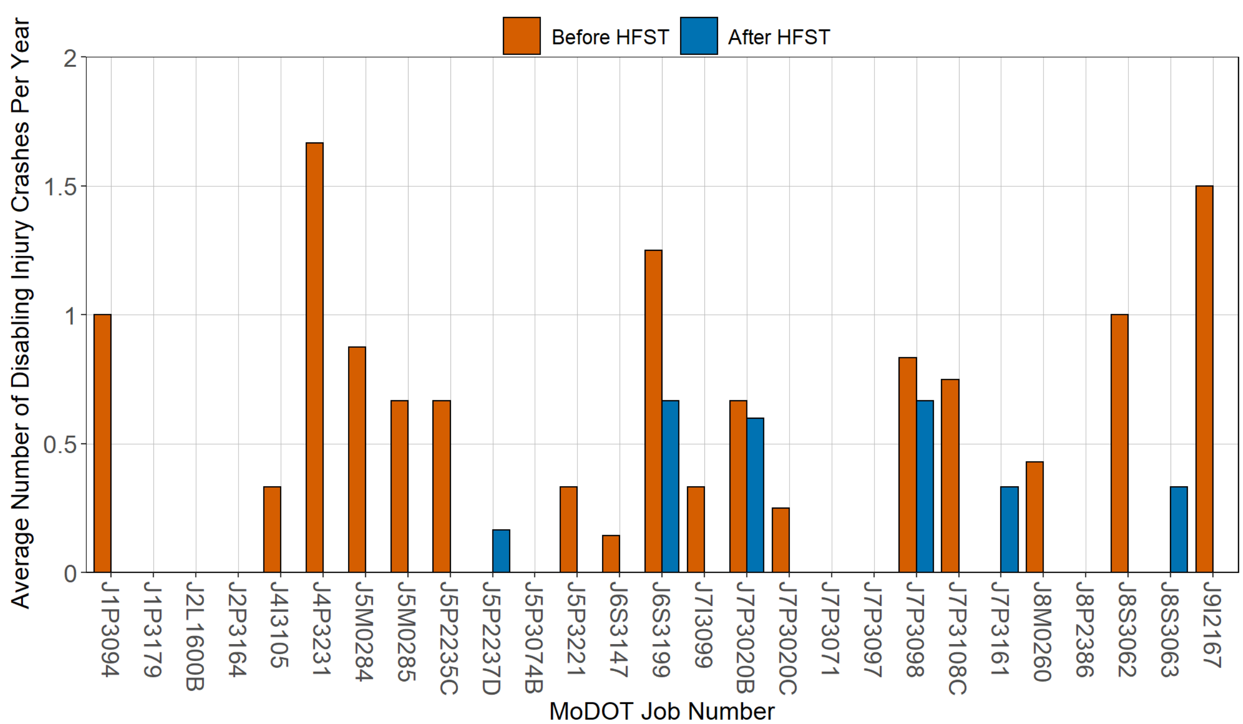

Figure 4.14. Average Number of Serious Injury Crashes Per Year Before and After HFST for Each Job Number

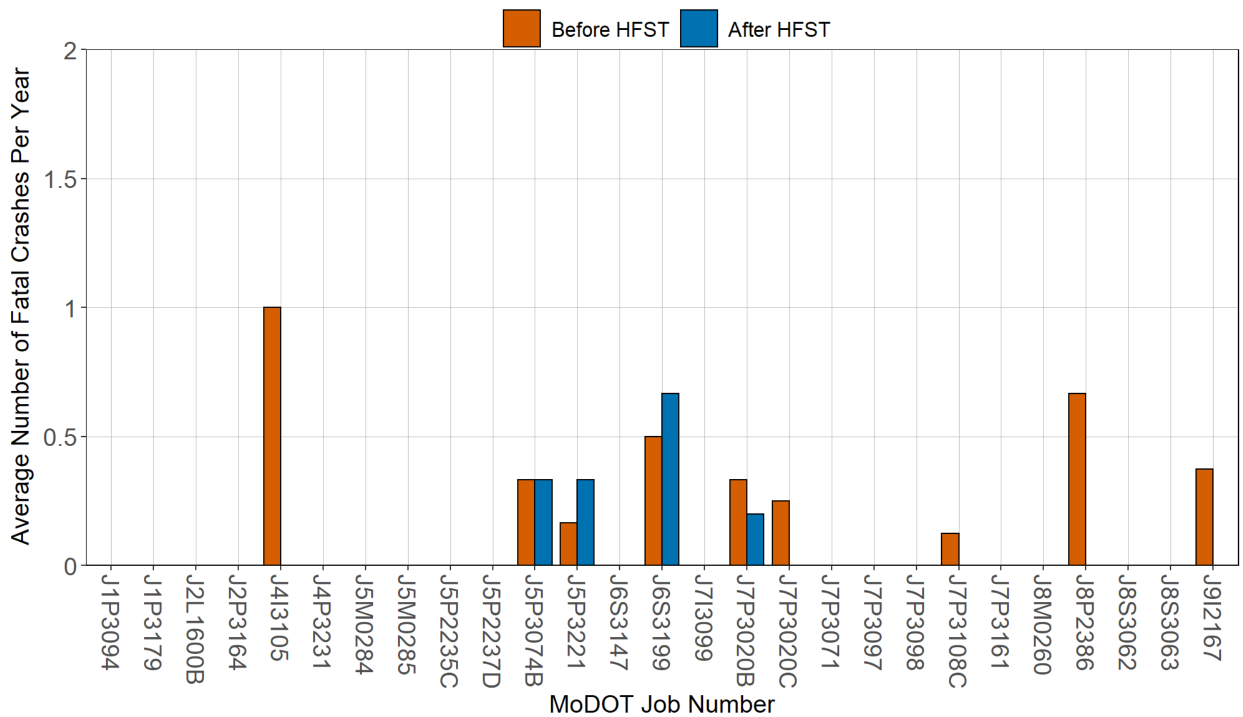

Figure 4.15. Average Number of Fatality Crashes Per Year Before and After HFST for Each Job Number

The BCA was carried out using the following procedure:

1. For each severity level and for each Job Number, the annual crash rate was multiplied by the respective crash cost in Table 4-4.
2. For each Job Number, the crash costs calculated in the previous step was summed over all severity levels to yield an overall total crash cost per year, annual crash costs per project.
3. The yearly benefit was calculated as the annual crash costs before HFST minus after HFST.
4. Assuming a typical service life of 7 years for the HFSTs, the total benefit was estimated as the yearly benefit multiplied by 7. The benefit-cost ratio (B/C) was obtained as the total benefit divided by the cost of HFST installation (shown previously in Table 4-1).

Figure 4.16 shows the side-by-side comparison of the yearly average crash cost before and after HFST installation, while the calculated benefit is shown in Figure 4.17. The BCA results are shown in Table 4-5 for each Job Number. The figure and table show that while the yearly benefit was positive (i.e., crash cost was reduced after HFST installation) for the majority of sections, a few sections exhibited negative benefit (i.e., higher crash cost after HFST installation). The Job Numbers with negative benefit are described in the following.

1. Job Numbers J5P3221 and J6S3199 showed crash reduction in all severity levels except for fatality. The negative benefit was caused by slightly higher number of average fatalities associated with a significantly higher crash cost.
2. Job Number J7P3161 exhibited higher PDO (Figure 4.12) and serious injury (Figure 4.16) crashes after HFST installation.
3. Similarly, Job Number J8S3063 exhibited higher serious injury crash after HFST (Figure 4.16).

Note that no fatalities occurred on the last two Job Numbers. As such, their negative benefit was due to the slightly higher serious injury crashes that occurred after HFST and higher crash cost associated with them.

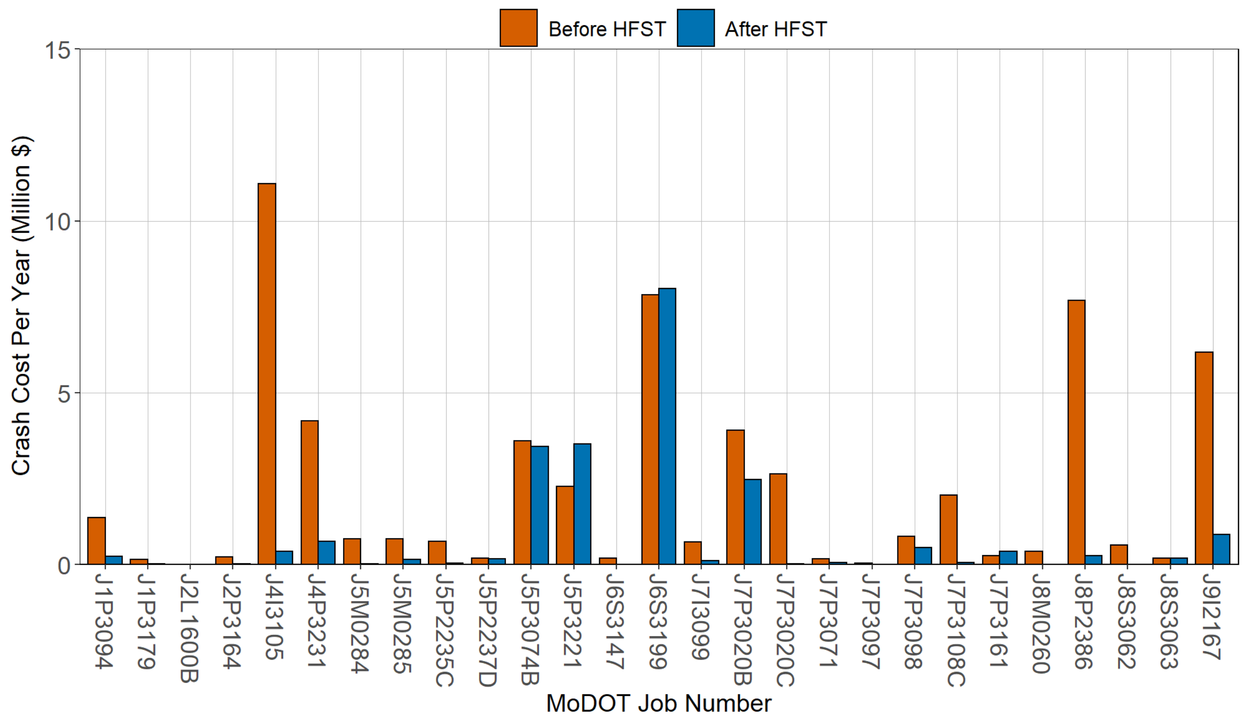

Figure 4.16. Average Crash Cost Per Year Before and After HFST for Each Job Number

