HIGH FRICTION SURFACE TREATMENT

SITE SELECTION AND INSTALLATION GUIDE

U.S. Department of Transportation
Federal Highway Administration

ZERO IS OUR GOAL
A SAFE SYSTEM IS HOW WE GET THERE

NOTICE

QUALITY ASSURANCE STATEMENT

NON-BINDING CONTENTS

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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 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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ACRONYMS

AADT	annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
AR	Arkansas
ATSSA	American Traffic Safety Services Association
BBI	ball-bank indicator
B/C	benefit-cost
CMF	crash modification factor
CPFM	continuous pavement friction measurement
CTE	coefficient of thermal expansion
DFT	dynamic friction tester
DOT	department of transportation
DOTD	Department of Transportation and Development
EB	empirical Bayes
EEC	excess expected crashes
FHWA	Federal Highway Administration
FDOT	Florida Department of Transportation
FL	Florida
HFST	high friction surface treatment
HFT	highway friction tester
HSIP	Highway Safety Improvement Program
HSM	Highway Safety Manual
HOSSOD	head-on sideswipe opposite direction
IL	investigatory level
KABCO	Injury Scale established by the National Safety Council
KY	Kentucky
KYTC	Kentucky Transportation Cabinet
LWST	locked-wheel skid tester
MDA	Micro-Deval Apparatus
MMA	methyl methacrylate

MPD	mean profile depth
mph	miles per hour
MTD	mean texture depth
NTPEP	National Transportation Product Evaluation Program
NZTA	New Zealand Transport Agency
OGFC	open graded friction course
PA	Pennsylvania
PC	point of curvature
PDO	property damage only
PennDOT	Pennsylvania Department of Transportation
PFMP	pavement friction management program
PSV	polished stone value
PT	point of tangency
QCP	quality control plan
QPL	qualified product list
RwDSIP	Roadway Departure Safety Implementation Plan
ROR	run-off-road
RSA	road safety audit
RTM	regression-to-the-mean
RwD	roadway departure
SPF	safety performance function
SSA	safe system approach
TCMS	Texas curve margin of safety
TTI	Texas Transportation Institute
usRAP	U.S. Road Assessment Program
ViDA	Vehicle Information and Diagnostics for Aftersales
WV	West Virginia

EXECUTIVE SUMMARY

The purpose of this Guide is to update and expand on the information provided in FHWA's 2016 High Friction Surface Treatment Curve Selection and Installation Guide. Over the past five years since that Guide was published, the use of HFST has increased dramatically in the U.S., and practices for site selection, materials, installation, and performance monitoring have evolved. While the 2016 Guide focused on HFST for curve applications, this Guide provides information on other applications such as ramps and intersections where pedestrians are most likely to cross the roadway, even though curves remain the predominant application for HFST.

The content of this Guide is based on successful practices and lessons learned from a number of agencies with mature HFST programs that have deployed HFST on a large scale. While some agencies maintain internal guidance for HFST deployment, there are few resources summarizing noteworthy practices that agencies without this form of guidance can use. This document does not seek to prescribe certain practices, but rather highlights those that have been successful.

This Guide is intended to assist agencies seeking to implement HFST as a safety countermeasure for the first time, to help agencies with limited deployment to expand and improve their program, and to help agencies with mature programs to further refine their program. Key topics for HFST deployment covered in this document include:

- **Site Selection**—Discussion of how to determine where to deploy HFST to address friction-related crashes. This includes guidance on site-specific (crash-history) site selection as well as systemic deployment. The Guide also highlights tools for data-driven approaches for site selection.
- **Field Verification and Design**—Information on how to verify if locations identified from the site selection process are appropriate for HFST deployment and guidance on factors that may be considered in a project design.
- **Materials and Specifications**—Summary of key properties for HFST resin binder and aggregate materials and guidance on specifications based on successful practices.
- **Installation and Inspection**—Discussion of the importance of proper installation practices and inspection of HFST placement for ensuring long-term performance to achieve the desired benefit/cost (B/C) ratio. Chapter 6 provides a stand-alone guidance document for installation inspection, complemented with an inspection checklist (Appendix C) and downloadable pocket guide.
- **Performance Monitoring**—Explores considerations for performance monitoring with respect to both safety performance and functional (friction and durability) performance.

HFST is a highly effective and mature safety countermeasure for reducing both wet and dry pavement friction-related crashes. When applied at appropriately selected locations and installed properly, exceptional B/C ratios have been realized by many agencies in the U.S. It is the intent of this Guide to help further improve HFST deployment practices in the U.S. to help agencies realize the benefits of this safety countermeasure.

CHAPTER 1—OVERVIEW

In 2019, there were approximately 6.76 million crashes reported in the U.S., accounting for 36,096 fatalities and over 2.74 million injuries (National Center for Statistics and Analysis 2020). Half of the 2019 fatalities were the result of roadway departure (RwD) crashes and more than 23 percent were intersection-related (NHTSA 2021).

Often, a small subset of the total highway network is responsible for a significant percentage of certain crash types. Roughly 25 percent of fatal crashes are associated with horizontal curves, yet horizontal curves make up only 5 percent of our Nation's roadways (FHWA 2016). And approximately 76 percent of curve-related fatal crashes are the result of roadway departure (Torbic et al. 2004). Intersections, likewise, make up a very small percentage of the total highway network.

Pavement friction plays a major role not only in stopping distance but also in helping keep vehicles in their lane. Agencies have identified pavement condition as one of the major contributing factors in RwD and intersection crashes. The level of pavement friction is reduced when a pavement surface is wet or polished from wear, which may lead to skidding or hydroplaning.

Vehicles have different friction demands depending on the characteristics of the roadway. For example, a vehicle traversing a horizontal curve requires a greater level of friction than vehicles on a tangent section, and furthermore, large trucks require a greater level of friction to traverse a curve than passenger vehicles. Common locations that require higher friction values are horizontal curves, ramps, steep grades, or intersection approaches. As a result of the increased friction demand, the roadway surface at these locations often becomes prematurely polished, reducing the pavement friction and contributing to higher crash rates. Excessive speeds or distracted driving can also contribute to the crash rates in areas where friction demand is high.

