Developing Crash-Modification Factors for High-Friction Surface Treatments

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FOREWORD

The research documented in this report was conducted as part of the Federal Highway Administration's (FHWA's) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS). FHWA established this PFS in 2005 to research the effectiveness of the safety improvements identified by the National Cooperative Highway Research Program's Report 500 Series as part of the implementation of the American Association of State Highway and Transportation Officials' Strategic Highway Safety Plan. The ELCSI-PFS research studies provide a crash modification factor and benefit–cost economic analysis for each targeted safety strategy identified as a priority by the PFS member States.

This report provides high-quality CMFs and B/C ratios for high-friction surface treatments (HFSTs) with calcined bauxite aggregate and recommends materials and specifications for applications to effectively reduce roadway-departure crashes. This data-driven study used before- and after-crash data to quantify crash-reduction benefits and used friction data collected by the research team before and after HFST installation to help quantify the impact of increased pavement friction on CMFs. The study collected data for HFST installations on curves and ramps in Arkansas, Georgia, Kentucky, Louisiana, Pennsylvania, and West Virginia. The results of this study indicate using HFSTs with calcined bauxite aggregate reduces roadway-departure crashes at curves and ramps, particularly for wet-weather crashes. This report is supplemented by FHWA-HRT-20-062, *Developing Crash-Modification Factors for High-Friction Surface Treatments: Friction Change Report*, and will benefit safety engineers and safety planners by providing greater insight into applications of HFSTs for improving highway safety.

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16. Abstract

Over the past 10 to 15 yr, the use of high-friction surface treatments (HFSTs) as a safety countermeasure has grown exponentially. HFSTs are pavement-surface treatments that restore or enhance pavement friction at locations with high friction demand, such as curves, ramps, and intersection approaches. While the crash-reduction benefits of HFSTs have been observed by many State highway agencies, the availability of crash-modification factors (CMFs) for HFSTs is limited. This study provides high-quality and robust CMFs and benefit–cost ratios for HFSTs with calcined bauxite aggregate and recommends materials and specifications (as appropriate) for applications. This study also notes where and under what conditions to use HFSTs to effectively reduce roadway-departure crashes. This study was data-driven and used before- and after-crash data to quantify crash-reduction benefits. The study also used friction data collected by the research team before (when available) and after HFST installation to help quantify the impact of increased pavement friction on the CMFs. Data were collected for hundreds of HFST installations in Arkansas, Georgia, Kentucky, Louisiana, Pennsylvania, and West Virginia on curves and ramps. The results for curves and ramps indicate significant benefits in terms of low CMFs, particularly for wet-weather crashes. A thorough disaggregate analysis of the before–after evaluation data for curves suggested a logical and consistent relationship between CMFs and three variables: friction improvement, annual average daily traffic, and expected crash frequency before treatment. A complementary evaluation was conducted under this study for friction changes of HFSTs over time; the results are documented in FHWA-HRT-20-062, *Developing Crash-Modification Factors for High-Friction Surface Treatments: Friction Change Report*. Friction testing was performed on several older HFST installations where previous friction data were collected. All friction testing was performed with the Federal Highway Administration's highway friction tester, a continuous fixed-slip measurement device. The friction data collected during this research and documented in this report were evaluated for friction change before and after HFST installation, friction change of the HFST and existing pavement over time, and friction change through a curve.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ABBREVIATIONS

AADT	annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
ARDOT	Arkansas Department of Transportation
B/C	benefit–cost
BBA HAPAS	Board of Agrément Highways Agency Product Approval Scheme
Caltrans	California Department of Transportation
C-G	comparison group
CMF	crash-modification factor
CMFunction	crash-modification function
DFT	dynamic friction tester
DOT	department of transportation
EB	empirical Bayes
ELCSI-PFS	Evaluation of Low-Cost Safety Improvements Pooled Fund Study
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FN40R	friction number value
GDOT	Georgia Department of Transportation
GLM	generalized linear modeling
GPS	global positioning system
HFST	high-friction surface treatment
HFT	highway friction tester
HOSSOD	head-on plus opposite direction sideswipe
HSM	*Highway Safety Manual*
KABC	injury and fatal
KDOT	Kansas Department of Transportation
KYTC	Kentucky Transportation Cabinet
LADOTD	Louisiana Department of Transportation and Development
LWST	locked-wheel skid tester
MMA	methyl methacrylate
MPD	mean profile depth
NCAT	National Center for Asphalt Technology
PCC	portland cement concrete
PDO	property damage only
PennDOT	Pennsylvania Department of Transportation
PSV	polished stone value
QC	quality control
QPL/APL	qualified/approved products list
RTM	regression to the mean
RTSA	Road Surface Treatments Association
SCDOT	South Carolina Department of Transportation
SEaHC	Surface Enhancements at Horizontal Curves
SN	skid number
SPF	safety performance function
STH	State Trunk Highway

TDOT	Tennessee Department of Transportation
VDOT	Virginia Department of Transportation
VTrans	Vermont Agency of Transportation
WisDOT	Wisconsin Department of Transportation
WSDOT	Washington State Department of Transportation
WVDOT	West Virginia Department of Transportation

EXECUTIVE SUMMARY

This report provides high-quality and robust crash-modification factors (CMFs) and benefit–cost (B/C) ratios for high-friction surface treatments (HFSTs) with calcined bauxite aggregate and recommends current materials and specifications (as appropriate) for applications. This report also notes where and under what conditions to use HFSTs to reduce roadway-departure crashes.

The research presented in this report was conducted as part of Federal Highway Administration's Development of Crash-Modification Factors Program, the goal of which is to identify CMF research needs, develop CMFs that meet the criteria for inclusion in the *Highway Safety Manual* (HSM), promote the installation of promising safety improvements as standard practice, and facilitate the development of practical guides for implementation.

The research presented in this report builds on research conducted under Phase VI of the Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS), which, through a detailed statistical analysis of crash data on various pavement-surface treatments, showed a significant reduction in wet-pavement crashes after treatments were applied (Merritt et al. 2015). The use of HFSTs showed substantial crash reduction using both naïve and comparison group analyses. Initially, a lack of treatment sites and reference groups prevented a state-of-the-art empirical Bayes (EB) analysis. In the years since the ELCSI-PFS was initiated, several State highway agencies have deployed HFSTs on a large scale, providing a greater number of treatment sites for a more rigorous EB analysis of the crash-reduction benefits of these treatments. With significant interest in HFSTs as a safety countermeasure by most State highway agencies, the need for reliable CMFs and B/C ratios is great, providing the motivation for this definitive study.

The state-of-the-art EB before–after methodology analyzed the effects of HFSTs on various crash types, including total, injury, wet-road, run-off-road (ROR), and head-on plus opposite-direction sideswipe (HOSSOD) using data collected in Arkansas (ramps), Kentucky (curves and ramps), Pennsylvania (curves), and West Virginia (curves). Limited data were also collected in Louisiana and Georgia but were not included in the rigorous EB analysis due to a lack of reference sites or after-period crash data.

The EB analysis results for curves indicate significant benefits in terms of low CMFs for each State and the three States combined, especially for the primary crash types targeted by HFST programs: wet-road, ROR, and HOSSOD. Because of the relative consistency in the results for the three States, the CMFs based on the three States combined are recommended for estimating the benefits of contemplated treatments and for use in the CMF Clearinghouse (FHWA 2020a).

The EB analysis results for ramps for Arkansas and Kentucky were highly inconsistent. The outlier was wet-weather crashes, for which the benefits in terms of low CMFs were significant. The benefits for all crash types were significant for Kentucky, while there were negligible benefits for crashes in Arkansas. This anomaly can be explained by the relatively small proportion of wet-weather crashes—the main HFST target—in Arkansas compared to Kentucky. To achieve the significant benefits of HFSTs, ramps should be identified for treatment based on a high proportion of wet-weather crashes.

A thorough disaggregate analysis of the before–after evaluation data was only feasible for curves. For this, univariate categorical and multivariable regression analyses were used to investigate the effects on the CMFs of a number of variables. The data suggest a logical and consistent relationship between CMFs and three variables: friction improvement, annual average daily traffic, and expected crash frequency before treatment. These three variables were used to develop recommended crash-modification functions.

CHAPTER 1. INTRODUCTION

IMPORTANCE OF PAVEMENT SAFETY

Approximately one-quarter of highway fatalities in the United States occur at or near horizontal curves. Roadway-departure crashes consistently account for more than half of fatalities and fatal crashes in the United States. Contributing factors to these roadway-departure crashes include excessive vehicle speed, distracted driving, and driver error. At some locations, however, the deterioration of pavement-surface friction may also be a factor, particularly during wet weather. The Federal Highway Administration (FHWA) estimates that 70 percent of wet-pavement crashes are preventable through improved pavement friction; recent studies on the effects of pavement-surface friction validate this estimate (FHWA Office of Safety n.d.a.; FHWA Office of Safety n.d.b.).

The research documented in this report was conducted as part of the Federal Highway Administration's (FHWA's) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS). FHWA established this PFS in 2005 to research the effectiveness of the safety improvements identified by the National Cooperative Highway Research Program's Report 500 Series as part of the implementation of the American Association of State Highway and Transportation Officials' Strategic Highway Safety Plan. The ELCSI-PFS research studies provide a crash modification factor and benefit–cost economic analysis for each targeted safety strategy identified as a priority by the PFS member States. Using both naïve and comparison group (C-G) analyses of crash data on various pavement-surface treatments, HFSTs showed a significant reduction in wet-pavement crashes after application. The lack of reference sites prevented a state-of-the-art EB analysis. In the years since the ELCSI-PFS was initiated, several State highway agencies deployed HFSTs on a large scale, providing a greater number of treatment sites for a more detailed analysis of the crash-reduction benefits of this treatment. With significant interest in HFSTs as a safety countermeasure by most State highway agencies, the need for reliable CMFs and B/C ratios is great.

HFSTs

HFSTs are specialty pavement-surface treatments that restore or enhance friction. HFSTs are commonly used for spot treatments of curves, ramps, intersections, and steep grades where friction demand is higher than what conventional paving materials can provide. HFSTs are installed by spreading a thin layer of polymeric resin binder (typically epoxy or polyester) over the pavement surface, then broadcasting or dropping a 1- to 3-millimeter abrasion- and polish-resistant aggregate onto the resin layer (figure 1 through figure 4). Calcined bauxite is the most commonly used aggregate for HFSTs worldwide, as it provides exceptional skid resistance not typically achieved with conventional pavement aggregates. Calcined bauxite also maintains high skid resistance over time. Recognizing the safety benefits of HFSTs, FHWA deployed them as a focus technology under the Every Day Counts 2 Program and continues to support their use (FHWA EDC2 n.d.).

Source: FHWA.

Figure 1. Photograph. Manual HFST installation.

Source: FHWA.

Figure 2. Photograph. Fully automated HFST installation.

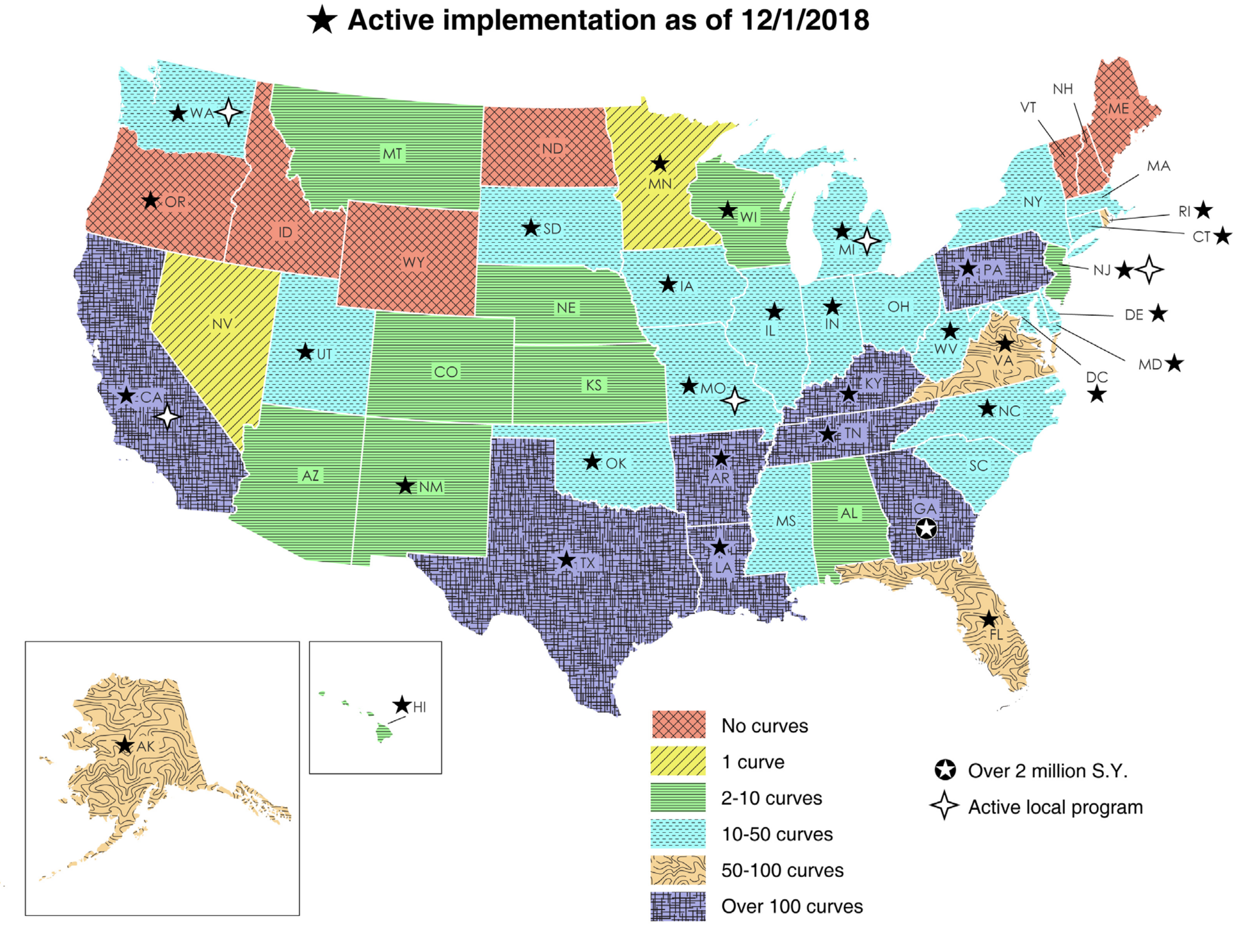
Source: FHWA.

Figure 3. Photograph. HFST post installation.

Source: FHWA.

Figure 4. Photograph. Curve with an HFST installed.

The use of HFSTs as safety countermeasures in the United States has grown exponentially over the past 10–15 yr (Cheung and Julian 2016). Although used as a bridge deck preservation treatment since the 1950s, as of 2005, there were only one or two known HFST demonstration installations on curves or ramps in the United States (Cheung and Julian 2016). By 2018, at least 43 States had at least one HFST installation, with multiple States reporting over 100 installations, accounting for millions of square yards of HFSTs (figure 5). Adequately assessing the cost and safety benefits is important as highway agencies continue to install HFSTs.



Source: FHWA.
S.Y. = square yard.

Figure 5. Map. Implementation of HFSTs as of December 2018.

SCOPE AND OBJECTIVES

This report provides reliable CMFs and B/C ratios for different types (in terms of applications to date) of HFSTs and recommends materials and specifications (as appropriate) for applications. This report also notes where and under what conditions to use HFSTs to effectively reduce roadway-departure crashes. This report will help State departments of transportation (DOTs) select pavement treatments for projects.

The objectives of this study included the following:

- Conduct a literature review of current HFST studies and their installation practices with relevant details.
- Identify HFST installations that have been used for safety improvements, documenting materials used, relevant specifications, and application practices, and recommend a set of HFST installations for safety and performance evaluation.
- Determine appropriate statistical methodologies and analysis procedures and tools.
- Design a data-collection plan, including selecting reliable and applicable data sources, data needs, and data-collection techniques and equipment.
- Work with volunteer States to collect crash, road geometric design, traffic, and performance data; pavement-surface characteristics; weather and environmental information; and other data for HFSTs installed in these States.
- Analyze the data using the most reliable and applicable statistical methodologies for scientifically determining the safety effectiveness of different HFSTs and develop reliable CMFs and/or crash-modification functions (CMFunctions) and B/C ratios.
- Develop statistical models for different types of HFSTs over time.
- Recommend a set of HFST installations with material requirements and specifications on the manner of installation; provide information on what, where, when, why, and how to use HFSTs; and identify road designs, facilities, and weather conditions that can benefit the most from HFSTs.
- Identify and recommend potential HFST materials and specifications that can be used for systemic safety improvements on a longer length of roadway.
- Develop this report and DTFH61-13-D-00001, Task B9, *High Friction Surface Treatment (HFST) Quick Reference*, for HFST types, materials, specifications, applications, performance, testing, proactive maintenance, and data-collection needs (FHWA 2020b).
- Develop FHWA-HRT-20-062, *Developing Crash-Modification Factors for High-Friction Surface Treatments: Friction Change Report*, documenting friction changes for surface treatments using calcined bauxite aggregate over time and curves and intersections for before, through, and after-the-road geometric design (Merritt et al. 2020).
- Prepare solicitation and evaluation criteria to identify volunteer highway agencies to implement systemic HFST installations for future evaluations.