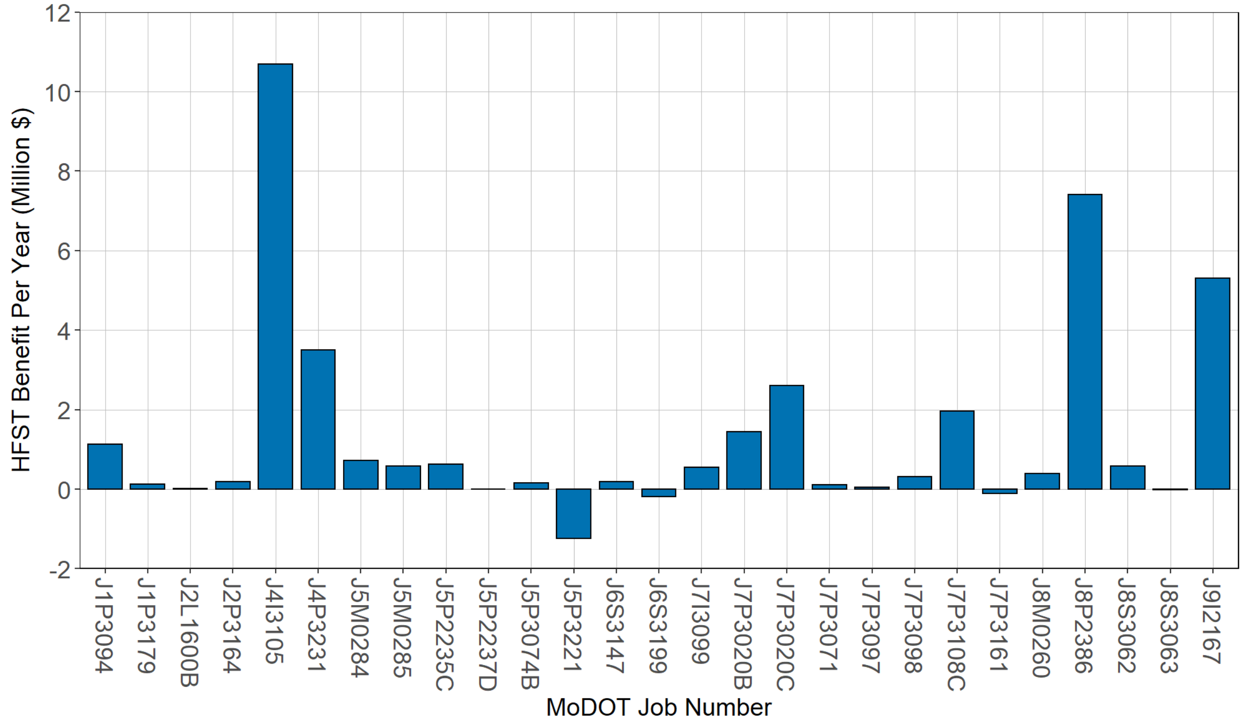

Figure 4.17. Average Benefit Per Year Before and After HFST for Each Job Number

It is noted that the sections with negative benefit (and hence negative B/C ratio) are concerning. However, evaluation of the individual locations over a short period of time, combined with the random nature of crashes may have caused a scatter of benefits. More specifically, the negative benefits were due to a slight increase (i.e., less than 1.0 crash per year) in high-severity crashes. Nevertheless, the cost associated with these crashes were significantly higher than the low-severity (PDO and minor injury) crashes and were responsible for the increased crash cost after HFST.

To sum up, the total cost of all HFST sections in Table 4-5 was calculated to be $4.6 million (for those that had the cost data available). The total benefit from the same sections was calculated to be $35.6 million per year and was further increased to $37.2 million per year when the negative benefits were removed. These numbers translated to an average, 7-year B/C ratio of 114.3 (including negative benefit) and 139.6 (without negative benefit). This clearly demonstrates that MoDOT's HFSTs exhibit a significant return on investment.

It is emphasized again that the results presented thus far, including the negative crash reduction and negative benefit, were all based on simple, observational crash counts before and after HFST. As noted in FHWA's HSIP manual (Herbal et. al., 2010), such a simple before/after evaluation is generally not recommended and the results from such analysis should be used with caution, due to the RTM bias and other simplifying assumptions.

Table 4-5. Before and After Crash Cost based on Simple, Average Crash Counts.

HFST Job Number	Average Crash Cost Per Year Prior to HFST Application (× $1,000)	Average Crash Cost Per Year After HFST Application (× $1,000)	B: Benefit Per Year (× $1,000)	C: Cost of HFST Application (× $1,000)	B/C: Benefit/Cost Ratio (Assuming 7 Years of HFST Life)
J1P3094	1,377	240	1,138	107	75
J1P3179	154	21	133	131	7
J2L1600B	11	0	11	56	1
J2P3164	224	32	192	187	7
J4I3105	11,078	392	10,687	103	723
J4P3231	4,178	677	3,501	158	155
J5M0284	744	21	723	N/A	N/A
J5M0285	745	161	584	N/A	N/A
J5P2235C	687	53	634	466	10
J5P2237D	182	178	3	164	0
J5P3074B	3,599	3,446	154	N/A	N/A
J5P3221	2,281	3,517	-1,235	236	-37
J6S3147	182	0	182	126	10
J6S3199	7,844	8,034	-190	658	-2
J7I3099	659	110	549	328	12
J7P3020B	3,917	2,474	1,443	164	62
J7P3020C	2,638	30	2,608	89	204
J7P3071	171	56	115	89	9
J7P3097	40	0	40	33	9
J7P3098	817	506	311	53	41
J7P3108C	2,024	63	1,961	514	27
J7P3161	268	381	-114	127	-6
J8M0260	388	0	388	108	25
J8P2386	7,684	270	7,413	41	1,261
J8S3062	578	4	574	45	89
J8S3063	182	196	-14	24	-4
J9I2167	6,188	888	5,300	562	66

5. SAFETY PERFORMANCE FUNCTION DEVELOPMENT

As discussed in the previous chapter, MoDOT's HFST sections showed great potential for reducing crashes and the associated cost. However, it was also noted in Section 3.2.2 above, that the direct comparison of before and after crash counts is generally not recommended due to the random nature of crashes as well as the other factors that affect crashes. Therefore, an effort was made to develop the Safety Performance Functions (SPF) based on the data made available to the research team. This chapter documents the process, results, and findings of the statistical SPF modeling.

5.1. BACKGROUND

For statistical modeling of crash counts, FHWA and AASHTO recommend the use of SPF as well as the Negative Binomial (NB) and Empirical Bayes (EB) methods (Hauer et. al., 2002; Srinivasan and Bauer, 2013). Recall that the SPF in its most basic form is given as the following equation (Srinivasan and Bauer, 2013).

$$\mu = L \cdot e^{\beta_0 + \beta_1 \cdot \ln(AADT) + \sum \beta_i \cdot X_i} \tag{8}$$

where μ is the expected number of crashes, L is the segment length, $AADT$ is the annual average daily traffic, β_0, β_1, and β_i are regression coefficients, and X_i's are additional variables that may be used for developing the model.

Generally speaking, the above SPF should be developed based on a large amount of data, typically collected from an Agency's network level data. While it is possible to develop a generalized SPF based on MoDOT's network level data, such an approach was not pursued. The primary reason behind this is that MoDOT does not conduct pavement friction testing for inventory purposes, i.e., the network level pavement friction data is not available, and the generalized SPF will have to be developed without friction information.

Since the primary purpose of HFST is to improve the surface friction of existing roadways, an initial attempt was made to develop the SPF based on MoDOT's HFST sections from which the before and after FN values were available.

5.2. GENERALIZED SAFETY PERFORMANCE FUNCTION

The primary objective of developing a generalized SPF was to understand the effect of FN as well as other pavement, roadway, and environmental factors on the number of crashes. The following variables were made available from the integrated database for this purpose:

- Pavement Variables
  - Friction Number (FN)
  - Pavement Condition Rating
  - Rut Depth (in inches)

- International Roughness Index (IRI, in in/mi)
    - Type of Pavement Surface Before HFST (Portland Cement Concrete [PCC] vs. Asphalt Concrete [AC])
- Roadway Variables
    - AADT (2-Way)
    - HFST Treatment Length (in miles)
    - Speed Limit (in mph)
    - Roadway Curvature (Length, Radius, and Angle)
- Environmental Variables
    - Lighting Condition (Daylight vs. Dark)
    - Condition of Pavement Surface (Wet vs. Dry)

As discussed in the previous chapter, higher number of crashes were observed on wet pavement surfaces than on dry surfaces before HFST installation (Figure 4.9). However, the trend reversed after HFST installation and higher number of crashes were observed on dry pavement surfaces than on wet surfaces. Due to the significantly higher crash reduction achieved on wet pavement surfaces, the generalized SPFs were developed separately for wet and dry pavement surfaces.

5.2.1. Generalized SPF for Total Number of Crashes

As the purpose of the initial SPF was to incorporate FN as an independent variable in Equation (8), it was developed using the data from 8 HFST sections from which the before and after FN values were available (Figure 4.5). Due to the limited amount of crash data from these sections, all available crashes were taken into account during the development of SPF. However, the roadway curvature data (e.g., curve radius) was not applicable to the crashes that occurred on tangent (i.e., straight) roadway segments. As such, the SPF was modeled by introducing a categorical variable (i.e., on curve vs tangent section) rather than eliminating the crashes from tangent segments.

Mathematically, the SPF with the necessary independent variables is written in terms of an exponential function given as the following.

$$\mu = L^{\beta_l} \cdot e^{\beta_0 + \beta_a \cdot \ln(AADT) + \beta_f \cdot FN + f(\beta)} \tag{9}$$

in which the function $f(\beta)$ is written as:

$$f(\beta) = \beta_s \cdot Speed + \beta_i \cdot IRI + \beta_r \cdot Rut + \beta_p \cdot Pavt.Condition + \beta_{Surface.Type} + \beta_{On.Curve} + \beta_{Light.Condition} \tag{10}$$

Using the R statistical package, NB regression was carried out to fit the above function to the data in the integrated database (see Appendix A for the R summary reports). Table 5-1 highlights the significant variables from the regression along with the p-values associated with each of the variables, while Table 5-2 and Table 5-3 show the coefficients determined for Equations (9) and (10). Table 5-1 also highlights the variables that were determined to have a significant effect on crash counts, based on a significance level of 0.05 (i.e., a p-value of less than 0.05 indicates that the variable has a significant effect on the dependent variable – the crash counts).

As an example of interpreting the coefficients for a numerical variable, the p-value corresponding to segment length was found to be less than 0.05 for crashes on both dry and wet pavement surfaces (Table 5-1), indicating that it is a statistically significant factor. Furthermore, the NB coefficients for the segment length (Table 5-2) were found to be positive for both conditions (dry and wet surfaces). The positive coefficient implies that higher number of crashes are to be expected if the segment length is increased, as expected.

On the other hand, the p-values for two of the categorical variables, namely "On Curve" and "Lighting Condition" were all found to be less than 0.05 (Table 5-1), meaning they are both statistically significant for crashes on dry and wet pavement surfaces. In addition, the "On Curve" coefficients in Table 5-3 indicates that the coefficients are negative for tangent segments – which indicates that less crashes are to be expected on tangent segments than on curved segments.

Table 5-1. Significant Variables from NB Regression [Eq. (9) and (10)]

Variable Category	Variable	Significant Variables* (p-value) for Dry Weather	Significant Variables* (p-value) for Wet Weather
N/A	Intercept	S (6.7e-04)	NS (0.819)
Pavement	Friction (FN)	NS (0.090)	S (4.9e-08)
Pavement	Condition Rating	NS (0.655)	NS (0.308)
Pavement	Rut Depth	S (0.017)	NS (0.439)
Pavement	IRI	NS (0.497)	NS (0.119)
Pavement	Existing Surf. Type	NS (0.639)	NS (0.465)
Roadway	AADT	S (6.9e-06)	NS (0.264)
Roadway	Treatment Length	S (1.9e-11)	S (6.1e-05)
Roadway	Speed Limit	S (0.018)	NS (0.079)
Roadway	On Curve	S (0.019)	S (0.014)
Environmental	Lighting Condition	S (1.1e-06)	S (2.5e-05)

Note*: S = Significant Factor, NS = Not Significant Factor, based on significance level of 0.05.