A high friction surface treatment (HFST) is a low-cost safety countermeasure used specifically for these purposes. HFST significantly increases pavement friction to help prevent drivers from losing control and decrease stopping distance when at least one of the following conditions exist (Atkinson et al. 2016):

- Vehicle friction demand exceeds available pavement friction.
- Vehicles are traveling too fast for the geometric design of a curve.
- Vehicles are traveling too fast for roadway conditions (e.g., wet or icy pavement).
- Pavement surface has been polished from wear.

1.1 WHAT IS HIGH FRICTION SURFACE TREATMENT?

HFST is a safety and pavement surface treatment that dramatically and immediately increases pavement friction to reduce crashes, injuries, and fatalities associated with friction demand issues. The treatment can help compensate for deficient geometric designs, such as sharp curves and/or inadequate or variable superelevation, by providing the necessary friction to maintain traction on the intended path. HFST can also restore pavement surface friction where traffic has polished existing pavement surface aggregates.

HFST is 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-mm abrasion- and polish-resistant aggregate (typically calcined bauxite) onto the resin layer (figure 1). The resin binder bonds the aggregate to the pavement surface, leaving a thin, superficial, pavement surface treatment (figure 2) that can be applied during a short closure of the roadway.

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Figure 1. Photograph. Example of HFST installation (Merritt et al. 2020a).

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Figure 2. Photograph. HFST placed over a conventional asphalt pavement surface (Merritt et al. 2020a).

HFST is not a pavement preservation treatment and is not known to provide any extension of pavement life which can be found with microsurfacing, slurry seals, and chip seals. It simply enhances the friction of an existing pavement surface using materials and installation methods unique to the treatment.

HFST as described herein is also different from thin-polymer bridge deck overlays. While the polymeric resin binder and installation methods used for polymer bridge deck overlays are similar to that used for HFST, bridge deck overlays are designed to help seal and preserve the bridge deck while also enhancing surface friction. As such, agencies typically use different aggregate materials for bridge deck overlays.

The use of HFST as a safety countermeasure in the United States has grown exponentially over the past 15 years. As of 2005, there were only one or two known HFST demonstration installations on curves or ramps in the United States, and by 2021, at least 44 States had at least one (1) HFST installation, with 10 states reporting over 100 installations, 5 states reporting 50-100 installations, 15 states reporting 10-50 installations, and the remaining states reporting one to ten installations. This accounts for millions of SY of HFST installed in just over 15 years. A State DOT HFST Status map and additional resources on HFST can be found at the following website: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/high_friction/.

1.2 HFST BENEFITS AND EFFECTIVENESS

HFST is a unique low-cost safety countermeasure because it is specifically intended to dramatically increase pavement friction for the purpose of reducing crashes. There are no other known pavement surface treatments that enhance pavement friction to the same level while sustaining this friction enhancement over time. When properly deployed, HFST can provide a dramatic crash reduction and substantial benefit-cost (B/C) ratio. This section describes some examples of safety effectiveness findings and lists the key advantages of HFST over other treatments.

1.2.1 SAFETY BENEFITS AND EFFECTIVENESS

HFST effectiveness varies by location, but agencies have found that HFST can more than double or triple existing pavement friction, reduce stopping distance by 25 to 30 percent, and provide crash reductions from 45 to 100 percent (Atkinson et al. 2016).

Table 1 provides examples of effectiveness for routine HFST deployment and summarizes estimated overall and wet crash reductions for three States with mature HFST programs. Note that while HFST is most effective in reducing wet pavement crashes, it is also effective in reducing dry pavement crashes, as evidenced by the dramatic reductions in total crashes.

Examples of Crash Reduction from HFST Deployment

Marquette Interchange West-North Connector Milwaukee, Wisconsin

Before HFST (3 year): 219 crashes

After HFST (3 year): 9 crashes

96% crash reduction

California Route 17, Laurel Road Curve Northern California

Before HFST (3 year): 156 crashes (141 wet)

After HFST (3 year): 8 (2 wet)

95% crash reduction

Table 1. Examples of crash reduction for HFST from States with mature programs.

State	Site Information	Total Crash Reduction	Wet Crash Reduction
Pennsylvania (PA)[1]	47 curve treatments	70%	87%
Kentucky (KY)[2]	43 curves and ramp treatments	73% (curves) 78% (ramps)	86% (curves) 85% (ramps)
Florida (FL)[3]	"Tight curve" treatments	44%	84%

1. **Locations had 3 to 5 years of before-after crash data (PennDOT 2018).**
2. **Three years of crash data before installation and 1 to 4 years of crash date after installation (Von Quintus and Mergenmeier 2015).**
3. **Florida DOT 2021.**

While the estimated crash reductions presented thus far are based on naïve before and after evaluations, a Federal Highway Administration (FHWA) study developed crash modification factors (CMFs) for HFST using the empirical Bayes (EB) methodology for horizontal curve and ramp applications in four States: Pennsylvania (PA), Kentucky (KY), Arkansas (AR), and West Virginia (WV) (Merritt 2020b). A CMF is used to estimate the expected number of crashes at a location after installing a countermeasure. It is a multiplicative factor used to estimate future crash frequency from a base crash frequency. For example, if a site observes 10 crashes per year, and the CMF for a countermeasure is 0.80, then you would expect 8 crashes per year after countermeasure installation (10 x 0.80 = 8). The research developed CMFs for several crash types, including total, injury, run-off-road, wet-road, and head-on sideswipe opposite direction (HOSSOD) crashes. Table 2 and table 3 show the CMFs from this study, which provide a more statistically rigorous estimation of the crash-reduction benefits of HFST.

Table 2. Aggregate CMF results for HFST curve sites from three States: PA, KY, and WV (Merritt et al. 2020b, Lyon et al. 2020).