CHAPTER 2. LITERATURE REVIEW

This literature review summarizes a number of State highway, FHWA, and international studies on HFSTs in recent years, as well as some specification requirements from various agencies. This literature review is divided into three sections. The first section provides a brief overview of HFSTs and how they relate to safety. The second section summarizes the findings of recent studies by various agencies that evaluated the application and field performance of HFSTs and their effects on safety. The bulk of the material in the second section comes from case study evaluations rather than large-scale safety evaluations. The third section reviews specifications from industry and State highway agencies for installing HFSTs.

OVERVIEW OF HFSTs

The following overview of HFSTs is adapted from the *Evaluation of Pavement Safety Performance* (Merrett et al. 2015):

> HFSTs are specialty pavement treatments that restore or enhance friction. HFSTs are commonly used for spot treatments of curves, intersections, and steep grades where friction demand is higher than conventional paving materials can provide. HFSTs are installed by spreading a resin binder (e.g., epoxy, methacrylate, or polyester) over the pavement surface followed by broadcasting or dropping a 1- to 3-millimeter abrasion- and polish-resistant aggregate onto the resin. Calcined bauxite, which exhibits exceptional polish resistance, is the most commonly used aggregate for HFSTs worldwide. However, similar aggregates that maintain excellent microtexture properties over time have also been used as the aggregate. Although a form of HFSTs has been used extensively for bridge decks and seals the bridge deck surface, it does not provide any documented preservation for pavements (pp. 36 and 37).

The American Traffic Safety Services Association explains that the key to cost effectively employing HFSTs is to identify sites where they will achieve the greatest impact (ATSSA 2013). One of the most successful applications of an HFST is at existing horizontal curves with a history of wet-pavement crashes where geometric improvements to change the radius of curvature and/or superelevation are not feasible and warnings to reduce vehicle speed are ineffective. HFST applications on other sites with high occurrences of wet-pavement crashes, such as ramps, intersections, and tangents, are not well documented.

In addition to a high occurrence of wet-pavement crashes, low pavement friction is another indicator to identify sites that would benefit from HFSTs. The Pavement Friction Management Technical Advisory (T 5040.38) recommends using pavement friction measurements along with crash and traffic data to complete the following (FHWA 2010):

- Evaluate pavement design, construction, and maintenance practices to ensure pavement surfaces with good friction characteristics are provided.

- Identify and investigate locations with elevated wet-weather crash rates relative to comparable locations for the purposes of minimizing locations with elevated friction-related crash rates.

- Provide data to prioritize projects to improve highway safety.

Pavement-friction data are not only used to identify potential sites for HFSTs but also to evaluate the performance of an HFST immediately after installation and over time. The Pavement Friction Management Technical Advisory (T 5040.38) lists four types of full-scale friction test equipment: locked wheel, fixed slip, side force, and variable slip (FHWA 2010). De León et al. (2016) explain that, even though the locked-wheel method (i.e., ASTM E274, *Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire*) is used widely in the United States, the other methods operate continuously, especially on curves, and provide a better indication of friction number values (FN40R) corresponding to braking with antilock brakes (ASTM 2011).

HFST EVALUATION STUDIES

Various agencies conducted studies to evaluate the performance of HFSTs on highway surfaces other than bridge decks. Most of these studies evaluated pavement friction, and many reported crash counts before and after HFST installation; HFST construction and durability were also evaluated. This section summarizes the most recent HFST studies and is by no means an exhaustive compilation of HFST evaluations, but it provides some of the more relevant information as it relates to this current study.

The following observations by Merritt et al. (2015) are applicable to the studies summarized in this section:

- Recent studies indicate, as would be expected, that higher skid resistance measurements are associated with lower crash rates, particularly wet-road-related collisions.

- Studies comparing the safety improvements after specific skid resistance improvement treatments are rare and the data and evaluation methods poor.

- These limited studies indicate reductions in crashes following treatment.

A study of HFST sites in Florida indicated that HFSTs may not provide the desired crash reduction at wide curves/tangents, intersection approaches, and intersections (Wilson et al. 2016). Wilson et al. (2016) concluded that the only statistically significant change in crash rates was the decrease in wet-weather accidents on tight curves. These results may not be reliable since they were based on a naïve before–after comparison that did not control for regression to the mean (RTM) and other changes in crashes that were unrelated to the treatment (e.g., those due to differences in weather between the before and after periods). In addition, researchers controlled traffic volume changes using crash rates rather than properly through safety performance functions (SPFs).

2015 Washington State: *Kwik Bond Polymers® High Friction Surface Treatment* (Anderson et al. 2015)

This report presented the interim findings of a study that evaluated the performance of the Kwik Bond Polymers® HFST in terms of pavement friction and crash reduction. Based on the results of the study, Anderson (2015) recommended Washington State Department of Transportation (WSDOT) use this product. This HFST consists of a polyester resin binder and calcined bauxite aggregate; it was applied to two interstate on-ramps in the Seattle area. The treatment was installed with automated installation equipment without notable problems. Table 1 summarizes the installation information and initial results, and the measurements right after the treatment show that the friction resistance was improved significantly. WSDOT plans to conduct friction testing and visual surveys on a yearly basis for a minimum of 5 yr and collect and analyze crash data for the same period to assess the long-term performance and B/C of this HFST.

Table 1. Summary of 2015 WSDOT HFST evaluation (interim results) (Anderson et al. 2015).

Site Description	Date	HFST Materials	Cost per Square Yard (U.S. Dollars)	Average Friction Before⁑	Average Friction After (07/2015)
Westbound I–90 on-ramp (from southbound 148th Avenue)	06/2015	Polyester resin binder with calcined bauxite aggregate	35.50	39	83
Westbound I–90 HOV on-ramp (from southbound 148th Avenue)	06/2015	Polyester resin binder with calcined bauxite aggregate	35.50	40	86
Southbound I–5 on-ramp (from eastbound SR 526)	06/2015	Polyester resin binder with calcined bauxite aggregate	35.50	38	75

⁑Date unknown.
HOV = high-occupancy vehicle.

2015 Kentucky: *Kentucky Transportation Cabinet's High Friction Surface Treatment and Field Installation Program* (Von Quintus and Mergenmeier 2015)

This report provided an overview of effort by Kentucky Transportation Cabinet (KYTC) to establish an HFST program to reduce crashes and fatalities as part of their Strategic Highway Safety Plan. Von Quintus and Mergenmeier (2015) discussed standards, guidance, and specifications for using HFSTs as a safety countermeasure, including the various elements to consider when selecting candidate roadway segments for HFSTs, and insights on lessons learned from HFST deployment in Kentucky since 2009.

Von Quintus and Mergenmeier (2015) explained that part of KYTC's success with HFSTs was due to their site-selection process and the supporting data analysis that identified locations likely to benefit the most from using FSTs. Von Quintus and Mergenmeier (2015) described the evolution of this effort through the following processes:

- Process I—the 30 Worst was Kentucky's first HFST screening system in 2009 that analyzed 3 yr of crash data on the two-lane, two-way rural State road system; curves; and ramps to identify the 30 highest crash sections with high wet/dry ratios.

- Process II—2010 Roadway Departure Safety Implementation Plan was developed in 2010 in collaboration with FHWA and analyzed 4 yr of crash data on the two-lane, two-way rural State road system, including roadway-departure crashes, segregating 3,000-foot sections and identifying them by county, route, and milepoint (FHWA Office of Safety n.d.c.). Sections with eight or more wet/total crashes and a minimum wet/total crash ratio of 0.35 were deemed HFST candidate sites.

- Process III—the EB methodology was implemented as a more advanced process incorporating EB methodology to estimate the number of crashes at sites if an HFST was not installed by using SPFs.

Once the screening process was completed, field assessments were conducted to corroborate the viability of HFSTs. Factors considered during field assessments include, but are not limited to: drainage, superelevation, driveways, future planned work, sight distances, crash analysis, ponding of water, constructability, existing pavement condition, HFST limits, and HFST treatment of one or both lanes. The post HFST installation timeframe was deemed inadequate to perform a more rigorous analysis. Thus, a simple 3-year before to a 1 to 4 yr after installation (depending on the age of the treatment) crash comparison was performed for curves and ramps. The analysis revealed substantial yearly crash reductions for both wet and dry crashes on both curves and ramps. However, the benefits were likely overestimated since they did not account for bias in selecting sites for treatment and the resulting RTM.

2014 Kentucky: *Evaluation of High Friction Surface Treatments* (Scully 2014)

This report presented the University of Kentucky Transportation Center's program to test HFST sites in Kentucky with a portable dynamic friction tester (DFT), a stationary spot measurement device. A DFT was used because the majority of HFST sites are curves and are difficult to test with the KYTC locked-wheel skid tester. The report contains 1-page summaries for the 90 curves and 15 ramps tested, including descriptions of the sites, observed distresses, and photos. Scully (2014) noted that distresses varied from site to site, with some exhibiting no distresses and others exhibiting cracking and HFST peel off. For seven new HFST installations from 2014, the friction before and after HFST application was measured. Scully (2014) noted an FN40R before treatment ranging from 27 to 40 and an FN40R after treatment ranging from 81 to 96. For older sites, testing revealed an FN40R ranging from 65 to 80 after nearly 4 yr of traffic.

2012 Washington State: *Evaluation of Tyregrip® High-Friction Surfacing* (Anderson et al. 2012)

This report presented the interim findings of a WSDOT study that evaluated the construction and performance of the Tyregrip® HFST in terms of pavement friction and crash reduction. Based on the results of the study, Anderson (2012) recommended WSDOT use this product. The installation consisted of a two-part epoxy binder with calcined bauxite aggregate applied to an interchange on-ramp with a high accident occurrence. Automated installation equipment was used, but there were problems with the aggregate spreader that resulted in poor aggregate distribution. Hand placement and application of a second layer the following night were required.

Table 2 summarizes the installation information and initial results, and measurements right after HFST installation show a modest increase in friction resistance. At the request of the supplier, WSDOT allowed the application of another Tyregrip® layer at no cost in May 2011. The measurements in May 2011 show a significant increase in friction resistance after the second layer was applied. A section of the ramp was left untreated comparison purposes (see the "Untreated section" row in table 2). WSDOT conducted friction testing and visual surveys on a yearly basis for a minimum of 5 yr. WSDOT also collected and analyzed crash data for the same period to assess the long-term performance and the B/C of the Tyregrip® HFST (Anderson et al. 2017).

Table 2. Summary of 2012 WSDOT HFST evaluation (interim results) (Anderson et al. 2012).

Site Description	Installation Dates	HFST Materials	Cost per Square Yard (U.S. Dollars)	Friction Before (05/2011)	Friction After (11/2010)	Friction After (05/2011)	Crash Count Before
Ramp from southbound 164th Avenue to westbound SR 14	08/2010 05/2011	Untreated section	—	47.4	44.1	44.5	27 crashes in 3 yr (20 wet)
		Two-part epoxy resin with calcined bauxite aggregate	36.50	47.4	54.1	76.7	

—No information available.

2009 Kansas: *Evaluation of High Friction Surface Locations in Kansas* (Meggers 2015)

This report presented the findings of a study that evaluated the long-term effectiveness and durability of four HFST installations as part of the FHWA Surface Enhancements at Horizontal Curves (SEaHC) Program. These HFSTs consisted of a Poly Carb Type III epoxy-based overlay with flint aggregate applied to two asphalt pavement highway sections and two concrete interchange ramps. The treatment was installed with automated installation equipment without notable problems. Evaluations in 2009, 2010, and 2013 consisted of visual inspection and friction, surface pull-off, and permeability testing.

Table 3 summarizes the installation information and friction testing results, showing a significant improvement in skid resistance after HFST installation. However, the skid resistance on the concrete ramps quickly deteriorated; in 2013, skid resistance was near the pretreatment values. The K–99 installation was milled off and replaced with asphalt in 2012 due to a significant number of isolated failures (e.g., potholes and HFST peel off). The other three sections were evaluated in 2013 and 2014; K–5 and the US 54 ramp exhibited partial HFST wear, while the I–635 ramp exhibited significant HFST wear. Kansas Department of Transportation (KDOT) concluded that the premature HFST failure on K–99 was due to insufficient surface preparation (i.e., sand blasting) before installation. KDOT now uses the AASHTO MP 41-19, *Standard*

Specification for High Friction Surface Treatment for Asphalt and Concrete Pavements Using Calcined Bauxite, which suggests shot blasting asphalt pavements before applying HFSTs (AASHTO 2019). KDOT installed HFSTs at four sites in 2014 and two sites in 2015. The new sites are divided by aggregate type, with four using bauxite and two using flint. KDOT is conducting a long-term evaluation of these sites with the goal to achieve an HFST lifespan of 7–10 yr on both asphalt and concrete pavements.

Table 3. Summary of 2009 KDOT HFST evaluation (Meggers 2015).

Site Description	Date	HFST Materials	Cost per Square Yard (U.S. Dollars)	Friction Before⁑	Friction After (08/2009)	Friction After (10/2010)	Friction After (11/2013)
K–99 (asphalt)	08/2009	Two-part epoxy with flint aggregate	†	NB 47.8 SB 50.1	NB 87.3 SB 88.3	NB 80.0 SB 77.8	—
K–5 (asphalt)	08/2009	Two-part epoxy with flint aggregate	†	NB 35.1 SB 35.1	NB 87.8 SB 82.1	NB 68.6 SB 59.9	NB 58.0 SB 55.7
Ramp from northbound I–35 to northbound I–635 (concrete)	08/2009	Two-part epoxy with flint aggregate	†	40.5	69.7	56.3	48.6
Ramp from eastbound K–96 to eastbound US 54 (concrete)	08/2009	Two-part epoxy with flint aggregate	†	46.4	76.1	66.1	47.9

⁑Date unknown.
—No information available.
†Not reported.
NB = northbound; SB = southbound.

2009 Vermont: *Ennis Paint, Inc. Tyregrip® High Friction Surface System* (Kipp and Sanborn 2014)

The Vermont Agency of Transportation (VTrans) conducted a study that evaluated the performance of the Tyregrip® HFST. The installation consisted of a highly modified exothermic epoxy resin two-part binder with calcined bauxite aggregate applied to a 266-foot section of the westbound lane of Route 9 (i.e., VT 9) in Woodford, VT. The section is on a curve with a steep grade of 8 percent and is considered a high crash location.

VTrans intended to install the treatment according to the manufacturer's recommendations using automated equipment; however, due to mechanical issues and trouble operating the truck on the steep grade, the treatment was placed by hand. Partial repairs were conducted in 2009; in 2010, significant cracking and delamination were observed, requiring milling and replacing the section in 2011. Failure was attributed to the underlying cracking and distresses of the existing pavement. Table 4 summarizes the installation information and results. The HFST showed promise in reducing crashes in the short time it was in use. Based on the results of this trial project, VTrans planned to evaluate a section of new or nondistressed pavement with automated installation.

Table 4. Summary of 2009 VTrans HFST evaluation (Kipp and Sanborn 2014).

Site Description	Date	HFST Materials	Cost per Square Yard (U.S. Dollars)	Friction Before⁑	Friction After⁑	Crash Count Before	Crash Count After
VT 9 westbound lane	10/2009	Two-part epoxy resin with calcined bauxite aggregate	26	†	†	13 crashes in 3 yr	1 crash in 3 yr

⁑Date unknown.

†Not reported.

2008–2010 South Carolina: *High Friction Surface Course (HFSC) Before and After Study* (Riddle 2012)

South Carolina Department of Transportation (SCDOT) conducted a simple before and after study on the performance of six HFST installations across the State. One of the installations was on a curvilinear four-lane divided highway, while the other five installations were on freeway ramps with a high percentage of wet crashes. The installations on ramps included signing improvements that also may have increased safety. Table 5 summarizes the installation information and some of the results. The installations occurred in 2008 and 2010, and crash data were available from 3 to 6 yr before and 1 to 3 yr after. The data showed an average crash reduction of 70 percent and a wet-crash reduction of 77 percent. B/C ratios of 23.8 and 3.93 were calculated for total and wet crashes, respectively.

SCDOT reported that recent HFST installations on pavement sections with open-graded courses presented challenges and they are updating their specification to require a double-layer system for such applications for better epoxy coverage.

Table 5. Summary of 2008–2010 SCDOT HFST evaluation (Riddle 2012).

Site Description	Date	HFST Materials	Total Cost (U.S. Dollars Rounded to Nearest Thousand)	Total Crashes per Year Before	Total Crashes per Year After	Wet Crashes per Year Before	Wet Crashes per Year After
I–526 at US 17	11/2010	*	74,000	4	0	3.8	0
I–85 at US 29	06/2009	*	25,000	8.3	0	6.3	0
US 25 (near S–41)	10/2008	*	1,200,000	9.6	4.2	8.1	2.6
SC 31 at SC 9	04/2010	*	160,000	8.2	2.5	3.4	1.2
SC 31 at SC 544	04/2010	*	60,000	2.1	1.9	0.4	0
SC 31 at US 501	04/2010	*	160,000	12.6	5	5.2	2.5

*The specification requirement for all sites was a two-part cold-applied modified exothermic nonvolatile organic compound epoxy resin binder treatment containing an epoxy/amine binder covered with natural or pigmented aggregates with bauxite aggregate.