Table 5-2. NB Coefficients for Numerical Variables [Eq. (9) and (10)]

Coefficient	Related Variable	Dry	Wet
β_0	Intercept	7.349	-0.994
β_f	Friction (FN)	-0.007	-0.033
β_p	Condition Rating	0.047	0.207
β_r	Rut Depth	3.644	2.471
β_i	IRI	0.002	0.010
β_a	AADT	-0.594	0.273
β_l	Treatment Length	1.113	1.249
β_s	Speed Limit	-0.032	-0.040

Table 5-3. NB Coefficients for Categorical Variables [Eq. (9) and (10)]

Coefficient	Related Variable	Value of Variable	Dry	Wet
$\beta_{Surface.Type}$	Existing Surf. Type	AC	0.000	0.000
$\beta_{Surface.Type}$	Existing Surf. Type	PCC	-0.259	0.587
$\beta_{On.Curve}$	On Curve	Curve	0.000	0.000
$\beta_{On.Curve}$	On Curve	Tangent	-0.416	-0.677
$\beta_{Light.Condition}$	Lighting Condition	Daylight	0.000	0.000
$\beta_{Light.Condition}$	Lighting Condition	Dark	-0.815	-1.112

Table 5-1 shows that FN was only found to have a significant effect on crashes occurring on wet pavement surfaces. However, it does not mean that the FN has no effect on dry weather crashes. Said differently, these results only mean that the FN improvements achieved by HFSTs may be more effective in reducing wet weather crashes than dry weather crashes. To demonstrate the effect of FN on crash counts, Equations (9) and (10) were used to predict the expected number of crashes by varying the FN from 20 to 100 while all other variables were fixed. Figure 5.1 shows these results for both dry and wet weather crashes. Clearly, the figure shows that wet weather crashes are more sensitive to FN than dry weather crashes. According to Table 5-1, other factors such as AADT and speed limit were found to have a more pronounced effect (than FN) on dry weather crashes.

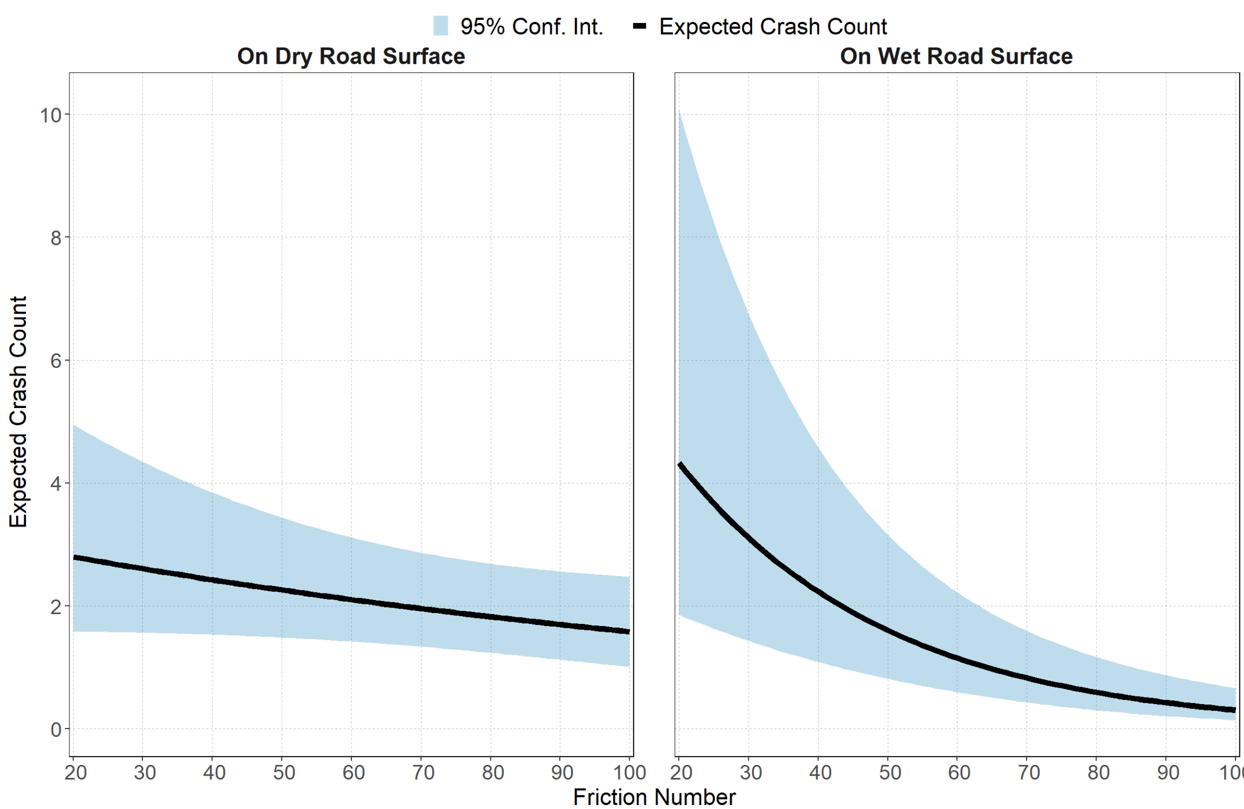

Figure 5.1. FN versus Expected Crash Counts for Total Crashes

5.2.2. Generalized SPF for Curved Roadways

As discussed previously, the NB model for total number of crashes (Equations (9) and (10)) indicated that more crashes are to be expected on curved roadway segments than on tangent segments. Therefore, it was also of interest to determine if any of the curve related factors (i.e., curve radius, length, and angle) had any significant effect on the expected number of crashes. As such, another SPF was fitted using a subset of the crashes that occurred on curves. For this purpose, the general SPF model remained the same as Equation (9), but the function $f(\beta)$ was modified to include the curve related inputs.

$$
\begin{aligned}
f(\beta) = {} & \beta_s \cdot Speed + \beta_i \cdot IRI + \beta_r \cdot Rut + \beta_p \cdot Pavt.Condition \\
& + \beta_{Surface.Type} + \beta_{Light.Condition} \\
& + \beta_{cl} * Curve.Length + \beta_{cr} * Curve.Radius + \beta_{ca} * Curve.Angle
\end{aligned} \tag{11}
$$

Table 5-4 through Table 5-6 show the results of NB modelling. Table 5-4 indicates that statistically, FN only had a significant effect on wet weather crashes. The curve related factors were all determined to have insignificant effect on wet weather crashes. Roughly speaking, this may indicate that FN is mostly crucial for wet weather crashes on curved roadways.

For dry weather crashes, the FN was again found to have an insignificant effect. However, other factors including the curve length and curve radius, as well as the pavement condition (condition rating, rut, and IRI) were found to influence dry weather crashes occurring on curved roadways.

Figure 5.2 shows the expected number of crashes on curved roadways as a function of FN. Again, the figure shows that wet weather crashes are more sensitive to FN than dry weather crashes.

Table 5-4. Significant Variables from NB Regression [Eq. (9) and (11)]

Variable Category	Variable	Significant Variables* (p-value) for Dry Weather	Significant Variables* (p-value) for Wet Weather
N/A	Intercept	S (0.001)	S (0.033)
Pavement	Friction (FN)	NS (0.253)	S (3.73E-08)
Pavement	Condition Rating	S (0.012)	NS (0.109)
Pavement	Rut Depth	S (1.56E-04)	NS (0.224)
Pavement	IRI	S (0.001)	NS (0.277)
Pavement	Existing Surf. Type	NS (0.070)	S (0.015)
Roadway	AADT	S (0.006)	NS (0.211)
Roadway	Treatment Length	S (5.05E-06)	S (0.001)
Roadway	Speed Limit	S (1.48E-05)	S (0.004)
Roadway	Curve Length	S (3.77E-04)	NS (0.305)
Roadway	Curve Radius	S (1.92E-08)	NS (0.073)
Roadway	Curve Angle	NS (0.634)	NS (0.074)
Environmental	Lighting Condition	S (1.43E-06)	S (1.48E-05)

Note*: S = Significant Factor, NS = Not Significant Factor, based on a significance level of 0.05.

Table 5-5. NB Coefficients for Numerical Variables [Eq. (9) and (11)]

Coefficient	Related Variable	Dry	Wet
β_0	Intercept	12.838	16.382
β_f	Friction (FN)	-0.005	-0.037
β_p	Condition Rating	0.380	0.513
β_r	Rut Depth	6.887	5.228
β_i	IRI	-0.021	-0.013
β_a	AADT	-0.616	-0.547
β_l	Treatment Length	1.201	1.572
β_s	Speed Limit	-0.145	-0.198
β_{cl}	Curve Length	-0.002	-0.001
β_{cr}	Curve Radius	0.001	0.001
β_{ca}	Curve Angle	0.003	-0.024

Table 5-6. NB Coefficients for Categorical Variables [Eq. (9) and (11)]

Coefficient	Related Variable	Value of Variable	Dry	Wet
$\beta_{Surface.Type}$	Existing Surf. Type	AC	0.000	0.000
$\beta_{Surface.Type}$	Existing Surf. Type	PCC	1.678	3.538
$\beta_{Light.Condition}$	Lighting Condition	Daylight	0.000	0.000
$\beta_{Light.Condition}$	Lighting Condition	Dark	-0.802	-1.207

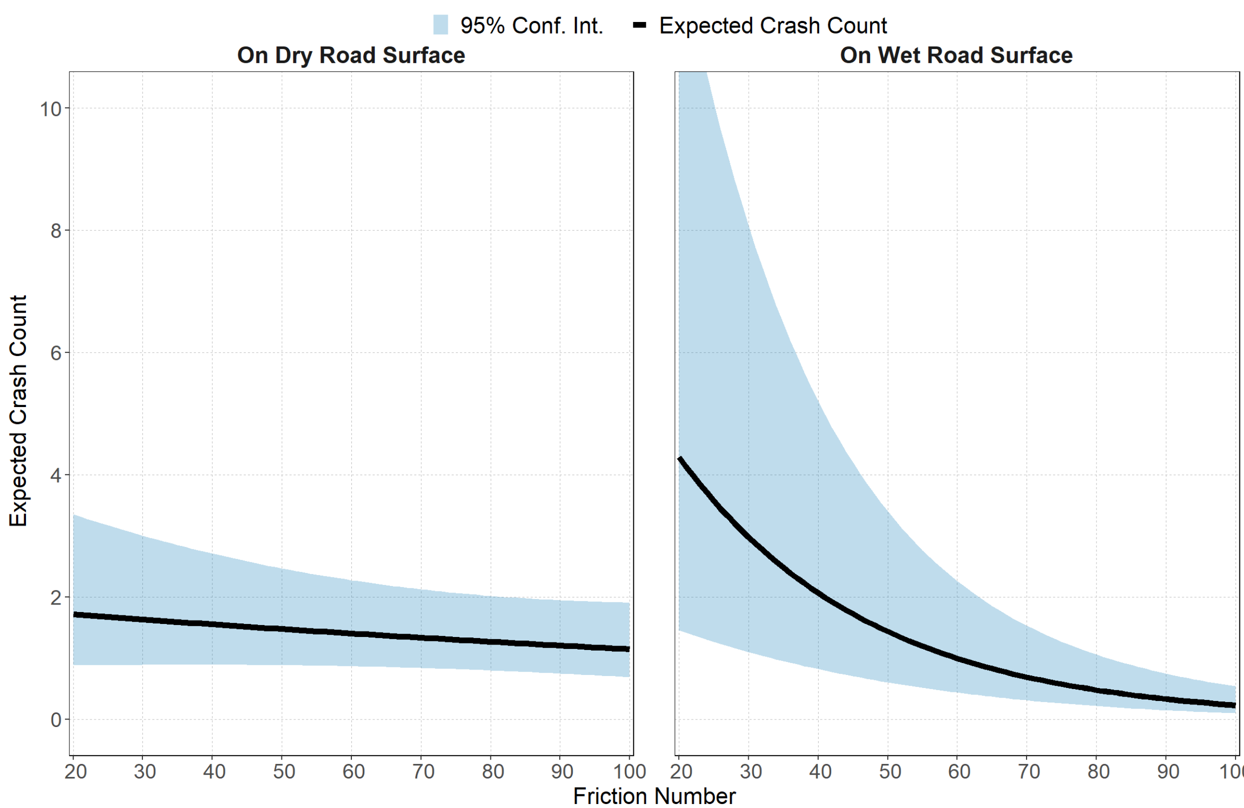

Figure 5.2. FN versus Expected Crash Counts for Crashes on Curved Roadways

5.2.3. Generalized SPF for Tangent Roadways

Similar to the development of the SPF for curved roadways, another set of SPFs were developed for tangent roadway segments to determine the factors that significantly affects the crash counts. Again, the general SPF model remained the same as Equation (9), but the function $f(\beta)$ was modified to exclude all curve related inputs.

$$f(\beta) = \beta_s \cdot Speed + \beta_i \cdot IRI + \beta_r \cdot Rut + \beta_p \cdot Pavt.Condition + \beta_{lc} * Light.Condition \quad (12)$$

Table 5-7 through Table 5-9 show the results of NB modelling while Figure 5.3 shows the expected number of crashes as a function of FN. These results generally indicate that from a statistics point of view, FN is not a significant factor for crashes occurring on tangent segments.