Crashes after treatment application			
Crash Type	Observed	EB Expected	CMF (s.e.)
Total	329	767.84	**0.430 (0.028)**
Injury	106	205.02	**0.515 (0.037)**
Run-off-road	92	333.49	**0.279 (0.032)**
Wet road	82	495.54	**0.168 (0.020)**
HOSSOD	59	81.29	**0.691 (0.105)**

***Note:* CMF = crash modification factor; EB = empirical Bayes; HOSSOD = head-on side-swipe opposite direction; s.e. = standard error. CMFs that are statistically significant at the 5-percent level are indicated in boldface. EB expected is an estimate of the number of crashes the sites would have experienced had HFST not been installed.**

Table 3. CMF results for HFST ramp sites from KY and AR (Merritt et al. 2020b, Lyon et al. 2020).

Crashes after treatment application				
State	Crash Type	Observed	EB Expected	CMF (s.e.)
Arkansas	Total	97	92.43	**1.045 (0.125)**
	Injury	19	17.72	**1.086 (0.281)**
	Run-off-road	3	3.64	**0.788 (0.464)**
	Wet road	6	44.63	**0.133 (0.055)**
Kentucky	Total	183	860.44	**0.212 (0.018)**
	Injury	46	125.13	**0.365 (0.061)**
	Run-off-road	6	29.51	**0.202 (0.084)**
	Wet road	49	621.07	**0.079 (0.012)**

***Note:* CMF = crash modification factor; EB = empirical Bayes; s.e. = standard error. CMFs that are statistically significant at the 5-percent level are indicated in boldface.**

HFST is an important countermeasure for a Safe System Approach (SSA) to improving roadway safety. SSA is a "holistic view of the road system that first anticipates human mistakes and second keeps impact energy on the human body at tolerable levels" (FHWA 2020c). HFST can help compensate for human error when drivers improperly navigate curves, ramps, and intersection approaches. HFST supports the Safe System elements (i.e., Safe Speeds, Safe Roads, Safe Users) because it helps keep vehicles in their lane, reduces stopping distance, and thus can improve safety for all road users.

1.2.2 ADVANTAGES OF HFST

Some of the key advantages of HFST include:

- **Low-cost treatment**—HFST is a low-cost, crash-reduction treatment capable of providing greater safety benefit than other low-cost safety measures such as advanced curve warning signs, advisory speed plaques, pavement markings, chevrons, and guardrail when strategically placed at targeted locations. It is a substantially lower-cost alternative to more drastic safety improvements such as repaving, curve realignment, and other roadway geometry changes.
- **Minimal impact to traffic**—HFST can generally be installed and opened to traffic within hours, minimizing lane closure time, and the associated impact on traffic (including the potential for secondary crashes from prolonged construction work zones), particularly if a detour is required. It can generally be installed during nighttime lane closures (temperature permitting) and can be installed using single-lane closures, allowing traffic to remain on other lanes.
- **Superficial treatment**—HFST is a thin, superficial overlay of the existing pavement which will not change the pavement cross-slope and alter drainage, reduce overhead clearance, or require guardrails or barriers to be raised.
- **Quick implementation**—Agencies can expect a relatively short planning process (with minimal construction drawings) and installation timeframe, compared to other alternatives. Some agencies have reported timeframes as short as 10 days for small applications or 6 months for larger projects from concept to completion.
- **Negligible environmental impacts**—The treatment is only applied between existing pavement edges and does not require disturbances to the surrounding ground. This can result in shortened environmental review periods and lessen environmental mitigation.
- **Durable and long lasting**—HFST has demonstrated excellent long-term pavement surface functional durability. A properly installed HFST over a sound pavement surface should have a service life of at least 7 to 10 (or more) years, depending on the level of traffic exposure.

1.3 STEPS FOR HFST DEVELOPMENT

The following is a summary of the step-by-step process for HFST implementation as a safety countermeasure to reduce friction-related crashes. The various chapters of this Guide will cover key components of HFST implementation as follows:

STEPS

1. Identify Candidate Locations for HFST (Chapter 2)
2. Field Verification and Design (Chapter 3)
3. Select HFST Materials (Chapter 4)
4. Develop Installation Specification (Chapter 5)
5. Estimate Costs and Identify Funding (Chapter 8)
6. HFST Installation (Chapter 6)
7. Performance Monitoring (Chapter 7)

The intent of this Guide is to assist agencies with HFST implementation for the first time or to help agencies with established HFST programs to further refine their program such that HFST becomes a routinely used safety countermeasure.

1.4 PURPOSE AND STRUCTURE OF THE GUIDE

The purpose of this Guide is to provide key information for HFST implementation as a safety countermeasure to reduce friction-related crashes. Each chapter provides information on the various steps of the implementation process as follows:

- Chapter 2 provides information on HFST candidate site selection. It discusses both site-specific and systemic approaches to site selection. This chapter also discusses the importance of considering pavement friction in the site selection process as well as other factors such as roadway geometry and speed differentials that may impact site selection.
- Chapter 3 provides information on field verification and design for HFST candidates. Field verification includes an assessment of pavement condition and other potential factors that may be contributing to crashes. Design includes issues related to project scoping, such as identification of treatment limits, traffic control considerations, surface preparation requirements, and other factors that may affect project cost.

- Chapter 4 discusses HFST materials, namely the polymeric resin binder and aggregate materials that constitute an HFST. This chapter also discusses key properties and site-specific considerations for these materials.
- Chapter 5 provides information on HFST specifications and installation practices based on the current state-of-the-practice in the HFST industry. This includes key components for a robust HFST specification and key considerations for installation methods.
- Chapter 6 is an Inspection Guide for HFST installation. This Inspection Guide, which is targeted towards project inspectors, provides an overview of the HFST installation process and key considerations for each aspect of the installation. The Inspection Guide will also serve as a standalone guide accessible via smart phone or tablet in the field for quick reference.
- Chapter 7 discusses the importance of performance monitoring and provides guidance for both safety performance (crash-reduction) monitoring as well as functional performance (friction, distress, etc.) monitoring. It also provides guidance on end-of-life failure, removal, and replacement.
- Chapter 8 provides information on HFST cost and discussion on methods for funding. The cost discussion includes guidance on B/C considerations and estimation for HFST.
- Appendix A provides some examples of other applications for HFST that are not common but have demonstrated the benefits of HFST nonetheless. Appendix B provides some examples of systemic deployment of HFST. And Appendix C provides a sample inspection checklist for HFST installation.