2006 Florida: *Evaluation of a High Friction Pavement Surface Treatment* (Savolainen et al. 2009)

Florida Department of Transportation (FDOT) conducted a study to determine the effectiveness of HFSTs for improving pavement friction and reducing crashes. The installation consisted of a highly modified exothermic epoxy resin two-part binder with calcined bauxite aggregate applied to an I–75 on-ramp. Table 6 summarizes the installation information and shows a significant increase in friction resistance right after HFST installation. Due to limited availability of crash data for the site after HFST installation, surrogate measures of safety, including mean and variance of vehicle speeds, vehicles traveling over the advisory speed limit, and vehicles encroaching across the lane edge lines, were evaluated to determine the effectiveness of the HFST. After HFST installation, all surrogate measures decreased.

Table 6. Summary of 2006 FDOT HFST evaluation (Savolainen et al. 2009).

Site Description	Date	HFST Materials	Cost per Square Yard (U.S. Dollars)	Friction Before (04/2006)	Friction After (05/2006)	Crash Count Before	Crash Count After
Ramp from Royal Palm Boulevard to northbound I–75	05/2006	Highly modified exothermic epoxy resin two-part binder with calcined bauxite aggregate	†	35	104	11 crashes in 4 yr	2 crashes in 1 yr

†Not reported.

1999 Wisconsin: *Investigative Study of the Italgrip™ System* (Bischoff 2008)

In 1999, Wisconsin Department of Transportation (WisDOT) installed the Italgrip™ HFST at five different locations with high crash rates due to wet/icy surfaces. Four installations were on bridge decks, while one was a section of portland cement concrete (PCC) pavement on State Trunk Highway (STH) 16 with a history of accidents due to black ice. Table 7 summarizes the information for the installation on STH 16 (not the bridge decks) and shows a significant improvement in skid resistance. Although the friction decreased after 5 yr, the FN40Rs were still higher than the pre installation values. Results also show there were no crashes during the 3-year period after HFST installation, compared to five accidents during the 3-year period before HFST installation. Bischoff (2008) reported annual progressive aggregate surface loss due to traffic and snowplow blades. By 2005, a surface loss of 60 percent was estimated at the STH 16 site.

Table 7. Summary of 1999 WisDOT HFST evaluation (Bischoff 2008).

Site Description	Date	HFST Materials	Cost per Square Yard (U.S. Dollars)	Friction Before⁑	Friction After⁑	Friction 5 yr After⁑	Crash Count Before	Crash Count After
Eastbound STH 16 in Waukesha County	10/1999	Two-part polymer resin with manmade aggregate of reworked steel slag	20	43.3	75.4	57.4	5 crashes in 3 yr	0 crashes in 3 yr
Westbound STH 16 in Waukesha County				42.5	75.7	60.3		

⁑Date unknown.

2012 California: *Northern California US 199 – Del Norte County, Case Study* (Cheung and Julian 2015)

This California Department of Transportation (Caltrans) case study prepared by FHWA describes the factors leading to an HFST installation along a section of US 199, a two-lane rural highway in northern California with a high frequency of wet crashes. Previous measures to improve safety, including center lane rumble strips, speed and chevron warning signs, and an open-graded asphalt overlay, were not effective at reducing accidents. The site is located within the Redwood National and State Parks, an environmentally sensitive location, and realignment/geometric improvements at the site require a lengthy and involved process. Table 8 summarizes the information for this case study, though a detailed evaluation with before-and-after friction and crash data was not provided.

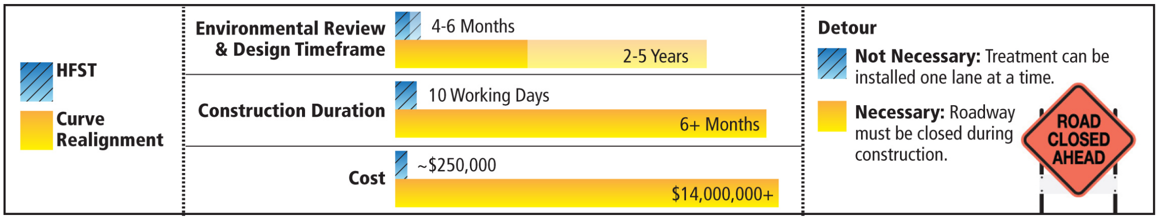
Table 8. Summary of 2012 Caltrans HFST application (Cheung and Julian 2015).

Site Description	Date	HFST Materials	Total Cost (U.S. Dollars)	Friction Before⁑	Friction After (11/2010)	Crash Count Before
US 199	Summer 2012	Double layer of epoxy-resin binder with calcined bauxite aggregate	250,000	†	†	26 wet crashes from 2006 to 2009

⁑Date unknown.

†Not reported.

In 2012, an HFST was installed, which minimized impacts on wildlife and did not require a detour estimated at longer than 8 hr due to the remote location of the site. Figure 6 shows the design timeframe, construction duration, and B/C analysis of installing an HFST over realigning the curve.



Source: FHWA.

Figure 6. Graphic. Comparison of an HFST versus curve realignment (Cheung and Julian 2015).

The literature reviewed previously in this section consists of small-scale case studies and safety analyses limited to simple before-and-after crash count comparisons, typically with small samples, where data were available. Hereafter, the literature reviewed is for studies that are considered more rigorous evaluations of HFSTs in terms of scope or that looked at the relationship between crashes and skid resistance, not necessarily HFST installations.

2015 FHWA: *Evaluation of Pavement Safety Performance* (Merritt et al. 2015)

Merritt et al. (2015) evaluated the safety effects of various pavement treatments, including HFSTs. Due to limitations in readily available data, including suitable reference sites and traffic volume counts, a preferred EB before–after study could not be performed for HFSTs; simpler naïve and C-G before–after analyses were performed depending on the data available (Hauer 1997). All treatment sites were either curves or interchange ramps, and intersection-related, animal, and snow/slush/ice crashes were not included. Merritt et al. (2015) noted that the results are likely biased toward exaggerating the expected crash reductions due to the methodological limitations and reported the results using a method-correction factor applied in the development of the HSM. The results using the naïve and C-G methods are shown in table 9 and table 10, respectively, for total and wet-road crashes. Despite the methodological concerns noted by Merritt et al. (2015), the results indicated that HFSTs can significantly reduce crashes on curves and ramps, particularly wet-road crashes.

Table 9. Results for the naïve before–after study based on all sites (Merritt et al. 2015).

Group	Number of Sites	Crashes After	Wet-Road Crashes After	CMFunction (and Standard Error) for Total Crashes		CMFunction (and Standard Error) for Wet-Road Crashes	
				Biased	With HSM RTM Correction	Biased	With HSM RTM Correction
All ramps	27	111	19	0.387 (0.041)	0.484	0.169 (0.041)	0.211
All curves	43	104	45	0.502 (0.052)	0.628	0.298 (0.048)	0.373

Table 10. Results for the before–after with C-G study for treatment sites for which comparison sites were available (Merritt et al. 2015).

Group	Number of Sites	Crashes After	Wet-Road Crashes After	Total Crashes—C-G		Wet-Road Crashes—C-G	
				Biased	With HSM RTM Correction	Biased	With HSM RTM Correction
Ramps	12	77	8	0.522 (0.092)	0.653	0.111 (0.042)	0.139
Curves	35	104	45	0.607 (0.067)	0.759	0.385 (0.064)	0.481

2014 Texas Transportation Institute: *Evaluating the Need for Surface Treatments to Reduce Crash Frequency at Horizontal Curves* (Pratt et al. 2014)

Pratt et al. (2014) developed an analysis framework, which includes three aspects, to assess the need for surface treatments at curves. The first aspect is developing models to predict vehicle speeds prior to and traversing a curve. The second aspect is using these predicted vehicle speeds to determine the side friction demand at several points within the curve, which is a function of vehicle speed, superelevation, grade, and curve radius. The third aspect is determining the side friction provided for the estimated travelling speed, which uses a formula to estimate skid numbers (SNs) for a desired vehicle speed with a measured SN as the baseline.

Pratt et al. (2014) also developed several SPFs relating crashes on curves of various crash types to traffic volumes, roadway geometry, and measured SNs. Separate SPFs were developed for two-lane, four-lane undivided, and four-lane divided roadways. The crash types for which SPFs were developed did not include property-damage-only (PDO) crashes but otherwise included all, wet-weather, ROR, and wet-weather ROR crashes. The parameter estimates for SNs in the various models can be used to calculate CMFs for SNs. The results indicated that, as skid resistance increases, crashes decrease, particularly wet-weather crashes. The implied CMFs for wet-weather crashes, for an increase in SN of 1.0, were 0.981, 0.967, and 0.969 for two-lane, four-lane undivided, and four-lane divided roadways, respectively. The data summary did not note the pavement types for the curves used by Pratt et al. (2014), but since data collection was not focused on HFSTs, it is likely that few, if any, sites had HFSTs installed. The mean SNs recorded were 44.2, 38.1, and 35.0 for two-lane, four-lane undivided, and four-lane divided roadways, respectively, well below what was expected with the installation of an HFST. Although some higher SNs were recorded, including at least one curve with an SN of 99, the distribution of SNs was not recorded; thus, the relevancy of CMFs based on SNs as they relate to HFSTs could not be assessed.

The site characteristic guidelines from Pratt et al. (2014) were input into a spreadsheet called the Texas Curve Margin of Safety that predicts margin of safety, crash frequency (including CMFs) and travel path distribution. The Texas DOT uses this tool when considering HFSTs for curves to conduct a margin of safety analysis and estimate its potential benefit, including the expected crash frequency reduction.

2016 Virginia Tech Transportation Institute: *A New Approach for Managing Pavement Friction and Reducing Road Crashes* (McCarthy et al. 2016)

McCarthy et al. (2016) conducted research to determine if adding routine skid resistance data to SPFs could improve crash predictions and help identify locations that would benefit from HFSTs. Skid resistance measurements with a continuous fixed-slip measurement device that reports friction data approximately every 3 ft were taken for approximately 2,000 lane-miles in the Salem District of the Virginia Department of Transportation (VDOT). In addition to the measurements, crash and traffic data from 2010 to 2012 were analyzed. Only accidents with wet or dry pavement-surface conditions were taken into account, excluding snow, mud, and others.

To relate the data collected to the VDOT locked-wheel skid tester measurements, McCarthy et al. (2016) applied a correction factor to the GripNumber of 0.007 for each mph greater or less than 40 mph. McCarthy et al. (2016) also used a moving average of 60 ft to identify the lowest friction within each 0.1-mile segment since locked-wheel skid tests are conducted at 40 mph over a 1-second interval and the SN value approximates the average over 58.7 ft.

The analysis found the GripNumber statistically significant for the SPFs, showing that crashes are expected to decrease with increased pavement friction. The SPFs were subsequently applied to the EB approach for preliminary screening of network segments with a high crash risk and prioritized them for HFST installations. A companion paper, discussed next, provides more details on the approach.

2016 Virginia Tech Transportation Institute: *Pioneering the Use of Continuous Pavement Friction Measurements to Develop New Safety Performance Functions, Improve the Accuracy of Crash Count Predictions, and Evaluate Possible Treatments for the Roads in Virginia* (de León et al. 2016)

de León et al. (2016) reported on McCarthy et al. (2016) but also discussed the B/C analysis of pavement treatments to improve friction, asphalt overlays, and HFSTs. To calculate the benefits of a pavement treatment at a specific roadway section, the SPFs developed by McCarthy (2016), including available friction, were used to derive CMFs by dividing the SPF prediction with the assumed reading after treatment divided by the CMF estimate with the current reading. The scale of the GripNumber ranged from 0 to 1.0. An increased GripNumber of 0.1 provided CMFs of 0.894, 0.905, and 0.946 for interstate, primary, and secondary routes, respectively. The CMFs were then applied to the EB estimate of expected crashes at the site. Because the data used to develop the SPFs included all roadways, with friction levels typically lower than that expected for HFSTs, it is unknown if the SPFs applied were accurate for the high range of frictions associated with HFSTs. The models did not account for any interactive effects between friction and horizontal curvature, although both variables were included in one set of models. HFSTs can be beneficial to safety on curves where a higher level of friction is demanded. de León et al. (2016) found the cost savings from crash avoidance through friction treatments was considerable and justified implementing a comprehensive pavement friction management program.

2012 Texas Transportation Institute: *Using High Friction Surface Treatments to Improve Safety at Horizontal Curves* (Brimley and Carlson 2012)

Brinley and Carlson (2012) cited and used the findings from several studies on HFSTs by different organizations to complete the following:

- Quantify the benefits of applying HFSTs on curves using research findings showing their effectiveness at reducing crashes.
- Provide a background on the historical and modern use of HFSTs.
- Show how Federal programs support the use of HFSTs.
- Present the physical components of a common HFST application.
- Derive the value of HFSTs based on a review of studies on their effectiveness.
- Project the benefits of applying HFSTs under various scenarios with consideration of product cost and expected life.
- Recommend HFST placement.

The studies Brinley and Carlson (2012) cited for estimates of safety effectiveness were based on only one or a few sites and are not reliable estimates of the safety effectiveness of HFSTs.

2015 National Center for Asphalt Technology: *High Friction Surface Treatment Alternative Aggregates Study* (Heitzman 2015)

Heitzman (2015) examined the performance of seven alternative aggregate sources in the United States to determine if they provided similar friction performance to calcined bauxite, which is an imported product. The alternative aggregates were granite, flint, basalt, silica sand, steel slag, emery, and taconite. The research was divided into three studies: LAB-1, FIELD, and LAB-2. LAB-1 evaluated HFST test slabs with calcined bauxite and seven alternative aggregates under accelerated laboratory polishing and testing procedures. None of the seven alternative HFST aggregates provided friction comparable to calcined bauxite based on DFT measurements. FIELD evaluated the friction performance of HFST pavement test sections with the same eight aggregates under heavy truck loading in the west end super-elevated curve at the National Center for Asphalt Technology Pavement Test Track. The calcined bauxite section maintained higher friction levels over the 24 mo of accelerated truck traffic conditioning. LAB-2 evaluated the influence of particle size on HFST friction performance and examined other laboratory aggregate tests as a simpler approach to qualifying friction aggregates in HFST specifications. Particle shape and angularity did not correlate to friction. Heitzman (2015) concluded the friction for the evaluated alternative HFST aggregates was not equal to calcined bauxite.

2011 Virginia Tech Transportation Institute: *Review of High-Friction Surface Technologies – Constructability and Field Performance* (Flintsch et al. 2011)

Flintsch et al. (2011) reviewed the constructability and performance of six HFSTs available in the United States. Flintsch et al. (2011) discussed the application procedures and key items for successful installation of the HFSTs, including the epoxy preparation composition, epoxy aggregate placement, existing pavement compatibility with HSFTs, the humidity and moisture of the pavement surface and aggregate, ambient temperature, and curing times. Flintsch et al. (2011) took friction and texture measurements with a DFT, circular track meter, and grip tester at bridge deck overlay locations in Tennessee, Virginia, and Wisconsin where the six HFSTs were installed. Flintsch et al. (2011) concluded HFSTs provide very high initial levels of friction and macrotexture. Based on limited data, Flintsch et al. (2011) estimated that some HFSTs can maintain high friction properties for 10 yr.

2015 Oklahoma State University: *3D Laser Imaging based Real Time Pavement Surface Evaluation for High Friction Surfacing Treatments* (Li et al. 2015)

Researchers at Oklahoma State University developed a 1-millimeter resolution three-dimensional laser imaging sensor technology. This technology was used to evaluate 23 HFST installations across the United States that were part of the FHWA SEaHC Program. Cracking, rutting, macrotexture, roadway geometry, and HFST surface loss were assessed with the technology at highway speeds and with full lane width coverage. Friction was also measured with FHWA's highway friction fester (HFT) to show FN40R comparisons before and after HFST installation. Li et al. (2015) found the HFST sections had statistically higher surface texture (i.e., mean profile depth (MPD)) and FN40Rs than the adjacent sections without HFSTs. Li et al. (2015) reported several sites with HFSTs exhibiting isolated failures, but available software was not capable of estimating HFST surface loss.

HFST SPECIFICATIONS

U.S. Specifications

A review of current State highway agency specifications/special provisions for furnishing, applying, and accepting HFSTs was conducted, including those for California, Florida, Georgia, Illinois, Kansas, Kentucky, Maryland, Nebraska, Pennsylvania, South Carolina, Tennessee, Texas, and Virginia. AASHTO MP 41-19 was reviewed as well, providing a baseline specification off which many State specifications are based. Although specific requirements (e.g., test methods and thresholds) are not provided for brevity, the following items are covered in the majority of State highway agency specifications.

Materials

Most specifications either indicate the type of binder resin to use or require it to be a material from the agency's qualified/approved products list (QPL/APL). Different QPLs/APLs can be provided for asphalt and concrete pavements. Epoxy resin is the most common binder resin, but polyester resin is becoming more common; methyl methacrylate (MMA) is another option generally permitted. Physical requirements and corresponding test methods for properties, such as viscosity, gel time, durometer hardness, tensile and compressive strengths, cure rate, water absorption, and adhesive strength, are provided in most specifications. AASHTO MP 41-19 provides separate requirements for polymeric and MMA resins.