It is also noted that the crash data used for developing the SPF for tangent segments with FN, was very limited (e.g., referring to Table 4-2, only 100 dry weather crashes and 31 wet weather crashes were available for after HFST condition). Development of a more general SPF from using a large set of data is recommended for a better understanding of the factors affecting crashes.

Table 5-7. Significant Variables from NB Regression [Eq. (9) and (12)]

Variable Category	Variable	Significant Variables* (p-value) for Dry Weather	Significant Variables* (p-value) for Wet Weather
N/A	Intercept	NS (0.330)	NS (0.306)
Pavement Variables	Friction (FN)	NS (0.962)	NS (0.290)
	Condition Rating	NS (0.221)	NS (0.492)
	Rut Depth	NS (0.083)	NS (0.236)
	IRI	NS (0.837)	S (0.019)
Roadway Variables	AADT	NS (0.206)	NS (0.354)
	Treatment Length	S (6.24E-05)	NS (0.105)
	Speed Limit	NS (0.514)	NS (0.655)
Environmental Variables	Lighting Condition	S (0.002)	NS (0.278)

Note*: S = Significant Factor, NS = Not Significant Factor, based on a significance level of 0.05.

Table 5-8. NB Coefficients for Numerical Variables [Eq. (9) and (12)]

Coefficient	Related Variable	Dry	Wet
β_0	Intercept	3.698	-13.132
β_f	Friction (FN)	3.53E-04	-0.016
β_p	Condition Rating	-0.219	0.313
β_r	Rut Depth	5.332	-20.890

β_i	IRI	-0.001	0.047
β_a	AADT	-0.400	0.825
β_l	Treatment Length	1.078	1.296
β_s	Speed Limit	0.019	0.021

Table 5-9. NB Coefficients for Categorical Variables [Eq. (9) and (12)]

Coefficient	Related Variable	Value of Variable	Dry	Wet
$\beta_{Light.Condition}$	Lighting Condition	Daylight	0.000	0.000
$\beta_{Light.Condition}$	Lighting Condition	Dark	-0.899	-0.530

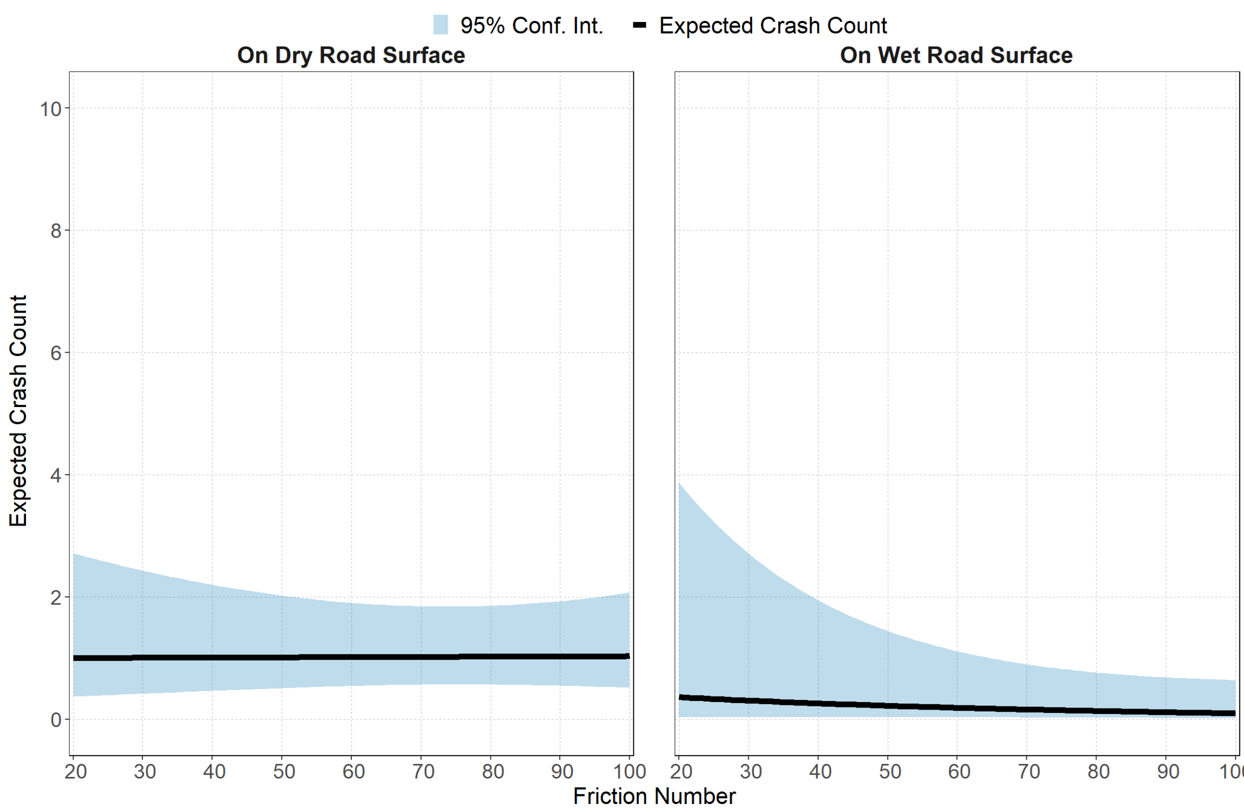

Figure 5.3. FN versus Expected Crash Counts for Crashes on Tangent Roadways

5.2.4. <u>Practical Application of Generalized SPF</u>

It is understood that Equations (9) through (12) may seem cumbersome to use due to the large number of variables and coefficients associated with them. Furthermore, not all of the independent variables may be available for MoDOT's immediate evaluation of these equations.

It is noted again that the SPF shown in Equations (9) through (12) were developed based on the limited crash data from MoDOT's HFST sections, not necessarily from the entire roadway network. In other words, these SPFs were developed for the change of installing HFST. As such, they should not be used for estimating the crashes for curves and/or tangents in general, but rather the reduction in crashes for installing HFST on curves or tangents. Owing to the exponential form of the SPF and with some additional simplifying assumptions, such a simple evaluation of before and after crash counts can be made relatively easily, as demonstrated below.

Consider a roadway where a large number of crashes were observed. Assuming all variables were available, let FN_{before} and μ_{before} be the existing friction number and the expected crash count calculated from Equation (9) for this roadway, respectively. Also assume that if this roadway is treated with HFST, an increased friction number of FN_{after} is produced but all other variables (e.g., AADT, IRI, etc.) remain unchanged. Then, the expected crash count after HFST is calculated to be μ_{after} from Equation (9). Then, taking the ratio between μ_{before} and μ_{after} results in the following equation:

$$\frac{\mu_{after}}{\mu_{before}} = e^{\beta_f \cdot \left(FN_{after} - FN_{before}\right)} \tag{13}$$

since all other unchanged variables in the exponential function cancel out. Using the β_f coefficient for wet weather (Table 5-2), the above equation can be rewritten as:

$$\frac{\mu_{after}}{\mu_{before}} = e^{-0.033 \cdot \left(FN_{after} - FN_{before}\right)} \tag{14}$$

which is a simple exponential function of friction numbers that produce a ratio of wet weather crash counts before and after HFST.

Finally, if an HFST improved the surface friction from FN_{before} value of 35 to an FN_{after} of 75 (while all other variables remain unchanged), the right-hand-side of Equation (14) is calculated to be 0.27. Therefore, it is expected that the HFST may reduce the wet weather crashes by a rough factor of 0.27 (or equivalently, a 73 percent reduction). Similarly, if the β_f coefficient for dry weather (equal to -0.007 in Table 5-2) is used in Equation (13), an expected dry weather crash ratio of 0.76 (i.e., 24 percent reduction in dry weather crashes) is obtained.

5.3. BASIC SAFETY PERFORMANCE FUNCTION

In the previous section of the report, the SPFs were developed for different conditions and an example was provided for practical application of these SPFs. Although these SPFs including most of the available variables (including FN as a continuous variable) may be useful, it was already recognized that many of MoDOT's HFST sections did not have the FN data available (Figure 4.5). Therefore, the generalized SPFs presented previously were all developed based on limited data and cannot be used for all HFST sections available for this study. Furthermore, the generalized SPFs could not be developed for different crash severities due to the lack of data.

In order to account for the crashes from all HFST sections and for different crash severities, a set of more simple and basic SPFs were developed herein. These SPFs were developed using a limited set of independent variables including the following:

- Pavement Variables
  - Before or After HFST
- Roadway Variables
  - AADT (2-Way)
  - HFST Treatment Length (in miles)
  - Speed Limit (in mph)

Note that the FN is not an independent variable in the above. Instead, the crashes on the HFST sections were categorized as before or after HFST installation. The mathematical form of the SPF is given as the following.

$$\mu = L^{\beta_l} \cdot e^{\beta_0 + \beta_a \cdot \ln(AADT) + \beta_{Before.After} + f(\beta) + \beta_s \cdot Speed} \tag{15}$$

The results of SPF fitting are shown in Table 5-10 through Table 5-12 for all crash severities. Table 5-10 indicates that all of the independent variables were found to be significant for minor injury and PDO crashes. On the other hand, none of the variables were found to have a significant effect on fatalities, which could be a result of not having enough number of fatalities in the crash data. Nonetheless, the before coefficient for fatality was found to be positive (equal to 0.636) which indicates that more fatalities would occur before HFST treatment.

Table 5-10. Significant Variables from NB Regression [Eq. (15)]

Crash Severity	Variable Category	Variable	Significant Variables* (p-value)
Fatality	N/A	Intercept	NS (0.161)
Fatality	Pavement	Before or After	NS (0.285)
Fatality	Roadway	AADT	NS (0.185)
Fatality	Roadway	Treatment Length	NS (0.508)
Fatality	Roadway	Speed Limit	NS (0.345)
Serious Injury	N/A	Intercept	NS (0.657)
Serious Injury	Pavement	Before or After	S (0.004)
Serious Injury	Roadway	AADT	NS (0.567)
Serious Injury	Roadway	Treatment Length	S (2.1e-04)
Serious Injury	Roadway	Speed Limit	S (0.005)
Minor Injury	N/A	Intercept	NS (0.052)
Minor Injury	Pavement	Before or After	S (1.6E-14)
Minor Injury	Roadway	AADT	S (2.0E-04)
Minor Injury	Roadway	Treatment Length	S (0.027)
Minor Injury	Roadway	Speed Limit	S (7.2E-09)
PDO	N/A	Intercept	S (1.9E-07)
PDO	Pavement	Before or After	S (<2.0E-16)
PDO	Roadway	AADT	S (<2.0E-16)
PDO	Roadway	Treatment Length	S (9.5E-07)

PDO	Roadway	Speed Limit	S (<2.0E-16)

Note*: S = Significant Factor, NS = Not Significant Factor, based on significance level of 0.05.