CHAPTER 2—IDENTIFICATION OF HFST CANDIDATE LOCATIONS

There are two primary methods for HFST candidate site identification currently used in the United States:

1. **Site-Specific Safety Approach**—also known as a hot-spot approach, is a reactive approach which uses historic crash data and predictive methodologies such as safety performance functions (SPFs) and EB to identify locations where HFST may provide benefit. This approach includes identifying sites over-represented with target crashes, in this case run-off-road and wet weather crashes, for individual installations.
2. **Systemic Approach**—this is a more proactive approach to treat locations deemed "high risk" for friction-related crashes. Predictive methods, such as SPFs help practitioners to identify high-risk features. Locations are identified based on the presence of several different risk factors such as roadway characteristics, traffic exposure, and pavement friction. This approach treats a broader series of curves based on risk of target crashes where HFST may provide benefit to locations that may not have historically observed crashes but are at higher risk for future crashes.

Based on a recent survey of State departments of transportation (DOTs) with HFST experience, approximately one quarter of the 26 states responding to the survey indicated that they have adopted a systemic approach to installing and managing HFST (Wilson and Saca 2021).

A third approach, although not discussed in detail in this document, is a policy-based approach (also referred to as a systematic approach). With this approach, HFST is effectively specified at the design stage of a paving project. HFST is applied at all locations meeting specific criteria regardless of crash history at these locations. Typically, the criteria are based on roadway characteristics and traffic exposure. This approach is used in the United Kingdom where HFST is effectively a standardized pavement surface treatment applied to new and newly-rehabilitated pavements. Table 4 shows the locations where HFST (indicated as "HFS" in the table) is mandated by design policy using this approach. The table provides the polished stone value (PSV) for a given investigatory level (IL).

Table 4. Modified design policy for use of HFST ("HFS") in the United Kingdom based on roadway and traffic characteristics (Highways England 2020).

Site category	Site description	IL	PSV required for given IL. Traffic level and type of site									
			Traffic (cv/lane/day) at design life									
			1-250	251-500	501-750	75-1000	1001-2000	2001-3000	3001-4000	4001-5000	5001-6000	Over 6000
A	Motorway	0.30	50	50	50	50	50	55	55	60	65	65
		0.35	50	50	50	50	50	60	60	60	65	65
Q	Approaches to and across minor and major junctions, approaches to roundabouts and traffic signals	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
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
G1	Gradients 5-10% longer than 50m	0.45	55	60	60	65	65	68+	68+	68+	68+	68+
		0.50	60	68+	68+	HFS	HFS	HFS	HFS	HFS	HFS	HFS
S2	Bends radius <500m – carriageway with two-way traffic	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

Deployment of HFST typically begins with installation of HFST at a few experimental locations, or spot treatments, to allow agencies to test the usefulness and application of the treatment. These spot locations are typically high-crash locations where inadequate pavement friction is believed to be a contributing factor in a significant number of the reported crashes. After initial experimental installations, agencies may expand the spot treatment approach on a large scale, consolidating multiple application locations under one contract. This treatment approach can quickly reveal the effectiveness of HFST such that it gains agency-wide acceptance, helping to convince policymakers of the benefits of this life-saving treatment.

Agencies comfortable with a systemic safety approach for other countermeasures may choose to add HFST as an option, resulting in a larger-scale systemic deployment. Other agencies may promote HFST deployment through Road Safety Audits (RSAs), Roadway Departure Safety Implementation Plans (RwDSIP), or in Highway Safety Improvement Program (HSIP) guidelines. Regardless of the method for implementation, agencies will benefit from documenting locations to track the safety performance of HFST installations for further fine-tuning of the site selection process and widespread deployment.

Agencies typically evaluate crash data through a network screening process to identify HFST candidate locations. Whether this is spot location crash data or crash data analyzed as part of a systemic approach, safety performance is the key justification for HFST implementation as it does not provide any benefits relative to pavement preservation.

The following sections discuss the more common methods for HFST candidate site identification currently used by agencies throughout the United States as well as new methods, such as pavement friction management programs (PFMPs), also being implemented for the purpose of site selection. While the focus of this Guide is on HFSTs on horizontal curves and ramps, it also discusses using HFST to reduce crashes at intersections. Appendix A highlights additional applications that have not seen widespread use but have shown great potential.

Regardless of the method used for initial identification, field verification of candidate locations is an essential component of HFST implementation and will be discussed further in chapter 3.

2.1 SITE-SPECIFIC SAFETY APPROACH

A site-specific safety approach focuses on reducing crashes at locations with high crash frequency. Agencies using this approach for HFST typically use a roadway network screening process to identify locations with a disproportionate number of crashes. Some agencies set a specific threshold crash frequency, above which the location is automatically recommended for potential countermeasure development. Other agencies use a ranking system by developing a list of locations that exhibit a significantly high concentration of collisions. They investigate the highest ranked locations on the lists, develop a list of potential countermeasures for each location, and select as many locations as possible for treatment based on funding availability and expected return on investment. Much of the following discussion is focused on HFST for horizontal curve applications, but the same principles apply to other locations such as ramps and intersections.

When selecting locations for HFST, some agencies look at the total crash frequency, wet-crash frequency, RwD crash frequency, and crash severity (i.e., focusing on fatal or serious injury crashes). For each crash, they may examine the crash report narrative to determine the factors contributing to the crash and to pinpoint the exact location within the curve. As crashes may occur or be recorded as happening before or after the horizontal curve, it is important to verify the location of the crashes in order to determine whether each crash belongs in the data set.