Virtually all the specifications reviewed specify calcined bauxite for the aggregate and physical/mineralogical requirements and corresponding test methods for properties, such as polish stone value, resistance to degradation, gradation, moisture content, and minimum aluminum oxide content. Most agencies use AASHTO T 96/ASTM C131, *Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*, for resistance to degradation, but Tennessee Department of Transportation (TDOT) recently switched to ASTM D7428, *Standard Test Method for Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus*, which may be more appropriate for smaller aggregates like those used for HFSTs (AASHTO 2002; ASTM 2015).

Most specifications require certification from the binder and aggregate manufacturers or test results from an independent laboratory demonstrating the materials meet agency specifications.

Installer Qualifications

Most specifications require installers have prior experience installing HFSTs, including a description of previous experience (e.g., minimum of three projects and 5,000–10,000 square yards), test results (e.g., friction measurements), and references from owner agencies. Some agencies allow work from installers not meeting minimum requirements if they are approved by the manufacturer and a manufacturer representative is on site during the installation.

Construction Practices

Items covered under the construction section of the majority of specifications include materials storage, weather and pavement-surface temperature requirements, pavement surface preparation, hand and mechanical mixing, application of the HFST, and curing.

Surface preparation items include removing pavement markings in areas to be treated, washing contaminated surfaces, pretreating cracks, cleaning asphalt surfaces with mechanical sweepers and air washing/vacuum sweeping, shot blasting, and vacuum sweeping concrete pavements.

If mechanical application is required, hand mixing and application is typically allowed for areas where mechanical application is not practical or economical, such as segments less than 250 ft in length or areas less than 200–800 square yards, depending on the agency. Mechanical application is not permitted by some agencies on sites with steep slopes (e.g., greater than 2.5 percent).

Quality control (QC) plans are required by most agencies. QC plans require an installer to describe in detail all personnel; equipment; materials; surface preparation, resin mixing and application, and aggregate application methods; and curing, sweeping, and opening to traffic requirements. An installer then submits the QC plan to the agency for approval prior to installation.

Some agencies require a test strip be constructed prior to full-scale installation. Test strips allow an installer to demonstrate their installation practices so the agency can verify the full-scale installation meets project requirements.

Acceptance Testing

The majority of specifications require the HFST be tested within 60 to 90 d after installation and meet a minimum FN40R per AASHTO T 242, *Standard Method of Test for Frictional Properties of Paved Surfaces Using a Full-Scale Tire*, of at least 65. TDOT requires FN40R of 70, and KYTC requires FN40R of 75 (AASHTO 2018).

Some agencies require additional testing of the in-place surface characteristics. For example, Georgia Department of Transportation (GDOT) specifies testing with a DFT within 5 d after installation and again 90 d after installation, requiring a value greater than 0.9 at 5 d and a value greater than 0.8 required at 90 d. TDOT and the Maryland State Highway Administration both require a minimum mean texture depth (per ASTM E965, *Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique*) or MPD (per ASTM E2157, *Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter*) of 1.0 mm (ASTM 2019a; ASTM 2019b).

Some agencies require a performance guarantee on HFSTs. For example, SCDOT requires the HFST be tested within 360 to 390 d after installation (after approximately 1 yr) and the average FN40R be at least 64 with no significant aggregate surface loss (e.g., at least a 90-percent intact surface).

International Specifications

The United Kingdom has the most extensive HFST usage history outside the United States with HFST installations dating back to the 1960s and widespread usage since the late 1980s (RSTA 2013). In 2011, the Road Surface Treatments Association (RSTA) produced *Code of Practice for High Friction Surface Treatments*, which provides best practices for selecting and installing high-friction surfacing systems to maximize their performance and durability (RSTA 2011). *Code of Practice for High Friction Surface Treatments* is based on HFST installations that improve skid resistance at high-risk locations in the United Kingdom. High-risk locations are highlighted as approaches to major junctions, approaches to pedestrian crossings, sites with grades steeper than 10 percent, and curves with radii smaller than 500 m (1,640 ft).

Table 11 summarizes the current Highways England requirements for minimum aggregate polished stone value (PSV) based on site characteristics (e.g., roadway type and traffic), showing that only HFSTs can provide the necessary friction at certain locations with a relatively high investigatory level friction threshold (Highways England 2006).

Code of Practice for High Friction Surface Treatments cites the Monitoring Local Authority Safety SchemES study of road safety schemes in the United Kingdom that found an overall weighted crash reduction of 35.1 percent (10/90 percent rural/urban site balance) for HFSTs between 1991 and 2001 (Gorell and Tootill 2001). *Code of Practice for High Friction Surface Treatments* also highlights the British Board of Agrément Highways Agency Product Approval Scheme (BBA HAPAS) certification process for ensuring that both the HFST product and HFST installer are certified for use on a project. BBA HAPAS provides some best practices for surface preparation prior to HFST installation, recommended specifications for aggregate properties, and guidance on performance criteria for projects with a performance guarantee.

Table 11. Road surfacing aggregate PSV requirements based on site characteristics from Highways England *Design Manual for Roads and Concrete Bridges* (Highways England 2006).

Site Category	Site Description	IL	Minimum PSV Required for Given IL, Traffic Level, and Type of Site									
			Traffic (CV/Lane/Day) at Design Life									
			0–250	251–500	501–750	751–1,000	1,001–2,000	2,001–3,000	3,001–4,000	4,001–5,000	5,001–6,000	Over 6,000
A1	Motorways where traffic is generally free-flowing in a relatively straight line	0.30	50	50	50	50	50	55	55	60	65	65
		0.35	50	50	50	50	50	60	60	60	65	65
A2	Motorways where some braking regularly occurs (e.g., on 300-meter approach to an off-slip)	0.35	50	50	50	55	55	60	60	65	65	65
B1	Dual carriageways where traffic is generally free-flowing in a relatively straight line	0.30	50	50	50	50	50	55	55	60	65	65
		0.35	50	50	50	50	50	60	60	60	65	65
		0.40	50	50	50	55	60	65	65	65	65	68+
B2	Dual carriageways where some braking regually occurs (e.g., on 300-meter approach to an off-slip)	0.35	50	50	50	55	55	60	60	65	65	65
		0.40	55	60	60	65	65	68+	68+	68+	68+	68+
C	Single carraigeways where traffic is generally free-flowing in a relatively straight line	0.35	50	50	50	55	55	60	60	65	65	65
		0.40	55	60	60	65	65	68+	68+	68+	68+	68+
		0.45	60	60	65	65	68+	68+	68+	68+	68+	68+
G1/G2	Gradients >5 percent longer than 50 m per HD 28, *Skid Resistance*	0.45	55	60	60	65	65	68+	68+	68+	68+	HFS
		0.50	60	68+	68+	HFS	HFS	HFS	HFS	HFS	HFS	HFS
		0.55	68+	HFS	HFS	HFS	HFS	HFS	HFS	HFS	HFS	HFS
K	Approaches to pedestrian crossings and other high-risk situations	0.50	65	65	65	68+	68+	68+	HFS	HFS	HFS	HFS
		0.55	68+	68+	HFS	HFS	HFS	HFS	HFS	HFS	HFS	HFS
Q	Approaches to major and minor junctions on single and dual carriageways where frequent or sudden braking occurs in a generally straight line	0.45	60	65	65	68+	68+	68+	68+	68+	68+	HFS
		0.50	65	65	65	68+	68+	68+	HFS	HFS	HFS	HFS
		0.55	68+	68+	HFS	HFS	HFS	HFS	HFS	HFS	HFS	HFS
R	Roundabout circulation areas	0.45	50	55	60	60	65	65	68+	68+	HFS	HFS
		0.50	68+	68+	68+	HFS	HFS	HFS	HFS	HFS	HFS	HFS
S1/S2	Bends (radii <500 m) on all types of roadways, including motorway link roads, and other hazards that require combined braking and cornering	0.45	50	55	60	60	65	65	68+	68+	HFS	HFS
		0.50	68+	68+	68+	HFS	HFS	HFS	HFS	HFS	HFS	HFS
		0.55	HFS	HFS	HFS	HFS	HFS	HFS	HFS	HFS	HFS	HFS

1 m = 3.28 ft.

CV = commercial vehicles; HFS = high-friction surface; IL = investigatory level.

LITERATURE REVIEW CONCLUSIONS

The literature review of HFSTs at the commencement of this current study in 2015 found few materials of direct relevance, likely because this is a relatively new treatment with a limited number of installations in the United States. The bulk of literature on HFSTs is related to case study evaluations of one or only a few HFST installations. Some literature was found investigating the available friction from various HFST materials. Some literature was also found relating crash expectancy to the level of road friction available. However, there was a lack of information on the safety effects of HFSTs as measured through a large-scale and methodologically reliable study. A review of HFST specifications from various States was also undertaken.

The literature review provided relevant information considered during this current study, including the following:

- HFST are installed to improve safety. Therefore, RTM is a significant issue to contend with for a safety evaluation.
- Most HFST are installed on curves and interchange ramps. Limited use of HFSTs for intersection approaches or short sections on steep grades has been reported, but not enough to be considered for a safety evaluation.
- Pavement friction is significantly improved immediately after HFST installation, but there is no established trend for how friction decreases over time.
- Long-term performance of HFSTs is not consistent. Early failures are observed at some installations, while others see excellent long-term performance. This is likely due to a general lack of institutional knowledge of best practices for HFST materials and installation specifications in the early stages of deployment. Some studies attribute early failures to issues during the installation process, including the following:
    - Inappropriate pavement surface preparation.
    - Installation on highly distressed pavements.
    - Inappropriate resin binder thickness on coarse-textured and open-graded surfaces.
    - Deterioration due to heavy traffic when using aggregates other than calcined bauxite.
- Available pavement friction has a measurable and significant effect on expected crash rates.
- Studies on the long-term safety benefits of HFSTs are limited because few sites have been evaluated and/or state-of-the-art statistical methodologies cannot be applied. The results indicate large crash reductions, particularly wet-weather crashes.
- The safety effects of HFSTs are likely related to the friction demand and the level of friction provided prior to treatment. The development of CMFunctions that are sensitive to these variables is desirable.

CHAPTER 3. DATA COLLECTION

OVERVIEW OF THE DATA-COLLECTION PROCESS

Researchers developed and submitted to FHWA a thorough data-collection plan before beginning the data-collection process at the commencement of Phase II of this current study. The plan summarized the types of data to be collected and listed the sites from various States included in the current study. Key components of the data-collection process included the following:

- Identifying HFST sites.
- Collecting crash data.
- Collecting friction data.
- Colleting roadway and pavement data.
- Identifying reference sites.

Climatic data collection was initially part of the data-collection effort. However, the research team found the effort required to collect usable climatic data over a large sample of HFST locations unjustifiable, especially considering the limited benefits based on the results of a previous pavement safety performance study (Merritt et al. 2015).

IDENTIFYING HFST SITES

The process to identify sites for inclusion in this current study was summarized in a memo to FHWA at the end of Phase I. The research team contacted all State highway agencies with known HFST programs to identify sites available for inclusion in this current study. Preference was given to States with large and/or mature HFST programs able to provide a large population of sites for analysis.

Specific criteria for selecting sites included the following:

- Site type—curves, ramps, and intersections were the focus of the HFST evaluation. Although there is a large population of HFST installations on bridges throughout the United States, the purpose of bridge treatments is typically preservation (i.e., sealing the bridge deck surface) with friction enhancement as a secondary benefit. A number of the curves or ramps included in the final analysis had bridge decks within the treated section.

- In-place and planned sites—site selection sought to capture a mixture of existing HFST sites as well as planned sites. Existing sites provide more after-period crash data, particularly for older sites. Planned sites provide an opportunity to test pavement friction before and after HFST installation. Planned sites were limited to those installed during the 2016 and early 2017 construction season.

- HFST materials—HFST sites selected for evaluation were limited to those consisting of calcined bauxite aggregate over a polymeric resin binder. Although alternative aggregates have been used in a number of States, calcined bauxite is the only aggregate permitted in AASHTO MP 41-19 and most State specifications (AASHTO 2019).

Table 12 summarizes the initial number of sites by State and site type (e.g., curve, ramp, intersection) initially proposed before beginning the data-collection process.

Table 12. Initial sites planned for testing.

	Number of Curves		Number of Ramps		Number of Intersections	
State	**In Place**	**Planned**	**In Place**	**Planned**	**In Place**	**Planned**
Georgia	26	98	—	—	—	—
Kentucky	54	0	23	0	1	0
Louisiana	18	77	—	—	—	—
Pennsylvania	85	22	—	—	—	—
Texas	5	20	—	—	—	—
West Virginia	25	14	—	—	—	—
Arkansas	—	—	0	24	6	0
Florida	—	—	15	3	4	0
South Carolina	—	—	24	0	2	0
Total	213	231	62	27	13	0

—No information available.

Friction data were considered essential for the analysis, so the ability to efficiently collect friction data was a key consideration in site selection. Additional considerations in site selection included the following:

- Availability of before-and-after friction data—priority was given to locations where researchers could collect friction data before and after HFST installation while ensuring the ability to collect after-period crash data. An estimate of before-treatment friction was important to link any change in safety to friction improvement. Four States (Arkansas, Louisiana, Georgia, and Pennsylvania) were identified as having a number of HFST sites that could be tested before and after HFST installation during the timeframe of this current study.

- Proximity to other sites—focusing on sites clustered in jurisdictions in relative proximity to one another allowed for more efficient friction data collection by minimizing driving distance between sites. Preference was given to sites on a single roadway over sites scattered on various roadways.

- Number of sites in the same jurisdiction—States with a large number of sites provide the opportunity to evaluate a large population of HFST sites more efficiently in terms of crash data and friction data collection than States with only one or two sites.

Table 13 summarizes the final list of sites planned for inclusion in this current study based on the initial data-collection plan. The final number of sites for each State included in the crash-data analysis is summarized in the following section.

Table 13. Final States and number of sites for data collection.

State	Number of Curves		Number of Ramps		Number of Intersections	
	In Place	Planned	In Place	Planned	In Place	Planned
Arkansas	5	0	17	0	6	0
Georgia	43	93	—	—	—	—
Kentucky	58	0	27	0	1	0
Louisiana	27	90	—	—	—	—
Pennsylvania	85	22	—	—	—	—
West Virginia	25	14	—	—	—	—
Total	243	219	44	0	7	0

—No information available.

Final Site Selection

Rationale for final site selection included the following for each State:

- Arkansas:
  - Large number of planned ramp locations for before–after evaluation.
  - Close proximity to other States with a large number of sites.
- Georgia:
  - Large number of sites in place and planned for 2016.
  - Close proximity to other States with a large number of sites.
  - Sites are generally clustered together in a few counties, making friction data collection efficient.
  - Curve selection represents a systemic approach to HFST deployment.
- Kentucky:
  - Large number of curves and ramps in place.
  - Close proximity to other States with a large number of sites.
  - Some of the oldest HFST installations that provide significant after-period evaluation and HFST performance over time.
- Louisiana:
  - Several curves in place and a large number planned for 2016.
  - Close proximity to other States with a large number of sites.
  - Curve site selection represents a systemic approach (different from Georgia) to HFST deployment.
- Pennsylvania:
  - Large number of sites in place and planned for 2016.
  - Primarily curves (similar to Georgia and Louisiana) but not representing a systemic approach as in Georgia and Louisiana.
- West Virginia:
  - Large number of sites in place and planned for 2016.
  - Many of the in-place sites are 4 to 5 yr old.
  - Close proximity to other States with a large number of sites.

Reasons for Exclusion

The following factors led to the exclusion of some sites from the original HFST site list:

- Reliability of friction data—some of the operational limitations of the HFT combined with site characteristics either precluded friction data collection on site or resulted in unusable friction data after processing. Ramps in Florida and South Carolina were excluded for this reason.

- Small number of sites—intersections were ultimately excluded from the final analysis due to the relatively small number of sites. There was significant variability of the characteristics of intersections, and most significantly, it was difficult to collect friction data at intersections.

- HFSTs applied to only one lane—for a number of two-lane rural-roadway curves, only one of the two lanes (or only one direction) had an HFST installation. Since crash data on two-lane roadways are not always coded with the direction of travel, it was difficult to assign crashes to one direction of travel and determine the true effects of HFST installation.

- Little or no after-period crash data—a number of planned sites that were tested for friction before HFST installation were delayed due to construction issues. Therefore, researchers lacked sufficient after-period crash data or post installation friction data.

- Removal of sites—a number of sites—particularly older ones—intended for inclusion no longer existed when the friction data-collection process began. Several of these sites were still tested for friction in case they could be useful reference sites.

CRASH DATA

Crash data were collected for each HFST and reference site for the periods before and after HFST installation. Ideally, a minimum of 3 yr of before-period and 3 yr of after-period crash data were compiled. While 3 yr of before-period data were generally not a problem, 3 yr of after-period data were only possible for older HFST installations. Many HFST sites included in this current study were installed in 2016 and 2017, limiting after-period data. The amount of after-period data was highly dependent on the currency of an agency’s crash database. Researchers decided to collect and use before–after analysis crash data for all sites with a minimum of a 1-year after period.

Method

The collection of crash data varied from State to State in terms of how the data were collected and the level of information contained in the crash data. Crash data were either provided directly by volunteer States or gathered from agency crash databases. A few States provided summary crash data for specific HFST sites using their internal processes for assigning crashes to the curve/ramp of interest.