Table 5-11. NB Coefficients for Numerical Variables [Eq. (15)]

Coefficient	Related Variable	Fatality Crashes	Serious Injury Crashes	Minor Injury Crashes	PDO Crashes
β_0	Intercept	-4.730	0.744	-1.915	-2.865
β_a	AADT	-0.420	-0.088	0.343	0.511
β_l	Segment Length	-0.244	0.697	0.221	0.254
β_s	Speed Limit	0.043	-0.052	-0.059	-0.045

Table 5-12. NB Coefficients for Categorical Variables [Eq. (15)]

Coefficient	Related Variable	Value of Variable	Fatality Crashes	Serious Injury Crashes	Minor Injury Crashes	PDO Crashes
$\beta_{Before.After}$	Before or After HFST	Before	0.636	0.828	1.248	0.835
$\beta_{Before.After}$	Before or After HFST	After	0.000	0.000	0.000	0.000

Figure 5.4 shows a comparison of the expected crash counts (per year per mile) for different crash severities obtained using the fitted SPF. Clearly, the results show that the expected crashes increase from high-severity to low-severity crashes, and HFSTs are expected to decrease the crashes of all severities. Figure 5.5 shows the expected crash cost (before and after HFST) expected crash counts, while Figure 5.6 shows the expected benefit calculated from the crash costs (i.e., before cost – after cost). These figures indicate that while PDO crashes constitute the largest portion of the crash counts, the benefit is relatively minimal due to the low crash cost associated with them (see Table 4-4). On the other hand, while fatality is the most expensive crash type, the benefit was lower than the injury crashes due to the minimal expected crash count. Considering both the crash counts and crash costs, the most significant benefit was expected to be gained from minor injury crashes followed by serious injury crashes.

Figure 5.4. Expected Crash Counts from Basic SPF Model

Figure 5.5. Expected Crash Cost from Basic SPF Model

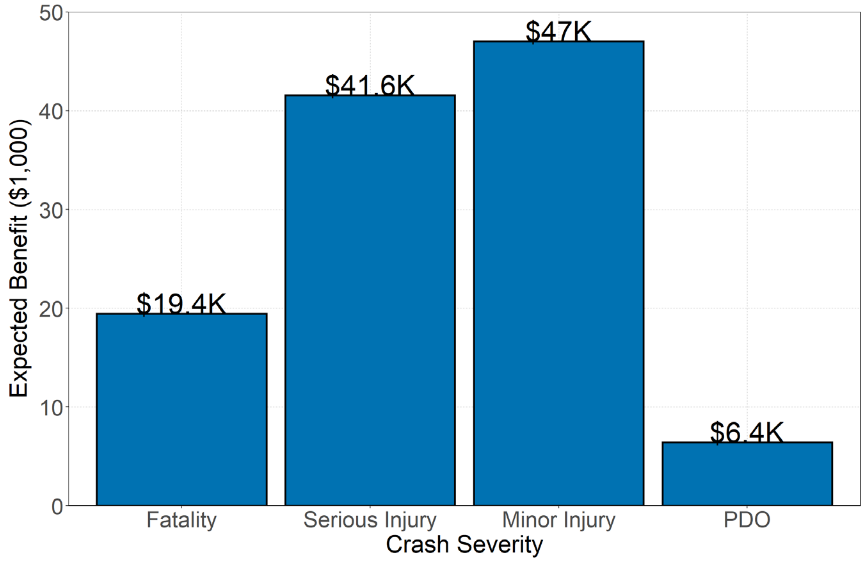

Figure 5.6. Expected Benefit from Basic SPF Model

5.3.1. <u>Practical Application of Basic SPF</u>

Similar to the generalized SPF discussed previously, application of the basic SPFs be limited to evaluation of a rough estimate of the expected crash reduction due to HFSTs (and should not be used for network level crash analysis). As such, these SPFs should only be used for estimating the benefit that may be gained by installing HFST over an area that has been identified to show high crash rates. Evaluation of before and after crash counts using the basic SPFs is straight-forward, as demonstrated below.

Consider a roadway where a large number of crashes were observed and an HFST is scheduled to be installed. Assuming all other variables (i.e., AADT and Speed Limit) remain unchanged before and after the HFST, the ratio between the expected crash count after HFST (μ_{after}) and before HFST (μ_{before}) is simply obtained as the following:

$$\frac{\mu_{after}}{\mu_{before}} = e^{\beta_{after} - \beta_{before}} \tag{16}$$

since all other variables in the SPF (i.e, Equation (15)) cancel out. Moreover, since all β coefficients for the after condition are equal to zero (Table 5-12), the above equation is further simplified as:

$$\frac{\mu_{after}}{\mu_{before}} = e^{-\beta_{before}} \tag{17}$$

Equation (17) allows for a quick and simple evaluation of the expected crash reduction for different severities. Table 5-13 shows the crash ratio (from Equation (17)) and the corresponding percent crash reduction calculated for different crash severities (i.e., using the β coefficients in Table 18).

Table 5-13. Estimated Crash Reduction from Basic SPF

Variable	Fatality Crashes	Serious Injury Crashes	Minor Injury Crashes	PDO Crashes
Crash Ratio $\left(\mu_{after} / \mu_{before}\right)$	0.53	0.44	0.29	0.43
Percent Reduction in Crash	47	56	71	57

5.4. EMPIRICAL BAYES METHOD

As described previously, FHWA recommends that the NB regression results be integrated with the observed number of crashes through the use Empirical Bayes (EB) method for estimating the statistically expected crash counts (Herbal et. al., 2010). It is recalled that the EB estimate is essentially a weighted mean of the expected crash counts (from SPF) and the observed crash counts (see Equations (6) and (7)).

To demonstrate an example of the EB counts, Figure 5.7 through Figure 5.10 show the crash counts (Observed, SPF prediction from Equation (15), and EB estimate from Equation (6)) for different crash severities on Job Number J5P2235C (which corresponds to IS44E in Phelps County from Log Mile 189.097 to 189.930 which includes two horizontal curves: one with a length of 1,534 ft. and radius 5,046 ft., the other with a length of 1,219 ft. and radius of 3,497 ft.). These figures show that the crashes at all levels are expected to decrease after HFST installation.

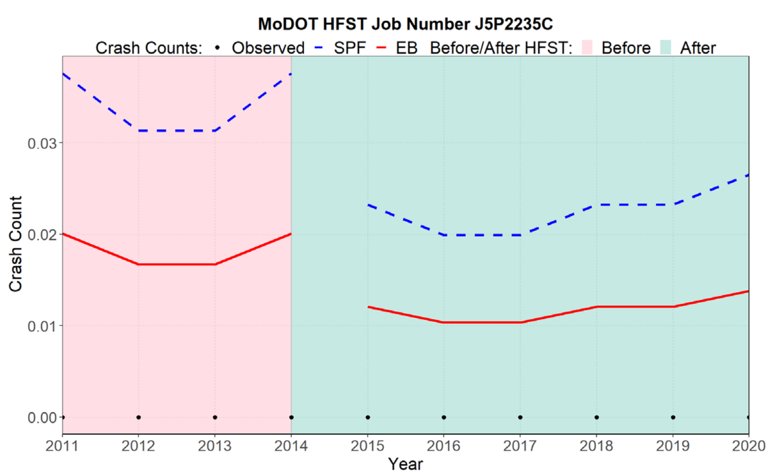

Figure 5.7. Observed Counts, SPF Predictions, and EB Counts for Fatality Crashes on HFST Job Number J5P2235C

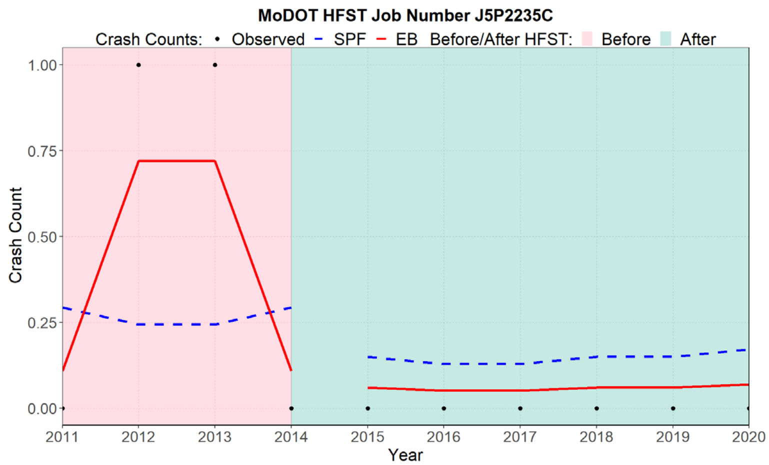

Figure 5.8. Observed Counts, SPF Predictions, and EB Counts for Serious Injury Crashes on HFST Job Number J5P2235C

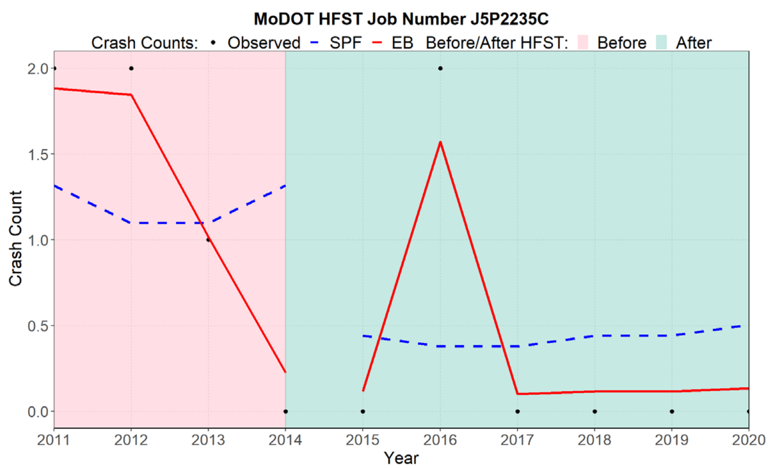

Figure 5.9. Observed Counts, SPF Predictions, and EB Counts for Minor Injury Crashes on HFST Job Number J5P2235C

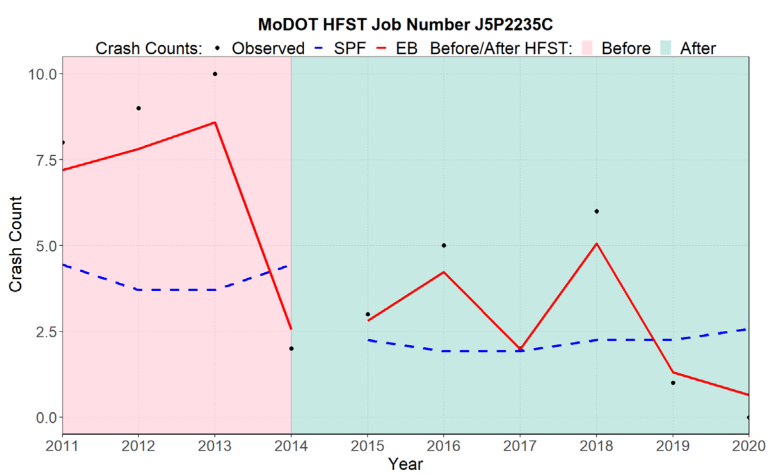

Figure 5.10. Observed Counts, SPF Predictions, and EB Counts for PDO Crashes on HFST Job Number J5P2235C

The EB counts similar to the above example were obtained for all 27 HFST Job Numbers. Then, the EB estimates for different severities were summed to yield the EB estimate for total crash counts. Finally, the total crash counts per year were averaged for different years to produce the average, before and after EB crash counts (per year per mile) for each Job Number. These results are shown in Figure 5.11.

Figure 5.11 shows that all HFST sections are expected to reduce crashes, with the reduction ranging from 13.7 percent to 79.5 percent. In addition, this figure does not show any sections with negative crash reduction (i.e., increase in crashes after HFST installation).