2.1.1 SPFS AND EB PROCESSES

The primary reason for implementing HFST is to prevent or mitigate future crashes. To maximize the actual return on investment, HFST should be applied at locations with the greatest potential to reduce number and severity of friction-related future crashes. Historically, observed crash frequency is one means of estimating the potential for future crashes at a given location. The Highway Safety Manual (HSM), published in 2010 by the American Association of State Highway and Transportation Officials (AASHTO), describes limitations of relying solely on recent crash history to identify locations with the greatest potential for improvement. These limitations include the natural variability in crash frequency, regression-to-the mean bias, and changes in roadway characteristics over time. The HSM provides predictive methods that address these limitations through SPFs and EB weighting of observed crash frequencies and SPF estimates.

SPFs are equations used to predict the average number of crashes per year at a location as a function of site characteristics. Site characteristics always include exposure (typically average annual daily traffic, AADT), but may also include roadway characteristics such as number of lanes, lane width, median and shoulder features, radius, or degree of curvature (Srinivasan et al. 2013; Donnell et al. 2019). Recent efforts have led to the development of SPFs which consider pavement friction (de León Izeppi et al. 2016a, de León Izeppi et al. 2016b, Pratt et al. 2018b). However, the regression coefficients for these SPFs are specific to the jurisdiction where friction data were collected and are specific to the device used to measure friction. While these SPFs may not be transferable across jurisdictions, agencies can use the documented process to develop their own friction-based SPFs (de León Izeppi et al. 2016a, de León Izeppi et al. 2016b).

Agencies can use SPFs in the network screening process for identifying HFST candidate locations. Specifically, agencies can use SPFs to predict crashes for a particular location and then compare the estimate to the observed number of crashes at the location, ranking candidates based on the difference (i.e., the greater the difference between observed and predicted, the higher the priority for treatment). This network screening process can further be improved by computing the expected number of crashes through EB weighting of predicted and observed crashes. The excess expected crashes (EEC) measure is the difference between expected crash frequency and SPF-predicted crash frequency at the location.

The EB expected crash frequency can provide a more reliable estimate of the site's long-term average crash frequency than the observed crash history. However, the reliability of the EB approach is dependent upon the SPF used for predicting average crash frequency. Agencies may choose to develop their own SPF or to calibrate existing SPFs to the local data. It is important for agencies to consider the cost of SPF development versus calibration, the amount of data required, and general availability and quality of data. One option is to first calibrate an existing SPF to local data and determine how well the calibrated SPF performs based on goodness-of-fit measures and a cumulative residual plot. The cumulative residual plot provides an indication of how well the calibrated SPF performs for a breadth of sites stratified by exposure (AADT) and other continuous variables such as calibrated predictions. This stratification is important to determine if the SPF shape is appropriate (a calibrated model cannot change the shape of the SPF). If the calibrated model does not provide good fit to the overall data, then SPF development may be necessary. FHWA's *Safety Performance Function Decision Guide: SPF Calibration vs SPF Development* provides further details (Srinivasan et al. 2013).

2.1.2 WET PAVEMENT CRASHES

Wet pavement conditions can lower the available pavement friction drastically, particularly if the pavement has been polished by traffic wear and lacks adequate macrotexture to allow water to evacuate between the tire and pavement surface. HFST is an ideal countermeasure for these conditions because it can increase pavement friction values up to 300 percent. (Note that friction measurements are typically performed on a wetted pavement surface.) As demonstrated by the CMFs presented in table 2 and table 3, the greatest crash reduction benefit (i.e., lowest CMF) is for wet-pavement crashes (Merritt et al. 2020b).

Most agencies focus heavily on wet crashes as a screening criterion for identifying HFST candidates. These locations are typically identified as either having a high frequency of wet crashes year after year or as having a high ratio of wet-to-dry or wet-to-total crashes. The process by which agencies select wet crash curve locations for potential HFST implementation varies. For example, agencies may develop a list of locations that have experienced a specific number of wet crashes within a single time period (e.g., 20 or more wet crashes in 5 years) or incremental time periods (e.g., 3, 6, or 9 wet crashes in 1, 2, or 3 years, respectively). Although not common practice, agencies may even normalize the yearly wet crash frequency by historical percent wet-time values obtained per location, to understand the overrepresentation of wet crashes for locations that are either particularly wet or dry. Wet crash ratios of 0.35 wet/total crashes (Von Quintus and Mergenmeier 2015) or 50-percent wet/dry crashes (PennDOT 2012) are two examples of these criteria.

In addition to wet pavement crashes, States that experience snow and ice conditions in the winter months have also reported a reduction in snow and ice crashes from HFST. The South Dakota DOT, for example, has 5 times more RwD crashes involving winter road conditions than wet road conditions. While there were not enough data to perform an advanced statistical analysis of crash reductions, a naïve before-after analysis showed an 80-percent crash reduction (77 percent with the Winter Severity Index applied) in 3 years at 4 initial HFST demonstration projects, and a 78-percent crash reduction in 2 years after HFST was installed at 15 additional locations (FHWA 2019). While HFST has shown potential to reduce snow and ice crashes, winter road conditions can be highly variable (e.g., icy, snow-packed, slushy, etc.), and therefore crash reduction benefits will also likely be highly variable.

2.1.3 ROADWAY DEPARTURE CRASHES

From 2016-2018 RwD crashes accounted for 51 percent of all traffic fatalities in the United States (FHWA 2020b). HFST is recognized as a proven countermeasure for reducing RwD crashes by helping to keep vehicles in their lane (FHWA 2021a). A 2018 NCHRP synthesis revealed that 90 percent of the States that responded to a survey on RwD countermeasure usage have deployed HFST for reducing RwD crashes, with 20 States indicating they use it often or at least sometimes. The survey also revealed HFST as one of four RwD countermeasures responding States deemed to be especially effective in reducing the frequency or severity of RwD crashes (McGee 2018). States are including HFST in their Roadway Departure Safety Implementation Plan.

A benefit of HFST compared to other curve-related RwD countermeasures (e.g., edge line or shoulder rumble strips, edge line pavement markings, horizontal curve delineation, etc.) is that HFST does not depend on the driver to recognize the information associated with delineation or noise/vibration and make corrections. Rather, HFST interacts directly with the vehicle, independent of the driver's awareness, by providing the necessary friction needed to help keep the vehicle on the roadway.