For crash data not provided directly by volunteer States, researchers used either publicly available or agency-provided crash databases. Although raw crash data with all possible variables were desired, researchers were limited to the various levels of data available for each State. The following were of most importance in the crash data:

- Crash date.
- Location type (e.g., intersection, nonintersection).
- Crash type (e.g., ROR, sideswipe).
- Crash severity (e.g., PDO, injury, fatal).
- Vehicle type.
- Pavement condition.
- Reported driver action.
- Direction of travel.
- Reference location (e.g., milepost).

The Summary of Data Collection by State section summarizes the data available for each State.

Challenges

Researchers encountered a number of challenges when collecting crash data for HFST installations, including the following:

- Accurately capturing curve-related crashes—because HFSTs on curves are typically short (as are the curves on which most HFSTs are installed) accurate milepost information and/or global positioning system (GPS) coordinates in crash records is critical. Researchers surmised that many crashes without accurate milepost information and/or GPS coordinates went uncaptured for this reason. When available, researchers relied on curve-related crash coding when milepost information and/or GPS coordinates were not available or when there was ambiguity about where on the curve a crash occurred.

- Accurately capturing ramp-related crashes—similar to the challenge for curves, it was difficult to ensure the accuracy of ramp-related crashes if GPS coordinates were missing or if one or both of the intersecting roadways was not recorded. When available, researchers relied on ramp-related crash coding when ramp identifiers and/or GPS coordinates were ambiguous or not available.

FRICTION DATA COLLECTION

Underlying pavement and HFST friction were essential components of the data for analysis. Agency-provided friction data for HFST sites were limited—depending on the State—and were collected using a variety of methods, making useful comparisons difficult. To help ensure consistency of the pavement and HFST friction data used in the analysis, researchers collected friction data on all HFST sites, including underlying and/or surrounding pavement.

Method

Friction data have been traditionally collected in the United States using an ASTM E274 locked-wheel skid tester (LWST). An LWST is a trailer-based testing system that measures friction by completely locking up the test wheel and recording the average sliding force for 3 s and reporting a 1-second average after reaching the fully locked state (i.e., 100-percent slip). Thus, with a 40-mph test speed, a 1-second test time is equivalent to testing the pavement surface for approximately 59 ft. The fully locked requirement means that measurements can only be recorded periodically over short intervals. Reporting one test per mile results in approximately 1.1 percent of the pavement surface being tested. Because testing with a trailer-based unit with a locking wheel in tight curves and intersections can be challenging or prohibitive, an LWST may not adequately characterize pavement friction in these locations.

Continuous friction-measurement systems report measurements as frequently as every 1 ft over the section of pavement. This allows for any variations in friction to be measured and quantified. Because of this advantage of continuous friction measurement and the nature of the location of most HFST installations, friction data for this current study were collected using FHWA's 6875H HFT (figure 7). The HFT is a continuous fixed-slip measurement device that complies with ASTM E2340, *Standard Test Method for Measuring the Skid Resistance of Pavements and Other Trafficked Surfaces Using a Continuous Reading, Fixed-Slip Technique*, and provides a continuous measurement of friction at prevailing highway speed (ASTM 2006). Friction data are reported by the HFT every 1 ft over the length of the pavement surface. The HFT uses a smooth-tread test tire that complies with ASTM E1551, *Standard Specification for a Size 4.00-8 Smooth Tread Friction Test Tire*, located in the left wheelpath of the lane with a slip ratio of 14 percent (ASTM 2016). The HFT applies a 0.5-millimeter water film to the pavement surface in front of the test tire during testing. The HFT is also equipped with a texture laser to estimate pavement texture as MPD.

Source: FHWA.

Figure 7. Photograph. FHWA's HFT.

Operating as a low slip ratio, the HFT measures friction numbers closer to the peak friction number for a pavement surface, as opposed to the fully locked (i.e., 100 percent slip) friction LWST. HFT measurements are more representative of the friction available from a pavement surface for vehicles with antilock brakes. As such, the friction numbers reported by the HFT are generally higher than those measured by highway agencies using an LWST. Because friction measurement is highly dependent on the method used by the device (e.g., fixed slip versus fully locked), the tire used by the device, and the characteristics of the pavement surface itself (e.g., micro- or macrotexture), friction numbers from the HFT are not directly comparable to the LWST. Therefore, differences in friction between HFSTs and the underlying pavement as reported in this current study were evaluated based on HFT friction test results only.

Testing Protocol

In general, one run was used to collect friction data in each lane at each site. However, if any anomalies were observed during friction data collection, repeat measurements were taken as needed and unreliable data were disregarded. Event markers were used to identify reference points in the data that could be retraced to field locations and anomalies within the test site, including bridge decks, pavement changes, pavement markings within the lane, and inconsistencies during testing (e.g., braking, deviation from wheelpaths).

A test speed of 40 mph was selected as the target for all sites, regardless of higher posted speeds. However, a number of sites limited testing speed to anywhere from 25 to 35 mph due to curve radius or prevailing traffic conditions. During trial runs, researchers noted that speeds less than 25 mph resulted in unreliable friction data, so 25 mph was established as the minimum test speed.

Of particular importance for this current study was collecting friction data before and after HFST installation. This was possible for most planned sites, but for in-place sites, friction data were collected on the underlying pavement leading up to (i.e., lead-in) and away from (i.e., lead-out) the HFST as a surrogate measure of pavement friction without an HFST. However, lead-in/lead-out pavement friction is not the same as the actual pavement prior to HFST installation due to the effects of aging on pavement friction and potential variation in friction through a curve. The ability to collect lead-in and lead-out friction data on surrounding pavement varied widely from site to site depending on the location of the site in relation to other curves, intersections, and so on. Researchers attempted to collect approximately 300–500 ft of lead-in and lead-out friction data whenever possible. For a number of sites, only 100–200 ft of data were collected.

Data Reporting

The HFT was selected for friction data collection due to its ability to measure friction continuously and report results at high resolution (i.e., every 1 ft), thereby capturing any changes in friction within a given curve or ramp. However, the quality of the pre-HFST friction data collected was inadequate. The issues related to friction data collection are discussed in the following section and in the companion report FHWA-HRT-20-062.

Friction data were manually processed for each site, and the average friction number over the HFST and the underlying or abutting (i.e., lead-in/lead-out) pavement was reported. For sites with two or more lanes, the average friction number for all lanes was reported. Any significant differences in friction between lanes was noted in case further evaluation was needed to determine the cause. Any significant difference in lead-in and lead-out friction was also noted. For the purposes of reporting herein, HFT Mu is used to distinguish HFT friction measurements from other friction measurements, and where appropriate, HFT(*S*) is used to designate HFT friction at speed in mph.

Challenges

Researchers encountered many challenges with friction data collection that effectively limited the number of sites tested and included in the current study. Some of these challenges included the following:

- Inability to collect friction data on stop-controlled and most signal-controlled intersections—the HFT must be operating at a relatively constant speed, as braking and acceleration affect the friction data. As such, researchers were unable to test HFST sites at stop-controlled intersections. Likewise, signal-controlled intersections were difficult to test, as testing needed to coincide with a green signal. Although researchers able to test several signal-controlled intersections, the total number was small.

- Inability to collect friction data on tight-radius ramps and curves—because the HFT must operate at a minimum of 25 to 30 mph, many tight-radius ramps and curves with advisory speeds less than 25 mph were excluded from testing due to safety concerns.

- Inability to collect friction data on ramps terminating at intersections—many of the ramps in the current study terminated at intersections, requiring the HFT to stop collecting data well in advance of the end of the ramp. While it was still possible to test many ramps with this configuration, several had to be eliminated.

- Lag in friction data at the beginning of HFST sections—due to the nature of collecting friction data via the HFT, friction numbers build over the first 100–200 ft. This required some post processing of the friction data to ensure the true friction numbers were reported and not skewed by this lag area. In some cases (i.e., short HFST sections), the data were unusable.

- Unforeseen mechanical failures—several mechanical breakdowns of the HFT led to delays in collecting data and ultimately reduced the scope of friction data collection.

ROADWAY AND PAVEMENT DATA

Similar to crash data, roadway and pavement data collection varied greatly from State to State in terms of the level of information available and how the data were collected. Roadway and pavement data were either provided directly by volunteer States, either as summary data or from a roadway information database, or gathered from publicly available databases. The following sections summarize the data sought by the researchers. Data provided by individual States are summarized in the Summary of Data Collection by State section.

Roadway Data

Roadway data collected for this current study included the following:

- Roadway classification (e.g., urban, rural, interstate, noninterstate).
- Traffic (i.e., annual average daily traffic (AADT)).
- Number of lanes.
- Lane width.
- Median type (e.g., divided, undivided).
- Geometrics (e.g., curvature, cross-slope/superelevation, grade).
- Shoulder type and width.
- Roadside features (e.g., driveways, guardrails).
- Safety features (e.g., striping, special signage, rumble strips/stripes).
- Intersection control type (e.g., stop-controlled, signalized).

Pavement Data

Pavement data collected for this current study included the following:

- Original/underlying pavement:
    - Asphalt pavement type (e.g., dense graded, open graded, surface treatment).
    - Concrete pavement type and texture characteristics (e.g., tined, turf drag, grooved, diamond ground).
    - Pavement age.

  - Pavement condition.
  - Pavement materials (e.g., aggregate materials, asphalt/concrete mixture).

- HFST information:
  - Installation date.
  - HFST vendor/product.
  - Installation process used (e.g., manual or automated application).
  - Single/double layer application.
  - Limits/length of installation.
  - Material properties (e.g., binder and aggregate type/properties).
  - Any documented issues during installation.

To help supplement agency-provided roadway data, researchers collected other field data during friction data collection, including the following:

- Pavement cross-slope using an inclinometer mounted to the HFT—while these data were collected from the majority of sites, analysis of the data did not provide reliable results for accurately assessing the cross-slope that could be used in the final crash-data analysis.

- GPS data to assist in estimating curve radius and locating sites—an algorithm for estimating curve radius from GPS data was developed and used when agency-provided curve data were not available.

- Dashcam video to assist in assessing site features and pavement type and pavement/HFST condition—this included documentation of shoulder and median characteristics, advisory speed, and other safety features (e.g., chevrons, arrow boards, guardrails). These data were not valuable for the final crash-data analysis but served as a backup to verify certain site characteristics if needed.

Challenges

Researchers encountered numerous challenges with roadway data collection that limited its usefulness in the final crash-data analysis. Some of these challenges included the following:

- Limited traffic data history—although researchers gathered current traffic data (i.e., AADT) for most sites, historical data were largely unavailable.

- Limited traffic data for ramps—for a number of ramps, traffic data were unavailable, as agencies do not commonly collect ramp traffic data.

- Underlying pavement type and history—while researchers assessed the basic pavement type (e.g., bituminous concrete or PCC), they were unable to discern specific types of each (e.g., open-graded, dense graded, or SMA for bituminous surfaces). Agency pavement history databases were generally unhelpful in confirming information other than basic pavement type.

- Curve radius discrepancies—although several States provided curve data (e.g., degree of curvature or radius of curvature) from geographic information system (GIS)-based roadway inventories, a given curve may consist of multiple arc segments with different radii, making it difficult to assign a single radius to each curve. In general, the tightest curve radius was assigned to the site after checking that the segment length for the arc was reasonable. Curve radii for ramps were estimated from GPS data collected during friction data collection, as this information is not typically found in agency curve inventories.

- Outdated roadway inventory databases—particularly for rural roadways and ramps, roadway inventory databases are usually not updated annually, and information found in such databases may be out-of-date.

- Unverifiable HFST installation date—few States maintain construction-related details, such as actual installation dates, in centralized databases. In many cases, researchers contacted agency district or county personnel to determine actual installation timeframes. In some cases, only the construction acceptance data, which were from many months or more than 1 yr after actual installation, were available.

REFERENCE SITES

Identifying reference sites for this current study proved to be one of the most challenging aspects of the data-collection effort. Most States do not have a readymade database of curves and ramps. Additionally, the large variety of curve and ramp characteristics made identifying reference sites difficult. The methods used to identify candidate reference sites are summarized in the following section.

Upstream/Downstream

One of the methods used to identify reference sites was to look for similar sites upstream and downstream or in the same vicinity (e.g., city, county, district) as HFST sites, ideally on the same roadway. This method worked best with ramps, as agencies generally design interchanges to consistent standards. However, a number of rural roadway curve reference sites directly upstream or downstream from one or more HFST sites were identified with this method. Challenges associated with this method included the following:

- Finding the RampID or roadway mileposts for the reference ramp or curve of interest so crash data could be collected.

- Gathering additional roadway information (e.g., traffic, curvature) already compiled by the agency for the HFST site but not for reference sites (i.e., additional roadway data gathering).

Curve Inventory

Another method for identifying reference sites was using agency curve inventories or GIS-based curve data to identify curves of similar geometry to the treated curves. However, this method only helps identify curves with similar geometry and still requires comparison of other characteristics (e.g., traffic) to determine the suitability of a reference site. Challenges associated with this method include the following:

- Ramp curvature data are not typically found in curve databases.
- GIS-based curve data are generally segmented by smaller arcs of varying length within a given curve, and identifying which arc best represents the curve of interest within the treated sites, then matching to arcs of potential reference sites, is a tedious process.

Similar Systemic Criteria

For States with systemic HFST programs (Georgia and Louisiana for the current study), reference sites can be identified from untreated roadways with characteristics similar to those identified for treatment by the systemic process. Under systemic treatment programs, curves without any crash history may be treated. Challenges associated with this method include the following:

- Systemic programs inherently treat locations/curves without any crash history, and selecting sites from nontreated roadways further increases the number of null-crash sites.
- Roadways with a systemic treatment likely have different crash rates than treated roadways despite having the same characteristics.
- After identifying a particular roadway, individual curves and mileposts must be identified so crash data can be obtained, which can be a tedious process; curve databases/inventories can help with this.

SUMMARY OF DATA COLLECTION BY STATE

Arkansas

Arkansas has a large but relatively new HFST program. The Arkansas Department of Transportation (ARDOT) provided an initial list[1] of approximately 50 in-place and planned HFST sites for curves, ramps, and intersections, with all sites installed between July 2015 and August 2016. From the initial list, approximately 30 ramps and intersections were selected for data collection. While the initial data-collection plan involved testing all the planned ramps before HFST installation, delays in friction data collection led to testing after HFST installation. In addition to ramps and intersections, friction data were also collected from several curves.

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[1] These are not published data. ARDOT provided this informal list to researchers for analysis in 2016. ARDOT explicitly stated that this list with specific locations cannot be published.

Crash Data

Statewide crash databases[2] were provided by ARDOT for 2011–2017 for researchers to gather data for treated and reference sites.

Reference Sites

Reference sites were identified in the vicinity of HFST sites. For curves, similar curves upstream, downstream, and along adjacent roadways were identified. For ramps, similar ramps in the vicinity (i.e., the same or adjacent county) were identified. After sites were chosen, GIS data were used to identify the RoadID and mileposts for collecting crash and roadway data.

Roadway Data

ARDOT provided a summary of roadway data based on the list of treated and reference sites from researchers. Roadway data included the following:

- Classification (e.g., urban, rural).
- Pavement type.
- Safety features.
- Roadside features.
- Traffic (i.e., AADT for 2011–2016).
- Speed limit (e.g., posted and advisory).
- Median and shoulder info.
- Number and width of lanes.

Friction Data

Researchers planned to test most ramps for friction before and after HFST installation, but construction delays prohibited collecting friction data before HFST installation; therefore, all friction data were collected after HFST installation. Lead-in and lead-out pavement were used to estimate friction of the underlying pavement. Table 14 summarizes the friction data for Arkansas HFST sites.

Table 14. Summary of friction data for Arkansas sites.

		Speed (mph)		**HFST Friction (HFT Mu)**		**Underlying Pavement Friction (HFT Mu)**		**Change in Friction (Percent)**	
Type	**Number**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**
Ramp	17	27.30–43.10	39.30	0.80–1.00	0.95	0.33–0.71	0.49	+35–203	+104
Curve	5	39.30–40.70	40.00	0.89–0.95	0.91	0.41–0.61	0.52	+48–122	+81
Intersection	6	38.10–40.80	39.70	0.79–0.91	0.85	0.35–0.69	0.43	+25–160	+108

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[2] These are not published data. ARDOT shared the data from this internal database with researchers for analysis in 2016.

Georgia

Georgia has one of the largest HFST programs in the United States in terms of the total number of sites and treated area. GDOT's program is relatively new, with installations beginning in 2014. Sites provided by GDOT for this study resulted from a systemic HFST program called Sharp Curve Treatment Process focusing on rural roadway curves. Ball-bank indicator readings of 12 or more at curves when driven at the posted speed limit were selected for HFST installations.

GDOT provided an initial list[3] of approximately 40 in-place and 285 planned sites across 55 counties primarily on rural roadway curves. Based on the site-selection criteria discussed previously, sites were selected to maximize the efficiency of friction data collection while also maximizing the number of planned sites for friction testing before and after HFST installation. Researchers established an initial list of 26 in-place and 98 planned sites. The final site list for this current study included 43 in-place sites and 93 planned sites. Of the 93 planned sites, 85 were tested before and after HFST installation; the remainder were only tested before HFST installation.