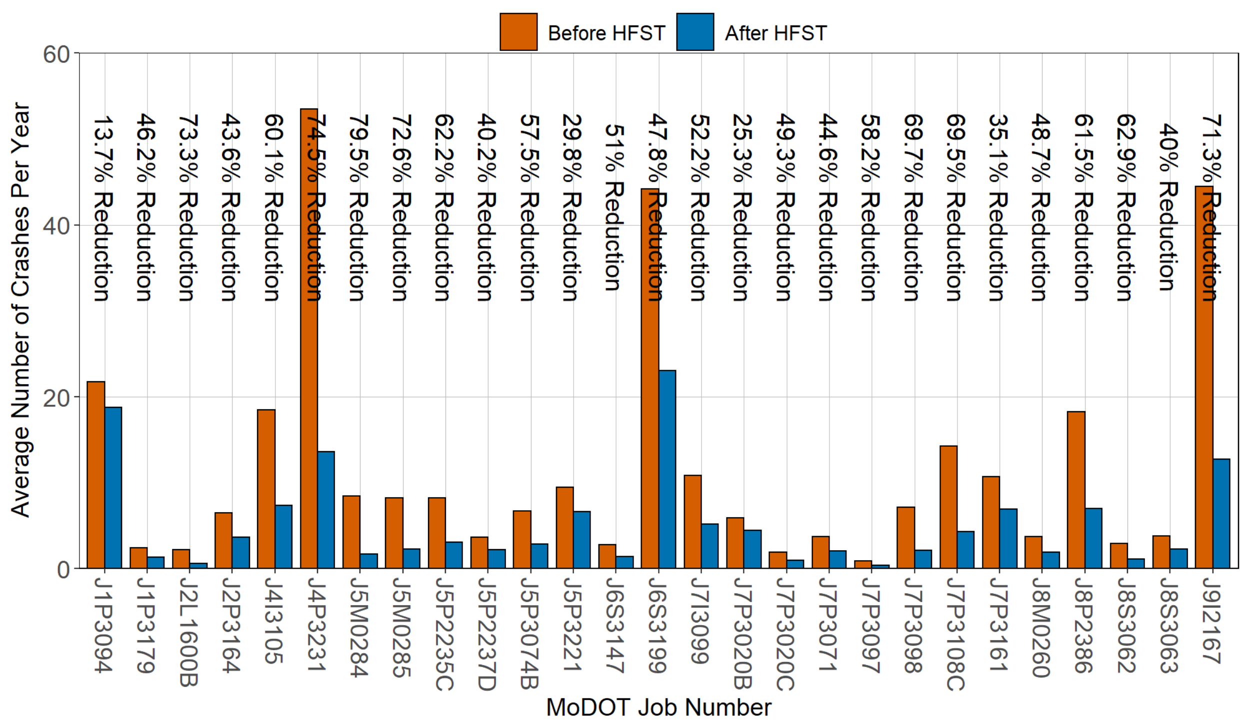

Figure 5.11. EB Based Average Crashes Per Year Before and After HFST for Each Job Number

5.5. BENEFIT-COST ANALYSIS BASED ON EMPIRICAL BAYES METHOD

The Benefit-Cost Analysis (BCA) previously conducted based on simple before and after HFST crash counts generally indicated that MoDOT's HFST sections are effective in reducing crashes. However, the simple crash counts for a few sections showed minor increases after HFST, which also led to an increase in crash cost (i.e., negative benefit). It is believed that such increase in crash counts and crash costs are due to the random nature of crashes which is inherent to the raw crash counts, and a better indicator of the true benefit may be obtained by taking the average crash counts into account (i.e., EB method).

On the other hand, although the degree of reduction varied from one job to another, the EB-based crash counts shown in the previous section indicated that all HFST sections showed a reduction in crash counts. It is believed that such a consistent reduction in crash counts is a consequence of the EB method effectively eliminating the RTM bias, which may lead to a better estimate of the benefit gained by HFSTs. As such, the BCA has been conducted again using the EB-based crash counts (as opposed to the observed, simple crash counts).

Figure 5.12 shows the side-by-side comparison of EB-based average crash costs (per year) before and after HFST installation, while Figure 5.13 shows the corresponding benefit. The BCA results (assuming 7 years of HFST life) are shown in Table 5-14 for each Job Number. The total cost of all HFST sections in was calculated to be $4.6 million (which remained unchanged from the preliminary analysis) and the total benefit was calculated to be $25.1 million per year. From these numbers, the average 7-year B/C ratio was obtained to be 60.8. On a project by project basis, the 7-year B/C ratio showed a relatively wide range, from 2.3 to 409.1.

It should be noted that the above B/C ratio of 60.8 is lower than the average B/C ratio of 114.3 previously obtained from simple before/after crash counts. This is due to the EB method pulling the observed crash counts towards the SPF prediction to remove the RTM bias (which in most cases, resulted in reduced crash counts). Nevertheless, this B/C ratio clearly justifies the effectiveness of MoDOT's HFST application.

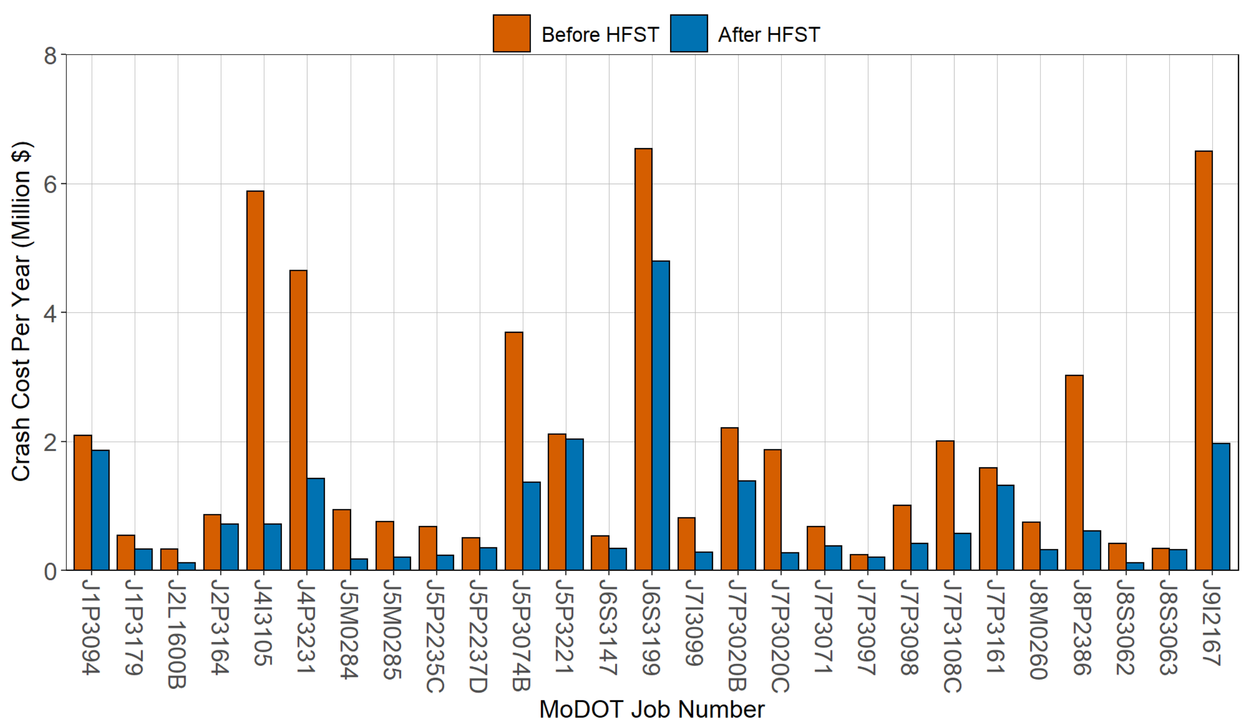

Figure 5.12. EB-Based Average Crash Cost Per Year Before and After HFST for Each Job Number

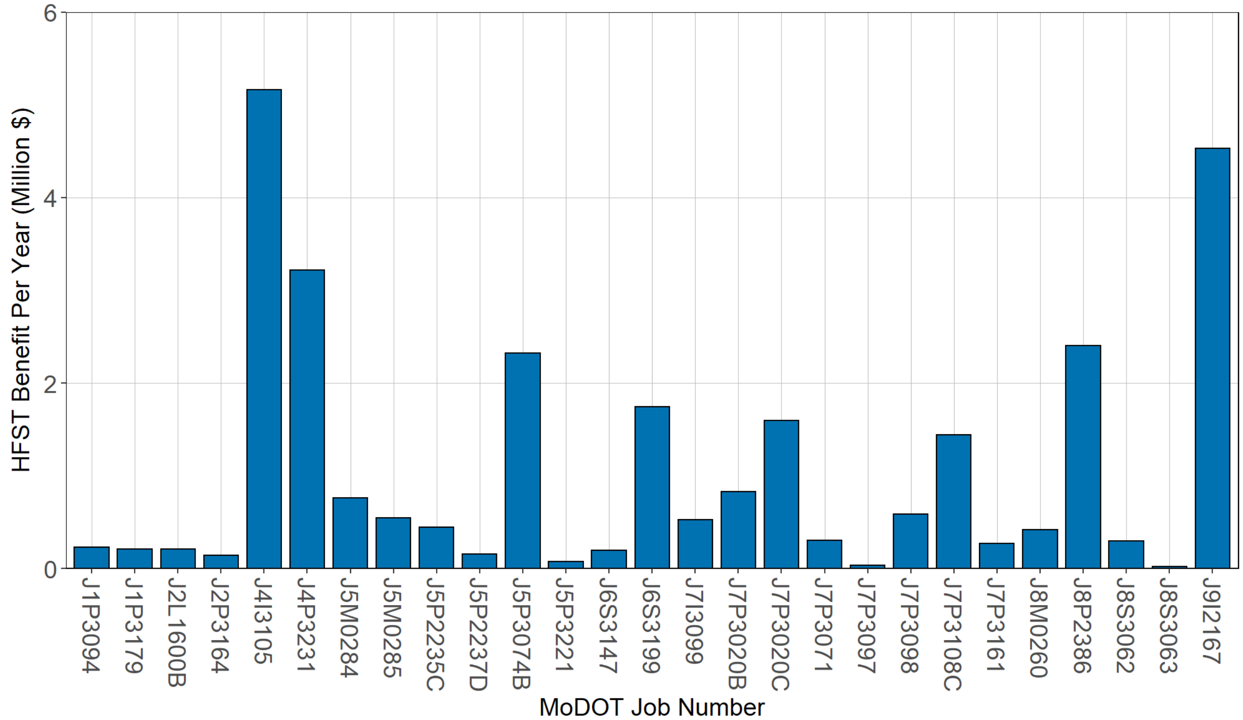

Figure 5.13. EB-Based Average Benefit Per Year Before and After HFST for Each Job Number

Table 5-14. Before and After Crash Cost based on Empirical Bayes Crash Counts.

HFST Job Number	Average Crash Cost Per Year Prior to HFST Application (× $1,000)	Average Crash Cost Per Year After HFST Application (× $1,000)	Benefit Per Year (× $1,000)	Cost of HFST Application (× $1,000)	Benefit/Cost Ratio (Assuming 7 Years of HFST Life)
J1P3094	2,093	1,863	230	107	15
J1P3179	544	331	213	131	11
J2L1600B	332	123	209	56	26
J2P3164	866	719	147	187	6
J4I3105	5,885	718	5,167	103	350
J4P3231	4,647	1,431	3,216	158	143
J5M0284	948	182	766	N/A	N/A
J5M0285	758	206	551	N/A	N/A
J5P2235C	678	233	445	466	7
J5P2237D	513	353	160	164	7
J5P3074B	3,689	1,365	2,324	N/A	N/A
J5P3221	2,111	2,035	77	236	2
J6S3147	541	343	198	126	11
J6S3199	6,544	4,798	1,745	658	19
J7I3099	817	289	529	328	11
J7P3020B	2,215	1,384	831	164	36
J7P3020C	1,871	272	1,599	89	125
J7P3071	683	379	304	89	24
J7P3097	244	204	39	33	8
J7P3098	1,012	421	591	53	78
J7P3108C	2,013	573	1,440	514	20
J7P3161	1,593	1,320	274	127	15
J8M0260	748	325	423	108	27
J8P2386	3,021	616	2,405	41	409
J8S3062	419	120	298	45	46
J8S3063	344	320	24	24	7
J9I2167	6,501	1,968	4,532	562	56

6. SUMMARY AND CONCLUSIONS

In order to improve safety and to reduce the number of crashes of all severities within MoDOT's highway network, the Department implemented and deployed several new innovative technologies. One of these innovative technologies is HFST, which is intended to significantly improve the frictional characteristics of a roadway surface.