While *rural* RwD crashes account for a significant percentage of RwD crashes (approximately 34 percent of all fatalities), these crashes tend to be spread out across long sections of roadway (FHWA n.d.). As such it is not often feasible to address rural RwD crashes through traditional site-specific ("hot spot") methodologies, and systemic approaches are necessary (Torbic et al. 2020). While formal results are not yet published, Louisiana and Georgia are two States which have deployed HFST for reducing rural RwD crashes using a systemic approach (McRae 2020, Tsai et al. 2018).

2.1.4 INTERSECTION CRASHES

Intersections are another key application for HFST. Pavement friction is necessary at intersections to help vehicles stop and start, which can also cause pavements to polish or wear more quickly than other sections of pavement. Higher friction at the approach to an intersection shortens stopping distance to reduce rear-end crashes and reduce crosswalk incursions for pedestrian safety. Higher friction within an intersection potentially reduces the occurrence or at least the severity of right-angle crashes. Because the number of intersection applications of HFST in the United States to date has been limited, there is little published information on the effectiveness of HFST for intersections.

The Ministry of Transportation and Infrastructure, British Columbia applied HFST at 10 signalized intersection approaches in 2019. Intersection locations were identified and ranked using an "excess proportion of specific crash types" method (HSM countermeasure-based approach), with rear-end crashes as the target crash type. Although initial anecdotal evidence suggests a significant reduction in rear-end crashes at these locations, a formal before-after analysis has not been completed and published.

Other studies have demonstrated the impact of friction enhancement (through traditional resurfacing or microsurfacing) in reducing rear-end crashes at intersection approaches. One such study from New York State DOT's Skid Accident Reduction Program revealed significant reduction in total, wet-road, rear-end, and rear-end wet-road crashes, with less significant benefit for right-angle crashes. For this study, crashes within 33 ft of the intersection were considered intersection-related crashes (Harkey et al. 2008).

2.1.5 CRASH SEVERITY

While some agencies prioritize improvement locations by the frequency and severity of crashes, it is also important to capture where frequent non-severe or property-damage-only (PDO) crashes occur. These less severe crashes may be predictors of future serious injury or fatal crashes, if left untreated. Additionally, the cost of non-severe crashes can become substantial if they are happening frequently. Many agencies use a weighted scale to assign either numeric or monetary values to each crash severity level, in order to capture instances where frequent, less severe crashes may accumulate to a situation that requires addressing. FHWA's *Crash Costs for Highway Safety Analysis* provides a method to assign monetary values to an injury level scale (the KABCO scale) (Harmon et al. 2018).

By using the KABCO scale, or similar, agencies may be able to identify a threshold at which horizontal curves, ramps, or intersections with few fatalities or serious injuries, but frequent, less severe crashes can be identified and treated.

Evolution of KYTC's HFST Site Selection Process

Initial Demonstration Project	KYTC's initial experience with HFST was a smaller-scale demonstration installation at two locations with a high number of wet pavement crashes. Based on the dramatic decrease in crashes in the 4 years following installation, KYTC looked for more opportunities for HFST.
First Iteration	KYTC identified 30 locations with high RwD crashes that could potentially benefit from HFST using a wet/dry crash ratio greater than 50 percent as screening criteria.
Second Iteration	As part of their RwDSIP, KYTC analyzed 4 years of crash data on rural roadway segments (3,000 ft in length) and identified HFST candidates based on a screening criterion of 8 wet crashes and a wet/total crash ratio of 0.35. This resulted in 227 candidate sites of which 160 were selected for installation after field assessment.
Third Iteration	KYTC has adopted an EB methodology for network screening of potential HFST candidate locations. This methodology uses wet-weather RwD SPFs with EB adjustment to determine EEC values for different facility types (curves and ramps) and for the different crash severities (i.e., K, A, B, C, O). The EEC values are then used with crash severity to prioritize locations for treatment.
Potential Future Enhancements	KYTC is currently collecting 15,000 miles annually of network-wide data using continuous friction measurement for the purpose of a preventative systemic approach. It is expected that incorporating continuous friction measurement data into SPF models will be a more effective and efficient systemic approach than one without friction data

2.2 SYSTEMIC APPROACH

A systemic approach to HFST site selection is a proactive approach that allows an agency to identify candidate locations based on high-risk roadway features that are correlated with particular crash types, rather than crash frequency (23 USC 148(a)(12)). In other words, systemic site selection is not based on crash history at a particular location but is based on a high probability of future crashes at that location.

The systemic approach does not replace the need to focus on individual locations with high numbers of severe crashes, but simply expands site selection to a more comprehensive and proactive approach to roadway safety efforts. Agencies can use the systemic approach to address the requirements for the HSIP, which focuses on fatal and serious injury crashes on all public roads. Additional information on balancing site-specific and systemic approaches to safety countermeasures is provided in the *Reliability of Safety Management Methods: Systemic Safety Programs* (Gross et al. 2016).

2.2.1 THE PROCESS

The systemic approach to safety involves widely implementing low-cost safety improvements, such as HFST, based on high-risk roadway features correlated with specific severe crash types. The approach provides a more comprehensive method for safety planning and implementation that supplements and complements traditional site-specific analysis. The approach helps agencies broaden their traffic safety efforts and consider risk as well as crash history when identifying where to make low-cost safety improvements. Note that the systemic process typically considers many different countermeasures, and it may or may not lead to selecting HFST as the recommended safety countermeasure. HFST has been identified as a countermeasure for roadway segments (i.e., curve treatments) and is currently being evaluated as a systemic countermeasure for intersections.

The key to the systemic approach is evaluating an entire system using a defined set of criteria, which results in an inferred prioritization that indicates some elements of the system are better candidates for safety investment than others. Section 2.2.4 provides risk factors used by agencies that have included HFST as a countermeasure in the systemic approach.