Crash Data

GDOT provided summary crash data[4] for before and after periods for individual sites. Crash data ranged from 2009 to 2018 depending on the HFST installation date.

Reference Sites

GDOT did not provide any reference sites.

Roadway Data

GDOT provided a summary of roadway data based on the list of treated and reference sites from researchers. Roadway data included the following:

- Classification (e.g., urban, rural).
- Traffic (i.e., current and previous AADT, truck percentage).
- Speed limit (e.g., posted and advisory).
- Median and shoulder type and width.
- Maintenance type and year.

Friction Data

The Georgia sites provide a large population of planned sites where before and after HFST installation friction data were collected. A number of in-place sites also provided additional friction data using lead-in and lead-out pavement friction to estimate underlying pavement

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[3] These are not published data. GDOT provided this internal list to researchers for analysis in 2016.

[4] These are not published data. GDOT shared the data from this internal database with researchers for analysis in 2019.

friction. Table 15 summarizes the friction data for Georgia HFST sites, including a summary by in-place and planned (i.e., before/after HFST installation friction testing) sites.

Table 15. Summary of friction data for Georgia sites.

		Speed (mph)		**HFST Friction (HFT Mu)**		**Underlying Pavement Friction (HFT Mu)**		**Change in Friction (Percent)**	
Type	**Number**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**
In place	43	35.50–42.00	39.90	0.84–1.00	0.98	0.48–0.76	0.61	+32–105	+64
Planned	93	37.30–42.50	40.00	0.74–1.00	0.96	0.58–0.87	0.73	+1–65	+33

Kentucky

Kentucky has one of the oldest and most extensive HFST programs with sites dating back to 2009. KYTC provided an initial list[5] of approximately 136 curves and ramps, all in-place sites. From this list, approximately 54 curves, 23 ramps, and 1 intersection were included in the initial data-collection plan. Actual data collection captured 58 curves, 14 of which the HFST was removed and 2 not on the original list; and 24 ramps, 3 of which the HFST was removed.

Crash Data

Researchers gathered crash data for before and after periods from a publicly available crash database maintained by the Kentucky State Police (2018). Crash data as far back as 2006 were queried to capture before periods for sites installed in 2009. Data through 2018 were available for most queries. Due to limitations on the size of the crash dataset, crash data for curves were queried by county, route, and milepost, capturing both treated and reference sites on a particular route. Crash data for ramps were queried by county and intersecting interchange routes to capture both treated and reference sites. Only crashes with a "Ramp Indicator" field were included.

Reference Sites

Reference sites were identified in the vicinity of HFST sites. For curves, similar curves upstream, downstream, and along adjacent roadways were identified. For ramps, similar ramps in the vicinity (i.e., the same or adjacent county) were identified. Rather than assigning each reference site to a specific treated site, three broad categories of reference sites were identified: rural roadway curves, clover-leaf-type ramps, and large-radius connector ramps.

After reference sites were identified, KYTC's online GIS database was used to identify the RouteID and mileposts for querying crash and roadway data (KYTC n.d.a.; KYTC n.d.b).

Roadway Data

KYTC's online GIS database was used to query various roadway data for treated and reference sites, including curve radius and traffic (i.e., current and previous AADT). Curve radii for ramps were unavailable and captured using GPS data during friction testing. Other roadway data were

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[5] These are not published data. KYTC provided this informal list to researchers for analysis in 2018.

manually documented for treated sites during friction data collection and subsequent review of video logs, including the following:

- Speed limit (e.g., posted and advisory).
- Median and shoulder type and approximate width.
- Other safety features (e.g., chevrons, arrow boards, guardrails).

Friction Data

The Kentucky sites provide a large population of in-place HFST sites for friction testing, ranging in age from 18 mo to 6.5 yr. Lead-in and lead-out pavement were used to estimate friction of the underlying pavement. Table 16 summarizes the friction data for Kentucky HFST sites where friction data were captured.

Table 16. Summary of friction data for Kentucky sites.

		Speed (mph)		HFST Friction (HFT Mu)		Underlying Pavement Friction (HFT Mu)		Change in Friction (Percent)	
Type	**Number**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**
Curves	42	30.20–43.70	38.40	0.80–1.00	0.95	0.38–0.74	0.55	+27–155	+76
Ramps	20	33.40–42.10	38.90	0.91–1.00	0.98	0.35–0.69	0.50	+45–186	+102

Louisiana

Louisiana has a large and relatively new HFST program with most HFST installations completed after 2016. Sites provided by the Louisiana Department of Transportation and Development (LADOTD) were from a systemic treatment approach for rural roadway curves. The characteristics of rural roadway curves deemed suitable candidates for HFSTs and other curve-related countermeasures included the following:

- Two-lane State-maintained rural roadways.
- AADT of 2,500–7,500.
- Lane width 12 ft or greater.
- Shoulder width of 2–6 ft.
- Degree of curve greater than 3.5 degrees (i.e., radius <1,640 ft).

LADOTD provided an initial list[6] of 226 sites across 34 parishes with HFST installations planned for 2016. Based on the site-selection criteria discussed previously, sites were selected to maximize the efficiency of friction data collection while also maximizing the number of planned sites for friction testing before and after HFST installation. Researchers established an initial list of 18 in-place and 77 planned sites for testing. While nine of the original planned sites were ultimately not installed, researchers added several additional sites to their list. The final site list included 27 in-place and 90 planned sites. Due to construction delays, researchers were unable to test any of the planned sites after HFST installation.

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[6] These are not published data. LADOTD provided this informal list to researchers for analysis in 2016.

Crash Data

LADOTD provided crash data for 2010–2017[7], capturing the before period for all sites. However, because only approximately eight sites were installed in 2016, only those eight sites had after-period crash data. Crash data for potential reference sites were also provided.

Reference Sites

LADOTD provided a curve inventory for State-maintained roadways with characteristics similar to HFST sites. Researchers identified reference site candidates from the inventory based on curve radii and lengths similar to HFST sites.

Roadway Data

In 2017, LADOTD provided roadway data[8] for the list of treated and reference sites identified by researchers. Additionally, LADOT provided a list of any other curve safety countermeasures implemented at various HFST sites. Roadway data included the following:

- Classification (e.g., urban, rural).
- Traffic (i.e., current AADT).
- Pavement type and width.
- Number of lanes.
- Shoulder type and width.
- Median type.

Friction Data

Louisiana had a large population of planned sites where friction data could be collected before and after HFST installation, but construction delays prohibited collecting friction data after HFST installation. However, a number of in-place sites provided HFST friction data as well as an estimate of underlying pavement friction data using lead-in and lead-out pavement friction. Table 17 summarizes the friction data for Louisiana HFST sites, including a summary by in-place and planned (i.e., before/after HFST installation friction testing) sites.

Table 17. Summary of friction data for Louisiana sites.

		Speed (mph)		HFST Friction (HFT Mu)		Underlying Pavement Friction (HFT Mu)		Change in Friction (Percent)	
Type	**Number**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**	**Range**	**Average**
In place	27	38.50–41.50	40.00	0.89–1.00	0.97	0.41–0.57	0.49	+74–138	+100
Planned	89	39.30–42.20	40.40	N/A	N/A	0.37-0.9	0.60	N/A	N/A

N/A = not applicable.

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[7] These are not published data. LADOTD provided these data to researchers for analysis in 2017.

[8] These are not published data. LADOTD provided these data to researchers for analysis in 2017.

Pennsylvania

Pennsylvania has one of the largest and oldest HFST programs in the United States, dating back to a pilot project in 2007, with implementation beginning in earnest in 2012. As of August 2018, the Pennsylvania Department of Transportation (PennDOT) reported approximately 42 mi of HFSTs over 248 locations.

PennDOT provided an initial list[9] of 150 in-place and 91 planned sites. From this list, 85 in-place and 22 planned curves were included in the initial data-collection plan. Additional sites were added as data collection began because several sites with multiple curves were split into separate sites. This resulted in data collection on approximately 200 sites, including 131 in-place and 37 planned sites (only 25 of which were tested after HFST installation). While these were all believed to be curves, 14 of the sites were classified as ramps and 21 were classified as intersections (i.e., intersection within a curve) during data collection. The remaining 32 sites consisted of sites not on the original list, sites where the HFST was removed, or sites where only one lane/direction was treated. The final list of curves for analysis consisted of 103 in-place and 17 planned sites.

Crash Data

Crash data were queried from statewide crash databases from 1998–2017[10], covering before and after periods for all of the HFST sites except those installed in 2017.

Reference Sites

Reference sites were identified from PennDOT's statewide curve inventory[11]. Sites located on the same roadway in the same county as a treated site were selected. Reference sites were selected to ensure their lengths, radii and traffic volumes were within the same range as treated sites.

Roadway Data

Curve radii for treated and reference sites were obtained from PennDOT's curve inventory. Traffic data were obtained from PennDOT online databases. Other roadway data were documented for treated sites during friction data collection and subsequent review of video logs, including the following:

- Speed limit (e.g., posted and advisory).
- Median and shoulder type and approximate width.
- Other safety features (e.g., chevrons, arrow boards, guardrails).

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[9] These are not published data. PennDOT provided this informal list to researchers for analysis in 2016.
[10] These are not published data. PennDOT provided these data to researchers for analysis in 2018.
[11] These are not published data. PennDOT provided these data to researchers for analysis in 2019.

Friction Data

Pennsylvania provided a large population of in-place HFST sites for friction testing, ranging in age from 3 mo to 4.5 yr, with one site nearly 10 yr old. For these sites, lead-in and lead-out pavement was used to estimate friction of the underlying pavement. A number of planned sites provided friction data before and after HFST installation. Table 18 summarizes the friction data for Pennsylvania HFST sites where friction data were captured.

Table 18. Summary of friction data for Pennsylvania sites.

Type	Number	Speed (mph)		HFST Friction (HFT Mu)		Underlying Pavement Friction (HFT Mu)		Change in Friction (Percent)	
		Range	Average	Range	Average	Range	Average	Range	Average
In place	98	28.70–42.20	37.40	0.74–1.00	0.93	0.37–0.86	0.54	+16–168	+76
Planned	14	28.40–41.60	34.60	0.75–1.00	0.90	0.42–0.73	0.56	+17–131	+70

West Virginia

West Virginia has an active HFST program with an extensive number of sites throughout the State, the oldest dating back to 2011. The West Virginia Department of Transportation (WVDOT) provided an initial list[12] of 49 locations, including 35 in-place and 14 planned sites set for installation in 2016. From this list, 25 in-place and 14 planned sites were included in the initial data-collection plan. Actual data collection captured 41 sites (2 sites were added), with 6 classified as ramps, intersections, or bridge decks and not included in the final analysis to maintain a focus on curves. Delays prohibited friction data collection at the 14 planned sites. Since they were installed prior to friction data collection, all 35 sites were considered in place when tested.

Crash Data

WVDOT provided summary crash data[13] for before and after periods for each HFST site. Crash data ranged from 2009 to 2017 depending on the HFST installation date. Summary crash data provided by WVDOT included the following:

- Date and time of crash.
- Collision type (e.g., rear end, sideswipe, single vehicle, angle).
- Injury and fatal (KABC).
- Light condition.
- Road surface condition.
- Animal involvement.
- Intersection indicator.
- Vehicle type.

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[12] This is not published data. WVDOT provided this informal list to researchers for analysis in 2016.

[13] This is not published data. WVDOT provided these data to researchers for analysis in 2017.

Reference Sites

WVDOT did not provide any reference site candidates.

Roadway Data

WVDOT provided summary roadway data for each site, including the following:

- Traffic (i.e., current and previous AADT).
- Number and width of lanes.
- Median type.
- Shoulder width.
- Curvature degree.
- Posted speed limit.

Other roadway data were documented for treated sites during friction data collection and subsequent review of video logs, including the following:

- Advisory speed limit.
- Other safety features (e.g., chevrons, arrow boards, guardrails).

Friction Data

West Virginia provided a large population of in-place HFST sites for friction testing, ranging in age from 5 mo to 6 yr. Lead-in and lead-out pavement were used to estimate friction of the underlying pavement. Table 19 summarizes the friction data for West Virginia HFST sites where friction data were captured.

Table 19. Summary of friction data for West Virginia sites.

Type	Number	Speed (mph)		HFST Friction (HFT Mu)		Underlying Pavement Friction (HFT Mu)		Change in Friction (Percent)	
		Range	Average	Range	Average	Range	Average	Range	Average
Curves	29	28.00–41.60	35.20	0.67–1.00	0.87	0.45–0.81	0.60	+7–87	+47

SUMMARY OF DATA USED FOR THE BEFORE–AFTER SAFETY EVALUATION

Researchers used data from Arkansas (ramps), Kentucky (curves and ramps), Pennsylvania (curves), and West Virginia (curves). Researchers were unable to use data collected for other site types and States for a rigorous evaluation for a variety of reasons, including the following:

- The recorded installation dates (i.e., construction acceptance) in Louisiana did not provide an after period for crash analysis.

- Reference sites were unavailable in Georgia, and sites with confirmed installation dates with available after-period crash data were few.

Summaries of the treatment and reference data for the site types and States used for the safety evaluation are in table 20 through table 23. Note that differences in the number of sites and friction change reported in table 20 through table 23 may be different from those reported in table 14 through table 19, as friction data were collected on more sites than were used in the crash-data analysis.

Table 20. Summary of curve treatment data used for safety evaluation.

State	Sites	Curve radius (ft)		Friction Increase (Percent)		Average AADT		Crashes/Mile-Year									
								Total		Injury		Wet		ROR		HOSSD	
		Range	Average	Range	Average	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
West Virginia	26	98–1,910	717	+7–87	+43	3,954	3,952	4.78	2.02	2.47	1.40	2.00	0.47	2.93	1.71	0.00	0.00
Pennsylvania	95	119–2,536	586	+14–168	+74	8,089	7,434	7.20	3.76	2.76	1.32	3.70	0.95	1.76	0.58	0.58	0.37
Kentucky	36	148–955	500	+27–155	+74	4,087	3,657	12.39	2.97	3.28	0.82	8.28	0.73	8.25	1.02	1.32	0.77

Table 21. Summary of ramp treatment data used for safety evaluation.

State	Sites	Average AADT		Crashes/Ramp/Year							
				Total		Injury		Wet		ROR	
		Before	After	Before	After	Before	After	Before	After	Before	After
Arkansas	15	8,491	9,293	2.64	6.47	0.57	1.27	1.33	0.40	0.11	0.20
Kentucky	21	11,587	11,561	7.43	1.59	1.47	0.40	5.47	0.43	0.91	0.05

Table 22. Summary of curve reference site data.

State	Sites	Curve radius (ft)			AADT			Crashes/Mile-Year		
		Range	Average	Range	Average	Total	Injury	Wet	ROR	HOSSD
Pennsylvania	1,011	121–2,534	1,151	342–43,950	6,797	2.16	0.80	0.48	0.35	0.21
Kentucky	128	109–1,508	605	474–17,903	3,181	4.38	1.24	2.09	2.12	0.51

Note: Kentucky reference sites were used for West Virginia evaluation.

Table 23. Summary of ramp reference site data.

State	Sites	Average AADT	Crashes/Ramp/Year			
			Total	Injury	Wet	ROR
Arkansas	67	6,199	0.80	0.22	0.19	0.08
Kentucky	71	8,183	0.87	0.16	0.39	0.03

CHAPTER 4. ANALYSIS

ANALYSIS OBJECTIVES

The objective of the crash-data analysis was to estimate the change in target crashes after HFST installation. Only nonintersection, nonanimal-related crashes and crashes not involving snow or ice were considered. Crash types examined include the following:

- Total.
- Injury.
- ROR.
- Wet-road.
- HOSSOD.

Further questions of interest that were examined include the following:

- Do effects vary by levels of traffic volumes?
- Do effects vary by the site-specific expected crash frequency prior to treatment?
- Do effects vary by State and the improvement in friction?
- Do effects vary with the value of geometric variables, such as curvature?

Meeting these objectives placed some special requirements on the data collection and analysis, including the need to accomplish the following:

- Select a large enough sample size to detect, with statistical significance, small changes in safety for some crash types.
- Carefully select untreated reference sites to properly account for changes in safety not due to HFSTs, including RTM, traffic volume changes, and time trends.
- Properly account for traffic volume changes.
- Pool data from multiple jurisdictions where possible to improve the reliability of the results and facilitate broader applicability of the research products.

As discussed in the Data Collection chapter, roadway, traffic volume, and crash data were acquired for curves in Pennsylvania, West Virginia, and Kentucky and for ramps in Arkansas and Kentucky to facilitate the crash-data analysis. The States also provided information related to the installation of HFSTs (i.e., location and date).

ANALYSIS METHODOLOGY

The general analysis methodology applied is the EB before–after approach. The methodology is well documented by Hauer (1997). The advantages of the EB method include the following:

- Accounting for RTM.
- Overcoming the difficulties of using crash rates in normalizing for volume differences between before and after periods.
- Reducing the level of uncertainty in the estimates of safety effects.

- Providing a foundation for developing guidelines for estimating the likely safety consequences of contemplated installations.
- Accounting for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions.

The EB before-after approach consists of the following three steps:

1. Predict what safety would have been in the after period had the status quo been maintained.
2. Estimate what the actual safety was in the after period.
3. Compare the two.