It is well-accepted that HFST is a cheaper alternative to any major safety improvements (e.g., realignment and/or geometric correction). In addition, the high level of friction provided by HFST is expected to provide the public with better control of the vehicle in necessary areas, thereby reducing the number of crashes substantially. A review of other SHAs' experience and case studies generally confirmed these expectations and indicated that HFSTs have potential to become a cost-effective pavement treatment for improving safety.

Due to its high potential for safety improvement, MoDOT had also deployed HFST at several areas experiencing high crash rates beginning in 2013, with the expectation that the HFSTs will generally reduce the number of crashes. As such, the primary objective of this study was to evaluate MoDOT's existing HFST sections with regard to their overall effectiveness (i.e., reduction in crashes) and benefit (i.e., return on investment). A secondary objective was to determine the factors that significantly affected the crash rates before and after HFST treatment.

To achieve the above objective, the research team gathered several data attributes (i.e., roadway, crash, pavement, friction, and HFST cost) from MoDOT's HFST sections. All of these different data attributes were merged back to the crash data based on location information (i.e., County, Route, Log Mile, Direction, and Lane Number) and MoDOT's Job Number. The merged data included a total of 1,829 crashes over 67 distinct HFST locations (and 27 unique HFST Job Numbers).

Prior to developing the statistical models between crash counts and roadway related features, a preliminary analysis was conducted using the available data to understand the trends in friction, traffic, and crash. MoDOT does not conduct network-level pavement friction testing for inventory purposes, so friction data (especially the FN before HFST treatment) was only available FN for a limited number of sections. Nonetheless, analysis of FN before and after HFST indicated that the FN values increased significantly upon installation of the HFST. The average FN before HFST installation was found to be 35 (based on 8 projects) whereas the average FN on HFST surfaces was 78 (based on 19 projects). Based on the FN data from two HFST sections where friction was monitored at different HFST ages, it was determined that the FN value of MoDOT's HFST may decrease at a rough rate of 4.0 points per year. Using this assumption, it was estimated that this rate of FN degradation would result in a rough HFST life of 5 to 10 years, which is consistent with the experience of other agencies. As such, an estimated HFST life of 7 years was used for the Benefit-Cost analysis.

The preliminary analysis of available crash data also indicated that the majority of crashes before HFST installation occurred during daylight and on curved roadways. Correspondingly, these conditions exhibited higher crash reduction following the installation of HFSTs. Furthermore, while both wet and dry crashes were reduced after HFST installation, by far the greater reduction was in the category of wet crashes. These results generally indicated that HFSTs have potential for significantly reducing crashes on both wet (approx. 86 percent reduction) and dry (approx. 50 percent reduction) pavement surfaces, with the benefit more pronounced for wet pavement surfaces.

As part of the preliminary analysis, the yearly observed crash counts (i.e., simple, average crash counts per year) were calculated and used to carry out the Benefit-Cost Analysis (BCA), along with the average crash costs provided by MoDOT. On average, the benefit-cost ratio (B/C) from all available sections was calculated to be 114.3 which clearly justifies the initial cost for MoDOT's HFSTs.

It should be noted that while pavement friction gained by HFST is a crucial factor for improving highway safety and for reducing traffic crashes, it is not the only factor affecting crashes. In fact, crashes are complicated events involving not only the vehicle and/or roadway features but also human factors (e.g., drinking and driving) and environmental factors (e.g., rain, snow, etc.) as well as other factors that are impossible to predict. For these reasons, crashes are often considered to be "random events" with its count statistic fluctuating naturally. Due to such random nature of crashes and crash counts, simple comparison of crash counts before/after a treatment (used in the preliminary analyses described above as well as in other SHAs' case studies) is generally not recommended.

The random nature of crashes and the simple BCA in this study resulted in 3 out of 67 HFST locations calculated to have negative benefit (i.e., higher crash cost after HFST installation), Each had less than 1.0 crash per year increase in a severe crash, which have a significantly higher cost associated with them. This illustrates the need for a better analysis.

Due to the limitations of the simple, observational comparison of crash counts before and after HFST, an effort was made to develop the Safety Performance Functions (SPF) based on the available data. The purpose of each SPF was (1) to estimate the expected number of crash reduction after HFST, (2) to identify the factors significantly affecting crashes, and (3) to allow for an Empirical Bayes (EB) estimate of crash counts as recommended by FHWA.

The initial SPFs were developed separately for wet and dry pavement surfaces, and for different conditions (total crashes as well as crashes on curves vs. tangent segments), while incorporating FN as an independent variable. These results generally indicated that FN had a more pronounced effect on wet weather crashes and on curved roadways. A practical example of such SPF indicated that if FN was improved from 35 to 75 by installing an HFST for a given curve, MoDOT may expect an average crash reduction of 24 percent and 73 percent under dry and wet weather conditions, respectively.

Although the initial, generalized SPFs described above may provide useful information, it is noted that these SPFs were developed based on limited HFST sections where the before and after FN values were available. To account for the crashes from all HFST sections and for different crash severities (leading to EB estimates and BCA), a set of more simple and basic SPFs were also developed. These SPFs were developed using a limited set of independent variables. Note that for these simplified SPFs, the FN was not used as an independent variable, and the crashes were simply categorized as before or after HFST installation. The results of the basic SPFs indicated that HFSTs are expected to decrease the crashes of all severities.

Using the basic SPFs, the EB estimates of crash counts were calculated for all HFST Job Numbers. The EB results pointed out that all HFST locations are expected to reduce crashes, with the reduction ranging from 13.7 percent to 79.5 percent. In addition, applying the EB method resulted in none of the HFST locations with negative benefit (i.e., increase in crashes after HFST installation). This is a consequence of the EB method correcting for the random nature of crashes (compared to the direct comparison of before/after crash counts).

Since the EB estimates resulted in a consistent reduction in crashes (i.e., less crashes after HFST in all sections), the benefit cost analysis was conducted again using the EB-based crash counts (as opposed to the observed, simple crash counts). Assuming 7 years of effective HFST life, the B/C ratio calculated from each Job Number ranged from 2.3 to 409.1, with an overall average of 60.8, indicating a high rate of return for MoDOT's HFST.

As discussed previously, MoDOT has the foundation necessary to perform an analysis to identify locations that would benefit from the application of HFSTs or other safety improvements. Currently, ARAN collects curve and superelevation data for the entire State highway system annually (with the exception of ramps). Such data may provide invaluable information that may be used for identifying the cause of high crash rates. Coupled with the ability to locate crashes and filter them by type, condition, severity, etc. makes very detailed analysis possible.

While the methodology developed here is not for identifying location where high crash rates exist, the equations can be used to determine how much reduction could be expected from the application of HFST, if implemented.

One thing that could be considered is the collection of additional friction data. This study was somewhat limited by the lack of FNs prior to construction, limiting the before and after analysis. Also, essentially one material, namely bauxite, was included in this study. While almost all projects included in this study resulted in FNs in the 80s and 90s, it could not be concluded if other aggregates may provide sufficient friction at a lower cost. It is recommended that additional studies be conducted to determine adequate friction for specific locations, based on individual curve data, speeds, etc. should such data become available in the future.

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8. APPENDIX A

Negative Binomial Regression Results from the Statistical Package R

```
Call:
glm.nb(formula = Total.Crash ~ Log.AADT + Log.Length + Light.Cond +
    Exist.Surface + On.Curve + IRI + Pavt.Condition + Rut + Speed.Limit +
    FN, data = Wet.Crash, control = mycontrol, init.theta = 2.774500896,
    link = log)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-1.4524  -0.5087  -0.3147  -0.1910   3.2281

Coefficients:
                  Estimate Std. Error z value Pr(>|z|)
(Intercept)      -0.993528   4.334934  -0.229   0.8187
Log.AADT          0.272678   0.244261   1.116   0.2643
Log.Length        1.248781   0.311568   4.008 6.12e-05 ***
Light.CondDark   -1.112392   0.263933  -4.215 2.50e-05 ***
Exist.SurfacePCC  0.586607   0.803185   0.730   0.4652
On.CurveStraight -0.676539   0.276881  -2.443   0.0145 *
IRI               0.010046   0.006443   1.559   0.1190
Pavt.Condition    0.206643   0.202876   1.019   0.3084
Rut               2.471281   3.195430   0.773   0.4393
Speed.Limit      -0.039679   0.022566  -1.758   0.0787 .
FN               -0.033047   0.006058  -5.455 4.90e-08 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for Negative Binomial(2.7745) family taken to be 1)

    Null deviance: 372.55  on 431  degrees of freedom
Residual deviance: 197.92  on 421  degrees of freedom
  (1175 observations deleted due to missingness)
AIC: 382.23

Number of Fisher Scoring iterations: 1


              Theta:  2.77
          Std. Err.:  1.94

 2 x log-likelihood:  -358.234
```

Figure A.1. Generalized Negative Binomial Regression Results for Wet Total Crash [Eqs. (9) and (10)]

```
Call:
glm.nb(formula = Total.Crash ~ Log.AADT + Log.Length + Light.Cond +
    Exist.Surface + IRI + Pavt.Condition + Rut + Curve.Length +
    Curve.Radius + Curve.Angle + Speed.Limit + FN, data =
Wet.Crash.On.Curve,
    control = mycontrol, init.theta = 2.247239962, link = log)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-1.2820  -0.5672  -0.3324  -0.1385   2.9620

Coefficients:
                   Estimate Std. Error z value Pr(>|z|)
(Intercept)      16.3816140  7.6868674   2.131  0.03308 *
Log.AADT         -0.5465136  0.4368970  -1.251  0.21097
Log.Length        1.5720297  0.4798340   3.276  0.00105 **
Light.CondDark   -1.2065483  0.2785403  -4.332 1.48e-05 ***
Exist.SurfacePCC  3.5376045  1.4511624   2.438  0.01478 *
IRI              -0.0130944  0.0120426  -1.087  0.27689
Pavt.Condition    0.5125702  0.3199898   1.602  0.10919
Rut               5.2281701  4.3017837   1.215  0.22423
Curve.Length     -0.0009529  0.0009286  -1.026  0.30478
Curve.Radius      0.0006261  0.0003493   1.793  0.07305 .
Curve.Angle      -0.0237906  0.0133037  -1.788  0.07373 .
Speed.Limit      -0.1983327  0.0690413  -2.873  0.00407 **
FN               -0.0365101  0.0066342  -5.503 3.73e-08 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for Negative Binomial(2.2472) family taken to be 1)

    Null deviance: 339.71  on 385  degrees of freedom
Residual deviance: 179.21  on 373  degrees of freedom
  (763 observations deleted due to missingness)
AIC: 365.23

Number of Fisher Scoring iterations: 1


              Theta:  2.25
          Std. Err.:  1.36

 2 x log-likelihood:  -337.23
```