The following are three common approaches or tools used for a systemic evaluation. For each, there is an indication of the basic data needs. Which tool an agency chooses to use will depend largely on the availability of crash and roadway data (Torbic et al. 2020).

- **FHWA Systemic Safety Project Selection Tool Methodology**—this is the least complex and most adaptable tool for agencies with incomplete or lower quality roadway inventory, traffic volume, and/or crash data. This tool allows for prioritization of sites with potential for safety improvement and related projects without the need for high-quality crash data (Preston et al. 2013). If quality crash data are available, there is an opportunity to include observed, predicted, or expected crash frequency as a risk factor in systemic site selection.
- **Application of SPFs Using State-Specific In-House Tools**—this methodology requires a special skill set (i.e., ability to develop and calibrate SPFs), and relies on high-quality robust roadway inventory, traffic volume, and crash datasets. Further, there is an opportunity to use the results from an EB-based network screening as a starting point for systemic safety analysis.

- **Application of U.S. Road Assessment Program (usRAP) Methodology and Vehicle Information and Diagnostics for Aftersales (ViDA) Software**—this is a more defined and methodological approach but requires robust roadway datasets (usRAP n.d.).

2.2.2 BENEFITS OF THE SYSTEMIC APPROACH

Agencies may see several benefits when using the systemic approach for HFST. The systemic approach:

- Identifies "issues" based on a system-wide analysis of the data. A significant number of severe crashes are spread over a wide area and relate to specific crash types. Some of these crashes are rarely identified through the traditional site analysis approach because it is difficult to isolate severe crash locations. The systemic approach provides State, regional, and local transportation agencies an alternative method to address severe, targeted crash types and fulfill a previously unmet need (Atkinson et al. 2016).
- Looks for roadway characteristics that are frequently present in severe crashes (i.e., risk factors). The systemic approach starts with a different premise for identifying safety concerns. While the site-specific approach is based on crash history at individual locations, the systemic approach looks at crash history on an aggregated basis to identify high-risk roadway characteristics that may contribute to future severe crashes. The site-specific approach results in safety investments at high-crash locations while the systemic approach leads to widespread implementation of low-cost improvements to reduce the potential for severe crashes (Atkinson et al. 2016).
- Focuses on one or more low-cost countermeasures that can be deployed widely across the system while identifying and prioritizing implementation locations. The systemic approach considers multiple locations with similar risk characteristics. When examining the system as a whole, a particular roadway characteristic may contribute to frequent or severe crash experiences. It can be more cost-effective to address some issues on a system-wide basis (or at least a wider deployment of countermeasures) rather than by individual crash location (Atkinson et al. 2016).
- Is a data-driven approach that is adaptable based on available data. Various options are available depending on the quality of the crash data available. This is beneficial for local agencies that may have very limited roadway inventory and traffic data, as well as incomplete or poor-quality crash data (Torbic et al. 2020).

2.2.3 CHALLENGES

One of the biggest challenges of implementing a systemic site selection process is related to the evaluation and justification of prior systemic strategies or programs. This stems from the fact that evaluations use several years of crash data after implementation. Therefore, results lag behind initial deployment for several years (Torbic et al. 2020). This can make assessments of the effectiveness (and justification to decision-makers for further funding) difficult. It can also make identification of necessary adjustments to the process for future deployments difficult to determine. Other challenges associated with implementing a systemic site selection process include:

- Data availability dictates the level of detail in the analysis. While a systemic analysis can be completed with nearly any amount of data, using more data will allow for refinement of potential risk factors.
- The availability of resources determines the extent of improvements that can be made. Resources may also impact the level of analysis that can be completed.
- The established priorities of an agency may define the direction of the analysis.
- The relationship between State and local transportation agencies may impact the funding available for systemic analysis on non-State routes as well as the extent to which systemic improvements are applied to non-State routes.

2.2.4 EXAMPLES OF SYSTEMIC APPROACHES FOR HFST

Agencies utilizing a systemic approach for HFST site selection have typically focused on rural RwD curve crashes. Two agencies, Louisiana Department of Transportation and Development (DOTD) and Georgia DOT, implemented systemic deployments that did not consider crash history at the specific locations selected for treatment, but rather treated curves based on risk criteria (Tsai et al. 2018, McRae 2020). Two other agencies, Thurston County, Washington, and Delaware DOT used systemic processes for identification of candidate locations based on risk factors, and focused treatment on specific locations with high potential for safety improvement (Davis 2014, Weiser 2016). Appendix B includes additional detail on these agencies' systemic processes.

The general risk factors used by these agencies for systemic deployment of HFST for RwD crashes at curves includes:

- Facility type: rural/local roads, arterials and collectors (typically two-lane).
- Traffic Volume: low to medium traffic volume with AADT ranging from 2,500-8,000 vehicles/day.
- Geometrics: sharp horizontal curves (degree of curvature > 3.5, radius < 1,640 ft) with and without grade.
- Grade: greater than 4 percent.
- Shoulders: narrow paved or unpaved/native shoulders (less than 6 ft).
- Speed: typically, higher speed such as 50 miles per hour (mph) speed limit.
- Ball-bank indicator readings: 12 or higher.

As agencies develop PFMPs and identify appropriate investigatory levels based on site conditions, pavement friction will likely become another risk factor for inclusion in systemic programs.

2.3 PAVEMENT FRICTION

As a countermeasure specifically used to enhance pavement friction, HFST deployment usually focuses on locations with a "friction issue" that may be contributing to observed crashes or may lead to crashes in the future. A high percentage of lane departure crashes and wet pavement crashes are key indicators that a friction issue may already exist. Systemic site selection processes may further be able to identify locations with the potential for friction issues through an evaluation of risk factors. As discussed in chapter 3, friction testing as part of HFST candidate site verification confirms that a friction issue exists or if there may be other contributing factors.

While pavement friction can be measured directly, there is no universally accepted friction value that indicates adequate friction for all locations (AASHTO 2008). Rather, adequacy of pavement friction is evaluated based on the concepts of friction demand and margin of safety, discussed in section 2.3.1. Furthermore, proactive approaches such as PFMPs using appropriate testing methodologies and devices can help to identify potential friction issues before they manifest in the form of increased crash rates, and help agencies establish appropriate levels of friction based on site characteristics.