The EB method requires the calibration of SPFs, as outlined in the next section, relating crashes of different types and severities to traffic flow and other relevant factors for each jurisdiction for sites without HFSTs with appropriate adjustments for temporal effects. This calibration enables simultaneous accounting for temporal and possible RTM effects, as well as those related to changes in traffic volume.

DEVELOPMENT OF SPFs

Fundamental to the EB method is the use of the SPFs to represent the roadway conditions before installation. Where sufficient data are available for a reference population of sites similar to HFST sites, SPFs should be calibrated directly for the jurisdiction and analysis period of interest.

Crash, traffic, and geometric data are required for SPF development for a sample of reference sites similar to those for which the SPF would be applied. The data are required for each year of the analysis period (i.e., the period of the before and after data at HFST sites). Friction data should also be included for SPF development since pavement friction influences the expected number of crashes. However, a friction variable could not be included in the SPFs for this current study because friction data were not collected at reference sites due to budget limitations. The EB methodology requires annual SPF estimates of expected crash frequencies at HFST sites. Therefore, annual friction data are required at reference and HFST sites for proper inclusion of a friction variable in developing and applying SPFs. Additionally, because FN40Rs are device-specific, any SPFs incorporating friction are specific to the device used for data collection.

SPFs were directly calibrated with generalized linear modeling (GLM) using the R software package, which allows the specification of a negative binomial error structure that is recognized as more appropriate for crash counts than the normal distribution assumed in conventional regression modeling (The R Foundation n.d.). The GLM procedure also estimated the overdispersion parameter of the negative binomial distribution used in the EB estimation (k). Crash counts at locations in the reference group were used as estimates of the dependent variable, which was the expected number of crashes per year by type and severity, while corresponding road characteristics and traffic data were used as estimates of the independent variables.

SPECIFICS OF THE EB BEFORE–AFTER EVALUATION

Overall Safety Effects

In the EB before–after evaluation of the effect of an HFST, the calculation of change in safety for a given crash type at a treated site is given in figure 8:

$$B - A$$

Figure 8. Equation. Change in EB before–after evaluation.

Where:

B = expected number of crashes in the after period without an HFST installed.
A = number of reported crashes in the after period with an HFST installed.

Because of changes in safety resulting from changes in traffic volume, from RTM, and from trends in crash reporting and other factors, the count of crashes before a treatment by itself is not a good estimate of B—a reality now commonly accepted (Hauer 1997). Instead, B is estimated from an EB method in which an SPF is used to first estimate the number of crashes expected each year of the before period at locations with traffic volumes and other characteristics similar to a treatment site being analyzed. The sum of these annual SPF estimates (P) is then combined with the count of crashes in the before period at the treatment site (x) to obtain an estimate of the expected number of crashes before treatment (m). This estimate of m is shown in figure 9:

$$m = w(P) + (1 - w)(x)$$

Figure 9. Equation. Calculation of *m*.

Where w is weight. The value of w is estimated as shown in figure 10:

$$w = 1 \div (1 + kP)$$

Figure 10. Equation. Calculation of *w*.

The value of k is estimated from the SPF calibration process with the use of a maximum likelihood procedure.

A factor is then applied to m from figure 9 to account for the length of the after period, differences in traffic volumes between the before and after periods, and other unknown differences between these two periods accounted for by using the yearly factor of the SPF. This factor is the sum of annual SPF predictions for the after period divided by P. The result, after applying this factor, is an estimate of B. The procedure also produces an estimate of the variance of B.

The estimate of B is then summed over all sites in a treatment group of interest (B_{sum}) and compared with the count of crashes during the after period in that group (A_{sum}). The variance of B is also summed over all sites in the group of interest.

The index of safety effectiveness (θ) is estimated as shown in figure 11:

$$\theta = (A_{sum} \div B_{sum}) \div \{1 + [Var(B_{sum}) \div B_{sum}{}^{2}]\}$$

Figure 11. Equation. Calculation of θ.

The standard deviation of θ is given in figure 12:

$$Stddev(\theta) = [\theta^{2}\{[Var(A_{sum} \div A_{sum}{}^{2}) + [Var(B_{sum}) \div B_{sum}{}^{2}]] \div [1 + Var(B_{sum}) \div B_{sum}{}^{2}]^{2}]^{0.5}$$

Figure 12. Equation. Standard deviation of θ.

The percent change in crashes is 100(1−θ); thus, a value of $\theta = 0.70$ with a standard deviation of 0.12 indicates a 30-percent reduction in crashes with a standard deviation of 12 percent.

Effects on Different Severity and Impact Types

The EB methodology for crashes of different severity and impact types is essentially the same as previously outlined. The difference is that crashes of interest are used along with SPFs specific to these crash types.

Effects of Design, Traffic, Operational, and Safety Characteristics

Where samples were large enough, researchers isolated sites with certain levels or ranges of a given variable and estimated the separate effects for each category. This current study explored the effects of several variables on the value of the CMF, including the following:

- Level of safety before installation measured as the expected crash frequency.
- Traffic volume levels.
- Friction levels before and after HFST installation.
- Curvature (for curve sites).

This univariate categorical analysis informed the exploration of continuous CMFunctions to mathematically relate CMFs to one or more of these variables.

SPFs

This section presents the SPFs developed and used in the EB methodology to estimate the expected number of crashes in the after period without an HFST installed.

GLM was used to estimate model coefficients assuming a negative binomial error distribution, which is consistent with the State of research in developing these models. Alternative models were evaluated by comparing the magnitude and statistical significance of the variables included as well as the value of *k*, which is in itself a reliable goodness-of-fit measure. A smaller *k* value indicates a model that better captures the overdispersion in the data.

Where possible, separate SPFs were developed for each State and for different site and crash types.

Pennsylvania Curves

The model form for Pennsylvania curve SPFs shown in table 24 is shown in figure 13.

$$Crashes/mile\text{-}year = exp(\ln(\alpha) + \ \beta_2(rad \ \div 1{,}000))(AADT)^{\beta_1}$$

Figure 13. Equation. Model form for Pennsylvania curve SPFs.

Where:

α = constant parameter (estimated in the modeling process).
β_1 = parameter for AADT (estimated in the modeling process).
β_2 = parameter for radius (estimated in the modeling process).
rad = curve radius in feet.
ln = natural log.

Table 24. SPF parameter estimates for Pennsylvania curves.

Crash Type	ln(α) (Standard Error)	β_1 (Standard Error)	β_2 (Standard Error)	*k* (Standard Error)
Total	−3.6534 (0.4157)	0.5979 (0.0480)	−0.6951 (0.0626)	0.4447 (0.0501)
Injury	−4.1633 (0.5917)	0.5362 (0.0680)	−0.6403 (0.0891)	0.4947 (0.1005)
ROR	−3.6113 (1.0163)	0.4241 (0.1201)	−0.9934 (0.1618)	2.4365 (0.4157)
Wet-road	−3.9216 (0.8582)	0.5181 (0.1009)	−1.2098 (0.1358)	1.5632 (0.2470)
HOSSOD	−3.9891 (1.1465)	0.4409 (0.1324)	−1.3525 (0.1884)	1.2549 (0.3796)

Kentucky Curves

The model form for Kentucky curve SPFs shown in table 25 is shown in figure 14.

$$Crashes/year = exp\,(\ln(\alpha) + (\beta_2(rad))(Length)^{\beta_3}(AADT)^{\beta_1}$$

Figure 14. Equation. Model form for Kentucky curve SPFs.

Where *Length* is curve length (miles).

Table 25. SPF parameter estimates for Kentucky curves.

Crash Type	$\ln(\alpha)$ (Standard Error)	β_1 (Standard Error)	β_2 (Standard Error)	β_3 (Standard Error)	k (Standard Error)
Total	−3.9789 (0.9141)	0.7126 (0.1071)	−0.0011 (0.0003)	0.7387 (0.1737)	0.5541 (0.0832)
Injury	−4.2862 (1.0280)	0.6210 (0.1208)	−0.0009 (0.0003)	0.9288 (0.1706)	0.3319 (0.0863)
ROR	−2.5408 (1.1253)	0.4254 (0.1357)	−0.0011 (0.0003)	0.5950 (0.1998)	0.6168 (0.1016)
Wet-road	−4.3685 (1.2709)	0.7722 (0.1698)	−0.0015 (0.0004)	1.0000 (N/A)	1.0637 (0.1606)
HOSSOD	−4.7706 (1.3216)	0.6506 (0.1760)	−0.0017 (0.0004)	1.0000 (N/A)	0.5676 (0.1711)

N/A = not available.

West Virginia Curves

Reference sites were not available for West Virginia. Thus, SPFs from the neighboring State of Kentucky were used. Annual factors for applying these SPFs in the EB methodology were obtained from statewide West Virginia crash counts available online.

Arkansas Ramps

The model form for Arkansas ramp SPFs shown in table 26 is shown in figure 15.

$$Crashes/year = exp(\ln(\alpha))(AADT)^{\beta_1}$$

Figure 15. Equation. Model form for Arkansas ramp SPFs.

Table 26. SPF parameter estimates for Arkansas ramps.

Crash Type	$\ln(\alpha)$ (Standard Error)	β_1 (Standard Error)	k (Standard Error)
Total	−5.8976 (1.1122)	0.6577 (0.1300)	1.0849 (0.2578)
Injury	−6.5328 (1.3908)	0.5897 (0.1631)	1.2231 (0.4118)
ROR	*	*	*
Wet-road	−9.5594 (1.9032)	0.9157 (0.2196)	1.6125 (0.5477)

*Apply a proportion of 0.10 to total crash SPF.

Kentucky Ramps

The model form for Kentucky ramp SPFs shown in table 27 is shown in figure 16.

$$Crashes/year = exp(\ln(\alpha))(AADT)^{\beta_1}$$

Figure 16. Equation. Model form for Kentucky ramp SPFs.

Table 27. SPF parameter estimates for Kentucky ramps.

Crash Type	$\ln(\alpha)$ (Standard Error)	β_1 (Standard Error)	k (Standard Error)
Total	−3.4367 (0.9194)	0.3960 (0.1122)	1.2741 (0.2416)
Injury	−6.0170 (1.2126)	0.4971 (0.1447)	1.5146 (0.3830)
ROR	−8.5549 (1.6135)	0.5801 (0.1797)	0.9891 (0.6748)
Wet-road	−4.9251 (1.2596)	0.5801 (0.1797)	0.9891 (0.6748)

CHAPTER 5. BEFORE–AFTER ANALYSIS RESULTS

A safety impact was calculated for each State, and where feasible, for combined data for multiple States. The latter was possible for curves, for which results from three States were combined. The combined data allowed a disaggregate analysis to explore the effects of design, traffic, operational, and safety characteristics.

AGGREGATE RESULTS

Table 28 through table 31 provide the estimated aggregate CMFs and standard errors broken down by crash type, site type, and State.

Aggregate Results for Curves

The results in table 28 through table 31 indicate significant benefits in terms of low CMFs for each State and for Kentucky, Pennsylvania, and West Virginia combined, especially for the primary crash types targeted by HFST programs: wet-road, ROR, and HOSSOD. While the average after period for the three States combined was 3.3 yr, the data for the longer after periods were too limited to facilitate a meaningful analysis of the effects over time.

Because of the relative consistency in the results for Kentucky, Pennsylvania, and West Virginia, the CMFs based on the three States combined were recommended for estimating the benefits of contemplated treatments.

Table 28. Aggregate results for Pennsylvania curves.

			CMF	
Crash Type	**Observed Crashes after Treatment**	**EB Expected Crashes after Treatment**	**Estimate (95-Percent Confidence Interval)**	**Standard Error (*p*-Value)**
Total	143	269.990	0.529 (0.431–0.627)	0.050 (<0.010)
Injury	50	101.550	0.490 (0.341–0.639)	0.076 (<0.010)
ROR	22	51.160	0.428 (0.240–0.616)	0.096 (<0.010)
Wet-road	36	139.610	0.257 (0.167–0.347)	0.046 (<0.010)
HOSSOD	14	33.260	0.416 (0.183–0.649)	0.119 (<0.010)

Table 29. Aggregate results for West Virginia curves.

Crash Type	Observed Crashes after Treatment	EB Expected Crashes after Treatment	CMF Estimate (95-Percent Confidence Interval)	CMF Standard Error (*p*-Value)
Total	12	29.140	0.403 (0.156–0.650)	0.126 (<0.010)
Injury	8	8.830	0.885 (0.230–1.540)	0.334 (0.740)
ROR	10	17.180	0.569 (0.187–0.951)	0.195 (0.030)
Wet-road	3	12.480	0.230 (0.000–0.497)	0.136 (<0.010)
HOSSOD	*	*	*	*

*No crashes identified.

Table 30. Aggregate results for Kentucky curves.

Crash Type	Observed Crashes after Treatment	EB Expected Crashes after Treatment	CMF Estimate (95-Percent Confidence Interval)	CMF Standard Error (*p*-Value)
Total	174	468.710	0.370 (0.305–0.435)	0.033 (<0.010)
Injury	48	94.640	0.505 (0.346–0.664)	0.081 (<0.010)
ROR	60	264.670	0.226 (0.163–0.289)	0.032 (<0.010)
Wet-road	43	343.550	0.125 (0.086–0.164)	0.020 (<0.010)
HOSSOD	45	48.030	0.926 (0.597–1.255)	0.168 (0.670)

Table 31. Aggregate results for curves for Kentucky, Pennsylvania, and West Virginia combined.

Crash Type	Observed Crashes after Treatment	EB Expected Crashes after Treatment	CMF Estimate (95-Percent Confidence Interval)	CMF Standard Error (*p*-Value)
Total	329	767.840	0.430 (0.375–0.485)	0.028 (<0.010)
Injury	106	205.020	0.515 (0.442–0.588)	0.037 (<0.010)
ROR	92	333.490	0.279 (0.216–0.342)	0.032 (<0.010)
Wet-road	82	495.540	0.168 (0.129–0.207)	0.020 (<0.010)
HOSSOD	59	81.290	0.691 (0.485–0.897)	0.105 (<0.010)

Aggregate Results for Ramps

The results for Arkansas and Kentucky, shown in table 32 and table 33, respectively, were highly inconsistent. The exception was wet-weather crashes, for which the benefits were large—although the results for Arkansas were based on few crashes. The benefits for total crashes and injury crashes were large for Kentucky, while there were negligible effects for these crashes in Arkansas. This anomaly can be explained by the relatively small proportion of wet-weather crashes, the main HFST target, in Arkansas compared to Kentucky as seen in the data summary in table 34.

To achieve the substantial benefits of HFSTs, ramps should be identified for treatment based on a high proportion of wet-weather crashes. The CMF results for Kentucky in table 33 are recommended for evaluating the potential benefits of HFSTs. The Kentucky sample of treatment sites was too small to facilitate a meaningful analysis of the effects over time.

Table 32. Aggregate results for Arkansas ramps.

			CMF	
Crash Type	**Observed Crashes after Treatment**	**EB Expected Crashes after Treatment**	**Estimate (95-Percent Confidence Interval)**	**Standard Error (*p*-Value)**
Total	97	92.430	1.045 (0.800–1.290)	0.125 (0.730)
Injury	19	17.720	1.086 (0.535–1.637)	0.281 (0.770)
ROR	3	3.640	0.788 (0.000–1.697)	0.464 (0.660)
Wet-road	6	44.630	0.133 (0.025–0.241)	0.055 (<0.010)

Table 33. Aggregate results for Kentucky ramps.

			CMF	
Crash Type	**Observed Crashes after Treatment**	**EB Expected Crashes after Treatment**	**Estimate (95-Percent Confidence Interval)**	**Standard Error (*p*-Value)**
Total	183	860.440	0.212 (0.177–0.247)	0.018 (<0.010)
Injury	46	125.130	0.365 (0.245–0.485)	0.061 (<0.010)
ROR	6	29.510	0.202 (0.037–0.367)	0.084 (<0.010)
Wet-road	49	621.070	0.079 (0.055–0.103)	0.012 (<0.010)

DISAGGREGATE RESULTS (FOR CURVES)

Where samples were large enough, as was the case for curves, researchers isolated sites with certain levels or ranges of a given variable and estimated the separate effects for each category. This univariate categorical analysis was first conducted to explore continuous CMFunctions.

Univariate Categorical Analysis Results

For this analysis, sites were separated into two categories of four key influential variables. The boundary for each category was determined by trial and error to provide the greatest difference in the CMF between the two categories while maintaining a significant number of sites and crashes in each.

Based on the HFT Mu measurement value, the results in table 34 suggest the beneficial effects are larger (i.e., CMFs are smaller) for larger friction absolute and percentage increases, AADTs are lower, and expected crashes per mile-year are greater before HFST installation. CMF results for friction increase are only applicable to friction measurements with the HFT device and within the context of HFSTs—not from other pavement treatments. The simplified friction increase category was used since the friction data collected for this current study was inadequate for a higher-resolution friction representation of the pavement due to factors previously presented in chapter 3.

Table 34. Curve CMF results from the univariate categorical analysis.