Figure A.1. Generalized Negative Binomial Regression Results for Wet Curve Crash [Eqs. (9) and (11)]

```
Call:
glm.nb(formula = Total.Crash ~ Log.AADT + Log.Length + Light.Cond +
    IRI + Pavt.Condition + Rut + Speed.Limit + FN, data =
Wet.Crash.On.Tangent,
    control = mycontrol, init.theta = 1.772707466, link = log)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-1.1971  -0.3799  -0.1589  -0.1008   2.7028

Coefficients:
                Estimate Std. Error z value Pr(>|z|)
(Intercept)    -13.13167   12.83310  -1.023   0.3062
Log.AADT         0.82529    0.89048   0.927   0.3540
Log.Length       1.29641    0.79930   1.622   0.1048
Light.CondDark  -0.52981    0.48787  -1.086   0.2775
IRI              0.04707    0.02002   2.351   0.0187 *
Pavt.Condition   0.31342    0.45560   0.688   0.4915
Rut            -20.89013   17.64415  -1.184   0.2364
Speed.Limit      0.02124    0.04755   0.447   0.6551
FN              -0.01602    0.01513  -1.059   0.2895
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for Negative Binomial(1.7727) family taken to be 1)

    Null deviance: 102.169  on 186  degrees of freedom
Residual deviance:  56.225  on 178  degrees of freedom
  (445 observations deleted due to missingness)
AIC: 121.85

Number of Fisher Scoring iterations: 1


              Theta:  1.77
          Std. Err.:  2.55

 2 x log-likelihood:  -101.846
```

Figure A.1. Generalized Negative Binomial Regression Results for Wet Tangent Crash [Eqs. (9) and (12)]

```
Call:
glm.nb(formula = Total.Crash ~ Log.AADT + Log.Length + Light.Cond +
    Exist.Surface + On.Curve + IRI + Pavt.Condition + Rut + Speed.Limit +
    FN, data = Dry.Crash, control = mycontrol, init.theta = 3.178468912,
    link = log)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-1.7934  -0.7825  -0.5174   0.1110   3.5275

Coefficients:
                   Estimate Std. Error z value Pr(>|z|)
(Intercept)        7.349301   2.159762   3.403 0.000667 ***
Log.AADT          -0.594430   0.132179  -4.497 6.89e-06 ***
Log.Length         1.112598   0.165756   6.712 1.92e-11 ***
Light.CondDark    -0.814980   0.167657  -4.861 1.17e-06 ***
Exist.SurfacePCC -0.258961   0.552082  -0.469 0.639024
On.CurveStraight -0.415524   0.177395  -2.342 0.019162 *
IRI                0.002372   0.003488   0.680 0.496598
Pavt.Condition     0.046570   0.104336   0.446 0.655347
Rut                3.644257   1.527710   2.385 0.017059 *
Speed.Limit       -0.032631   0.013761  -2.371 0.017730 *
FN                -0.007136   0.004210  -1.695 0.090090 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for Negative Binomial(3.1785) family taken to be 1)

    Null deviance: 468.58  on 406  degrees of freedom
Residual deviance: 325.76  on 396  degrees of freedom
  (1175 observations deleted due to missingness)
AIC: 696.03

Number of Fisher Scoring iterations: 1


              Theta:  3.18
          Std. Err.:  1.49

 2 x log-likelihood:  -672.032
```

Figure A.1. Generalized Negative Binomial Regression Results for Dry Total Crash [Eqs. (9) and (10)]

```
Call:
glm.nb(formula = Total.Crash ~ Log.AADT + Log.Length + Light.Cond +
    Exist.Surface + IRI + Pavt.Condition + Rut + Curve.Length +
    Curve.Radius + Curve.Angle + Speed.Limit + FN, data =
Dry.Crash.On.Curve,
    control = mycontrol, init.theta = 5.578330157, link = log)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-1.8769  -0.7832  -0.4303   0.0479   2.3034

Coefficients:
                   Estimate Std. Error z value Pr(>|z|)
(Intercept)      12.8383650  3.9289714   3.268 0.001085 **
Log.AADT         -0.6164753  0.2223716  -2.772 0.005567 **
Log.Length        1.2010999  0.2632468   4.563 5.05e-06 ***
Light.CondDark   -0.8024572  0.1664388  -4.821 1.43e-06 ***
Exist.SurfacePCC  1.6776529  0.9268090   1.810 0.070274 .
IRI              -0.0209047  0.0060314  -3.466 0.000528 ***
Pavt.Condition    0.3798928  0.1516310   2.505 0.012232 *
Rut               6.8873449  1.8217756   3.781 0.000156 ***
Curve.Length     -0.0019289  0.0005425  -3.555 0.000377 ***
Curve.Radius      0.0009467  0.0001685   5.619 1.92e-08 ***
Curve.Angle       0.0033677  0.0070653   0.477 0.633604
Speed.Limit      -0.1445897  0.0333850  -4.331 1.48e-05 ***
FN               -0.0050376  0.0044046  -1.144 0.252744
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for Negative Binomial(5.5783) family taken to be 1)

    Null deviance: 459.09  on 362  degrees of freedom
Residual deviance: 284.76  on 350  degrees of freedom
  (762 observations deleted due to missingness)
AIC: 618.37

Number of Fisher Scoring iterations: 1


              Theta:  5.58
          Std. Err.:  3.83

 2 x log-likelihood:  -590.372
```

Figure A.1. Generalized Negative Binomial Regression Results for Dry Curve Crash [Eqs. (9) and (11)]

```
Call:
glm.nb(formula = Total.Crash ~ Log.AADT + Log.Length + Light.Cond +
    IRI + Pavt.Condition + Rut + Speed.Limit + FN, data =
Dry.Crash.On.Tangent,
    control = mycontrol, init.theta = 4.332913562e+16, link = log)

Deviance Residuals:
   Min      1Q  Median      3Q     Max
 0.000   0.000   0.000   0.000   3.358

Coefficients:
                Estimate Std. Error z value Pr(>|z|)
(Intercept)     3.698262   3.796514   0.974  0.33000
Log.AADT       -0.399929   0.316488  -1.264  0.20636
Log.Length      1.078246   0.269314   4.004 6.24e-05 ***
Light.CondDark -0.898814   0.286551  -3.137  0.00171 **
IRI            -0.001246   0.006071  -0.205  0.83737
Pavt.Condition -0.218910   0.178862  -1.224  0.22099
Rut             5.332461   3.075146   1.734  0.08291 .
Speed.Limit     0.019062   0.029225   0.652  0.51424
FN              0.000353   0.007492   0.047  0.96242
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for Negative Binomial(4.332914e+16) family taken to
be 1)

    Null deviance: 176.76  on 174  degrees of freedom
Residual deviance: 112.66  on 166  degrees of freedom
  (490 observations deleted due to missingness)
AIC: 20

Number of Fisher Scoring iterations: 1
```

Figure A.1. Generalized Negative Binomial Regression Results for Dry Tangent Crash [Eqs. (9) and (12)]

```
Call:
glm.nb(formula = Fatality ~ Log.AADT + Log.Length + Speed.Limit +
    BeforeAfter, data = Crash.Data.with.Zeros.Final.with.SpeedLimit,
    control = mycontrol, init.theta = 0.02151617882, link = log)

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-0.16841  -0.12102  -0.10273  -0.08368   2.58376

Coefficients:
                  Estimate Std. Error z value Pr(>|z|)
(Intercept)       -4.72962    3.37613  -1.401    0.161
Log.AADT          -0.42025    0.31725  -1.325    0.185
Log.Length        -0.24427    0.36902  -0.662    0.508
Speed.Limit        0.04346    0.04598   0.945    0.345
BeforeAfterBefore  0.63613    0.59520   1.069    0.285

(Dispersion parameter for Negative Binomial(0.0215) family taken to be 1)

    Null deviance: 88.452  on 2962  degrees of freedom
Residual deviance: 84.485  on 2958  degrees of freedom
  (226 observations deleted due to missingness)
AIC: 234.11

Number of Fisher Scoring iterations: 1


              Theta:  0.0215
          Std. Err.:  0.0140

 2 x log-likelihood:  -222.1100
```

Figure A.1. Basic Negative Binomial Regression Results for Fatality Crash [Eq. (15)]

```
Call:
glm.nb(formula = Disbling.Injury ~ Log.AADT + Log.Length + Speed.Limit +
    BeforeAfter, data = Crash.Data.with.Zeros.Final.with.SpeedLimit,
    control = mycontrol, init.theta = 0.08656151348, link = log)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-0.3713  -0.2538  -0.2097  -0.1653   3.8649

Coefficients:
                  Estimate Std. Error z value Pr(>|z|)
(Intercept)        0.74447    1.67816   0.444 0.657317
Log.AADT          -0.08813    0.15406  -0.572 0.567302
Log.Length         0.69683    0.18808   3.705 0.000211 ***
Speed.Limit       -0.05159    0.01847  -2.793 0.005228 **
BeforeAfterBefore  0.82814    0.29064   2.849 0.004381 **
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for Negative Binomial(0.0866) family taken to be 1)

    Null deviance: 358.13  on 2962  degrees of freedom
Residual deviance: 332.92  on 2958  degrees of freedom
  (226 observations deleted due to missingness)
AIC: 776.08

Number of Fisher Scoring iterations: 1


              Theta:  0.0866
          Std. Err.:  0.0257

 2 x log-likelihood:  -764.0760
```

Figure A.1. Basic Negative Binomial Regression Results for Serious Injury Crash [Eq. (15)]

```
Call:
glm.nb(formula = Minor.Injury ~ Log.AADT + Log.Length + Speed.Limit +
    BeforeAfter, data = Crash.Data.with.Zeros.Final.with.SpeedLimit,
    control = mycontrol, init.theta = 0.1355024872, link = log)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-0.7146  -0.5060  -0.4384  -0.3217   3.6275

Coefficients:
                  Estimate Std. Error z value Pr(>|z|)
(Intercept)       -1.91509    0.98376  -1.947 0.051570 .
Log.AADT           0.34290    0.09212   3.722 0.000197 ***
Log.Length         0.22097    0.09992   2.211 0.027006 *
Speed.Limit       -0.05895    0.01019  -5.786 7.21e-09 ***
BeforeAfterBefore  1.24815    0.16255   7.679 1.61e-14 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for Negative Binomial(0.1355) family taken to be 1)

    Null deviance: 983.22  on 2962  degrees of freedom
Residual deviance: 893.44  on 2958  degrees of freedom
  (226 observations deleted due to missingness)
AIC: 2505.9

Number of Fisher Scoring iterations: 1


              Theta:  0.1355
          Std. Err.:  0.0147

 2 x log-likelihood:  -2493.9250
```
Figure A.1. Basic Negative Binomial Regression Results for Minor Injury Crash [Eq. (15)]

```
Call:
glm.nb(formula = Property.Crash ~ Log.AADT + Log.Length + Speed.Limit +
    BeforeAfter, data = Crash.Data.with.Zeros.Final.with.SpeedLimit,
    control = mycontrol, init.theta = 0.6428809685, link = log)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-1.2765  -0.8515  -0.6725   0.1241   3.7508

Coefficients:
                   Estimate Std. Error z value Pr(>|z|)
(Intercept)       -2.864914   0.549667  -5.212 1.87e-07 ***
Log.AADT           0.510784   0.052515   9.726  < 2e-16 ***
Log.Length         0.253796   0.051780   4.901 9.51e-07 ***
Speed.Limit       -0.045238   0.005206  -8.689  < 2e-16 ***
BeforeAfterBefore  0.834500   0.081235  10.273  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for Negative Binomial(0.6429) family taken to be 1)

    Null deviance: 2400.3  on 2962  degrees of freedom
Residual deviance: 2139.9  on 2958  degrees of freedom
  (226 observations deleted due to missingness)
AIC: 5288.6

Number of Fisher Scoring iterations: 1


              Theta:  0.6429
          Std. Err.:  0.0529

 2 x log-likelihood:  -5276.5810
```

Figure A.1. Basic Negative Binomial Regression Results for PDO Crash [Eq. (15)]