Category	Number of Sites	After-Period Crashes		CMF (Standard Error)	
		Total	Wet	Total	Wet
HFT Mu friction percentage increase ≥0.4	46	78	22	0.319 (0.400)	0.124 (0.028)
HFT Mu friction percentage increase <0.4	73	197	47	0.469 (0.045)	0.176 (0.028)
HFT Mu friction percentage increase ≥55	72	165	44	0.378 (0.037)	0.138 (0.022)
HFT Mu friction percentage increase <55	47	110	25	0.482 (0.066)	0.200 (0.044)
AADT ≤3,000	48	60	15	0.272 (0.042)	0.097 (0.026)
AADT >3,000	96	267	67	0.493 (0.041)	0.200 (0.027)
Crashes/mile-year >9.48	44	166	44	0.341 (0.032)	0.123 (0.020)
Crashes/mile-year <9.48	100	161	38	0.584 (0.069)	0.290 (0.053)

Investigation of CMFunctions

Researchers used multiple variable regression modeling investigate the effects of a number of factors, including AADT, curvature, expected crash frequency before treatment, and friction improvement, on the CMF. The objective was to investigate whether CMFunctions can be developed to capture the effects of these factors and more precisely estimate CMFs for prospective HFST installations.

In the GLM regression approach taken to estimate CMFunctions, each site was considered an observation. The observed crash frequency in the after period was modeled using a negative binomial model with the EB estimate of expected crashes in the after period had no HFST been installed used as an offset. Variables affecting the CMF value were then added to the model. This approach is illustrated in figure 17 where EB_{after} is the EB estimate of expected crashes in the after period. The value of observed crashes after being divided by the EB estimate is an approximate CMF for a site, as seen in figure 18. This approximate CMF is modeled as a function of site characteristics. This function is a CMFunction that predicts a CMF value for an individual site based on the characteristics in the model seen in figure 19.

$$Observed\ Crashes\ After = EB_{after} \times f(site\ characteristics)$$

Figure 17. Equation. Calculation for observed crashes.

Where:

Observed Crashes After = number of reported crashes at a site after HFST installation.

f = percentage HFST friction increase.

site characteristics = characteristic of interest (e.g., friction, traffic, rainfall).

$$\frac{Observed\ Crashes\ After}{EB_{after}} = f(site\ characteristics)$$

Figure 18. Equation. Approximate CMF for a site.

$$ln(Observed\ Crashes\ After) - ln\ (EB_{after}\ ) = f(site\ characteristics)$$

Figure 19. Equation. CMF for an individual site based on the site characteristics.

The CMFunctions developed were not as robust as might have been obtained with larger samples. The direction of effect for some variables, such as AADT, was not always consistent, and the statistical significance of estimated parameters tended to be poor. Nevertheless, there were useful insights, suggesting value in developing robust CMFunctions in future research. These insights confirmed the indications from the univariate categorical analysis that there was a logical and consistent relationship between CMFs and three variables: friction improvement as measured by the percentage HFST friction increase, AADT, and expected crash frequency before HFST installation. Other friction-related variables, such as estimated FN40Rs before HFST installation and the actual change in friction, were not as significant as the one eventually selected.

Table 35 and table 36 indicate the estimated parameters and standard errors of the recommended CMFunctions for total and wet-weather crashes. Asterisks indicate the data ranges where the CMFunction is applicable in table 36.

The functional form of the CMFunctions is shown in figure 20.

$$CMF = exp[\alpha + \beta_1(m) + B_2(f \div 100)]\,AADT^{\beta_3}$$

Figure 20. Equation. Functional form for CMFunctions.

Table 35. CMFunction parameter estimates for curves.

	Parameter Estimate (Standard Error)	
Parameter	**Total Crashes**	**Wet-Weather Crashes**
$In(\alpha)$	−2.9798 (1.0250)	0.8158 (0.3894)
β_1	−0.0131 (0.0110)	−0.0417 (0.0253)
β_2	−0.6437 (0.2512)	−0.6200 (0.4594)
β_3	0.3299 (0.1228)	N/A

N/A = not available.

Table 36. Applicable ranges of variables for curve CMFunctions.

	Values at Site with Minimum			**Values at Site with Maximum**		
Variable	***m* (total)**	***f***	***AADT***	***m* (total)**	***F***	***AADT***
m	0.47*	37	2,270	38.05*	43	3,561
f	6.66	12*	2,400	1.57	168*	3,330
AADT	0.97	23	650*	5.40	48	24,853*

*Variables within the applicable range.

In applying the CMFunction estimates in conjunction with the point CMF estimates for the States combined in table 31 for a prospective HFST installation, whichever estimate provides the most conservative value can be used (i.e., the larger CMF be used). If a site has a variable value outside the applicable range of the CMFunction, the value of the variable at the extremity should be used to estimate the CMF.

The combination of a higher expected crash frequency and the associated smaller CMF yielded the greatest crash reductions and the highest B/C ratios. These impacts were somewhat mitigated by the larger CMF values implied by the CMFunction for the higher AADTs at sites with high crash frequencies.

CHAPTER 6. B/C ANALYSIS

METHODOLOGY

B/C analyses allow agencies to assess, compare, and prioritize potential HFST installations by considering the quantified benefits in terms of crash reduction and lifespan—not just the installation cost.

In this current study, separate analyses are provided for ramps (based on Kentucky sites) and curves (based on sites for Kentucky, Pennsylvania, and West Virginia combined) considering the benefits for total crashes. The annualized cost of an HFST installation is computed as follows in figure 21.

$$Annual\ Cost = C \times R \div 1 - (1 + R)^{-N}$$

Figure 21. Equation. Annualized cost of an HFST.

Where:

Annual Cost = cost of treatment per year if annualized over its life.
C = treatment cost.
R = discount rate (as a decimal).
N = expected service life (years).

Based on information provided by States, conservative values of 5 yr for service life and $35 per square yard for an HFST installation cost were used.

Based on information from the Office of Management and Budget and FHWA recommendations, a real discount rate of 7 percent was used to determine the annual cost of the HFST installation (U.S.C. 2015).

For the benefit calculations, the most recent FHWA mean comprehensive crash costs disaggregated by crash severity, location type, and speed limit were used as a base (Council et al. 2005). Council et al. (2011) developed these costs based on 2001 crash costs and found the unit costs (in 2001 U.S. dollars) for PDO and KABC crashes for posted speed limits less than 50 mph (assumed for ramps) were $7,068 and $91,917, respectively; for all speed limits combined (assumed for curves), the unit crash costs were $7,428 and $158,177, respectively. These were updated to 2019 U.S. dollars by applying the ratio of the projected value of a statistical life of $9.8 million (projected from latest published values of $9.4 and $9.6 million for 2014 and 2016, respectively) to the 2001 value of $3.8 million (USDOT 2014; USDOT 2016; Zaloshnja et al. 2006). Applying this ratio of 2.58 to the unit costs for PDO and KABC crashes, and then weighting by the frequencies of PDO and KABC crashes in the after period (223 and 106 for curves and 137 and 46 for ramps, respectively) unit costs for total crashes of $144,744 and $68,719 were obtained curves and ramps, respectively.

The total crash reduction was calculated by subtracting the actual crashes in the after period from the expected crashes in the after period had an HFST not been installed. The number of crashes prevented per year was obtained by dividing the total crash reduction (438.84 for curves and

677.44 for ramps) by the average number of after-period years per site (3.285 for curves and 5.476 for ramps). The annual benefit (i.e., crash savings) is the product of the total crash reduction per year and the aggregate cost of a crash (all severities combined). The B/C ratio is calculated as the ratio of the annual benefit to annual cost.

The annual benefit (i.e., crash savings) of $19,300,113 and $9,063,309 for curves and ramps, respectively, is the product of crash reductions per year (133.59 and 123.71, respectively) and the aggregate costs of a crash, all severities combined ($144,744 and $68,719, respectively). The B/C ratios are estimated to be 6.00 for curves and 18.74 for ramps. The DOT recommends a sensitivity analysis by assuming values of a statistical life of 0.56 and 1.41 times the recommended value (USDOT 2016). These factors were applied directly to the estimated B/C ratios to get a range of 3.36 to 8.45 for curves and 10.50 to 26.44 for ramps. These results suggest that HFSTs, even with conservative assumptions on cost, service life, and the value of a statistical life, are cost effective—especially for ramps.

CHAPTER 7. DISCUSSION AND CONCLUSIONS

SAFETY EVALUATION AND RECOMMENDATIONS

This current study was limited in scope because the amount of data anticipated at the beginning did not materialize in a timely manner for a variety of reasons. Nevertheless, defendable and application-ready CMF results were obtained and the cost effectiveness of HFSTs was confirmed.

The objective of this current study was to estimate the effect of HFSTs on crashes by evaluating different site types from several States. The state-of-the-art EB before–after methodology evaluated the effects on various crash types (e.g., total, injury, wet-road, ROR, and HOSSOD) using data collected in Arkansas (ramps), Kentucky (curves and ramps), Pennsylvania (curves), and West Virginia (curves). Data were also collected in Louisiana and Georgia but did not include enough after-period data or reference sites for a rigorous EB evaluation. A complementary evaluation was conducted under this current study for friction change of HFSTs over time, the results of which are documented in the companion report FHWA-HRT-20-062. Friction was tested on several older HFST installations where previous friction data were collected. All friction was tested with FHWA's HFT, a continuous fixed-slip measurement device. The friction data collected for this current study and documented in this report were evaluated for friction change before and after HFST installation, for HFST and existing pavement over time, and through a curve.

The results for curves indicated significant benefits in terms of low CMFs for each State and Kentucky, Pennsylvania, and West Virginia combined, especially for the primary crash types targeted by HFST programs: wet-road, ROR, and HOSSOD. CMFs of 0.279, 0.168, and 0.691, respectively, were estimated for the three States combined. Because of the relative consistency in the results for the three States, the CMFs based on the three States combined were recommended for estimating the benefits of a contemplated HFST installation and for use in the CMF Clearinghouse.

The results for ramps for Arkansas and Kentucky were highly inconsistent. The exception was wet-weather crashes, for which the benefits were large. The benefits for all crashes and injury crashes were large for Kentucky, while there were negligible effects for these crashes in Arkansas. This anomaly can be explained by the relatively small proportion of wet-weather crashes, the main HFST target, in Arkansas compared to Kentucky. To achieve the substantial benefits of HFSTs, ramps should be identified for treatment based on a high proportion of wet-weather crashes.

A thorough disaggregate analysis of the before–after evaluation data was only feasible for curves. For this, univariate categorical and multivariable regression analyses were used to investigate the effects on the CMFs of a number of variables. There was a logical and consistent relationship between CMFs and three variables: friction improvement, AADT, and expected crash frequency before HFST installation. These variables were used to develop the recommended CMFunctions.

An economic analysis suggested HFSTs, even with conservative assumptions on cost, service life, and the value of a statistical life, are cost effective—especially for ramps. Table 37 summarizes the B/C ratios along and the recommended CMFs.

Table 37. B/C ratios and recommended CMFs.

Crash Type	Curves	Ramps
CMF for total crashes (95-percent confidence interval)	0.430 (0.375–0.485)	0.212 (0.177–0.247)
CMF for injury crashes (95-percent confidence interval)	0.515 (0.442–0.588)	0.365 (0.245–0.485)
CMF for ROR crashes (95-percent confidence interval)	0.279 (0.216–0.342)	0.202 (0.037–0.367)
CMF for wet-road crashes (95-percent confidence interval)	0.168 (0.129–0.207)	0.079 (0.055–0.103)
CMF for HOSSOD crashes (95-percent confidence interval)	0.691 (0.485–0.897)	N/A
B/C ratio based on total crashes (sensitivity range)	6.000 (3.360–8.450)	18.740 (10.500–26.440)

N/A = not available.

PERFORMANCE EVALUATION AND RECOMMENDATIONS

Some of the objectives for this current study centered around recommending materials, specifications, and HFST installation evaluations. Although researchers collected data from a large number of HFST installations encompassing a wide variety of ramp and curve characteristics from six States, the data gathered were inadequate for conclusive recommendations regarding materials, specifications, or installation evaluations.

It was impossible to identify specific materials (i.e., HFST products) beyond the basic components used for all the projects: polymeric binder resin (e.g., epoxy or polyester) and calcined bauxite aggregate. Friction measurements confirmed the materials used for virtually all projects evaluated were indicative of what was expected from an HFST, with calcined bauxite aggregate demonstrating high levels of friction, regardless of HFST age.

There are currently no established standards for rating HFST condition, making performance evaluation difficult. Due to safety concerns for researchers, only a subjective windshield survey of HFST condition was captured for the sites tested. While this information was helpful, it was inadequate for conclusive recommendations on HFST performance over time, especially without knowing the condition of the underlying pavement prior to installation. However, based on discussions with representatives from the agencies involved with these HFST programs, the following are some reasons for premature failure of HFSTs based on their experience:

- Underlying pavement type and condition—while HFSTs can be applied to virtually any pavement surface, they should not be applied to heavily distressed pavements, including those with extensive fatigue cracking (e.g., alligator and block cracking), deep rutting, or durability-related cracking (e.g., deep spalls, map cracking).

- Inadequate surface preparation—a mechanical bond between the HFST resin binder and underlying pavement surface is critical for preventing debonding or delamination of the

HFST. In general, HFSTs adhere well to clean, dry asphalt surfaces. However, concrete surfaces require shot blasting to ensure a mechanical bond and prevent debonding. AASHTO MP 41-19 provides guidelines for surface preparation.

- Moisture beneath the pavement surface—for asphalt pavements where subsurface moisture migrates to the surface, the moisture can become trapped in the asphalt layers after HFSTs are applied. This can lead to stripping and degradation of the underlying asphalt pavement and eventual failure, also causing failure of the HFST.

- Inadequate resin binder thickness—the thickness of the resin binder should be approximately 50 percent of the nominal maximum aggregate size. The resin binder application rate is dependent on the texture depth of the existing pavement, with coarse- and open-textured pavements requiring more resin binder than lower-texture pavements. If the resin binder application rate is not adjusted for texture, inadequate thickness that does not securely hold the HFST aggregate in place—leading to premature aggregate and overall friction loss—can occur. Additionally, installing HFSTs on pavement surfaces with significant cross-slope steep grade requires additional care to prevent the resin from flowing downhill and leaving inadequate thickness at the high side. Resin binder thickness should be regularly checked during installation and further verified by application rate/material usage.

- Poor installation practices—while this is a broad category, issues with improper installation include improper formulation and/or inadequate proportioning and mixing of the resin binder components, which results in the binder resin not curing; dirty aggregate, which inhibits a bond between the resin binder and aggregate; proper timing of aggregate placement onto the resin binder so the resin binder securely holds the aggregate in place; and proper timing of sweeping of excess aggregate so aggregate is not pulled out of the resin binder before it is fully cured.

The application practices and methods for the projects evaluated under this current study varied greatly from State to State and even within States. While all projects were single-layer HFSTs, application processes varied widely from a variety of semiautomated to fully automated practices, and in some specific situations, manual installation. However, the application practices for each project were not specifically documented, making any recommendations on best practices based on observed performance impractical.

While each volunteer State provided specifications, most were in the process of revising their specifications from lessons learned through widespread HFST installations and evaluations. There was no consistent specification used across all projects researchers could point to as best practice. AASHTO MP 41-19 provides a good baseline specification to which State-specific materials, QC, testing requirements, and installation practices can be added based on local experience. A properly developed HFST specification should include the following key items:

- QC plan requirements—a good QC plan ensures the installer has thoroughly documented all aspects of installation, from material supply and installation equipment/methods to contingency plans and opening to traffic. The QC plan also gives an agency a clear plan to review before installation and documentation to hold the installer accountable during construction.

- Material properties for resin binder and aggregate—key resin binder and aggregate properties are provided in AASHTO MP 41-19. Additional State-specific requirements for these materials based on previous experience can be added as needed. Many agencies have a prequalified product approval process to ensure proposed materials were evaluated.

- Sampling and testing methods—HFST resin binder and aggregate materials should be regularly sampled and tested during installation to identify any changes in the materials from what was accepted for installation.

- Packaging and materials certification—HFST resin binder and aggregate materials are specialty materials that require additional care during storage. If an agency does not test the materials themselves, certification of the material properties should be provided by the installer and/or material suppliers.

- Surface preparation requirements—critical for HFST performance, surface preparation includes removing striping and other pavement markings, cleaning and roughening the pavement surface, and protecting the prepared surface prior to HFST installation. AASHTO MP 41-19 provides guidance on proper surface preparation requirements.

- Resin binder and aggregate installation requirements—resin binder installation requirements include the required thickness and/or application rate and any restrictions on installation conditions (e.g., pavement/air temperature, precipitation). Aggregate installation requirements include application rate and timing of aggregate placement to ensure it will properly embed in the resin binder.

- Acceptance requirements—requirements generally center around uniformity and appearance of the finished surface, complete curing of the resin binder, texture depth, and/or friction of the finished surface. Friction testing is typically performed after some amount of traffic exposure to provide a wear-in period for the HFST, anywhere from 3 to 90 d after installation.

- Test strip requirements—test strips allow an installer to demonstrate their installation processes and methods to the agency on a smaller scale before full installation. Any issues with installation can be identified and remedied before full installation.

Because the focus of this report was curves and ramps, researchers cannot confidently recommend any different specifications or practices for HFST installations on longer length sections of roadway. While installation practices for HFSTs for longer sections of roadway should not differ from targeted curves and ramps, the B/C of such installations have not been evaluated.

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