2.3.1 FRICTION DEMAND AND MARGIN OF SAFETY

Friction demand is the level of friction needed to safely perform braking, steering, and acceleration maneuvers (AASHTO 2008). Friction demand is a function of vehicle speed and roadway geometry (curve radius, superelevation rate, grade) as well as driver behavior (e.g., how a driver navigates a curve with respect to travel path braking and acceleration). Furthermore, for curve locations in particular, driver behavior may be influenced by roadway geometry as it affects driver comfort, which in turn may influence the speed at which they approach and navigate a curve. Friction demand increases as speed increases and curve radius or superelevation rate decrease. For non-curve and other high-risk locations such as steep grades, intersection approaches, pedestrian crossings, and roundabouts, friction demand is driven by the ability to perform short-term maneuvers such as sudden braking, lane changes, and minor changes in direction within a lane (AASHTO 2008).

Friction supply is the available pavement-tire friction capability. It is affected by tire-pavement interface properties (e.g., tire tread condition), pavement texture, and the presence of water or solid contaminants on the pavement surface (Pratt et al. 2014). A combination of pavement macrotexture which allows water to evacuate from beneath vehicle tires, particularly at higher speeds, and microtexture, which provides the actual tire-pavement contact, is necessary for good pavement friction.

Figure 3 illustrates conceptually the relationship between friction demand, friction supply, and vehicle speed. Note that the greater the friction supply, the greater the capability of handling friction demand as speed increases (i.e., the higher the speed of impending skid).

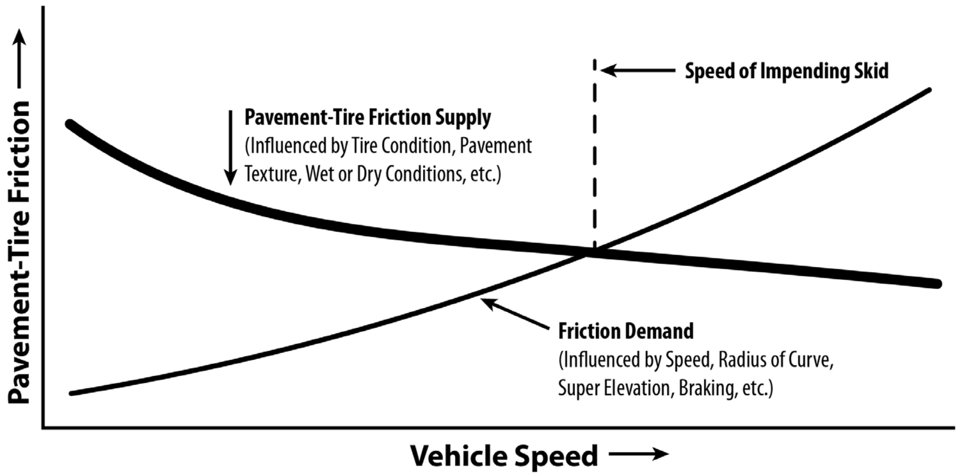

Figure 3. Graphic. Relationship between speed, friction demand, and friction supply (AASHTO 2008).

Locations with high friction demand are prone to losing friction over time as the surface wears or polishes faster than pavement with low friction demand, all else being equal. This necessitates a pavement surface that not only provides the necessary levels of friction to meet friction demand, but also one that can sustain those friction levels over time. HFST provides exceptional levels of friction and sustains high levels of friction over time under traffic wear.

Margin of safety is the difference between friction supply from the pavement surface and friction demand from vehicles traversing the surface (Pratt et al. 2014). If friction demand exceeds friction supply, vehicle skidding is likely to occur.

A larger margin of safety allows for drivers to compensate for mistakes such as driving too fast for conditions. Margin of safety can be increased by increasing friction supply or by decreasing friction demand. Decreasing friction demand can be much more challenging as it may require altering the geometry of the roadway (e.g., increasing curve radius or superelevation rate) or reducing vehicle speed, which is dependent upon driver behavior (Pratt et al. 2014). Increasing friction supply, however, can be accomplished fairly simply through the application of HFST which provides substantially higher friction values than conventional pavement surfaces and other surface treatments.

The Texas Transportation Institute (TTI) developed the Texas Curve Margin of Safety (TCMS) tool (Pratt et al. 2018a, Pratt et al. 2018b) to evaluate the margin of safety for curves. This tool considers the influence of driver behavior in navigating curves in order to provide a better estimate of the margin of safety. The procedure uses roadway geometry (curve radius, deflection angle, superelevation rate, and grade) and vehicle speed (85th percentile on the approach and curve midpoint) to estimate friction demand at the beginning point of curvature (PC), midpoint, and end point of tangency (PT) of a curve. For friction supply, the tool considers the maximum available side friction supply as a function of friction measured through standard locked-wheel skid testing procedures along with consideration of a reduction in side friction supply due to acceleration and/or braking tractive friction. Friction demand is compared to friction supply to determine the margin of safety at three points (PC, midpoint, and PT) along the curve. A margin of safety of at least 0.08 to 0.12 is suggested along the entire length of the curve (Pratt et al. 2014, Glennon and Weaver 1971).

Agencies input friction supply either directly from friction measurements or from default values for common pavement surfaces and treatments, including HFST. Friction change over the life of the treatment is modeled for the purpose of evaluating changes in the margin of safety over time. Safety prediction models for curves on two-lane, four-lane undivided, and four-lane divided roadways are also included in the tool and use CMFs for total crashes, run-off-road (ROR) crashes, and wet weather ROR crashes based on curve radius, skid number, lane width, shoulder width, and annual precipitation. The safety prediction analysis is further used to perform a B/C analysis for assessing the long-term benefits of different pavement surfaces/treatments (Pratt et al. 2018b). While there are currently no known similar tools for assessing margin of safety for intersections, the basic principles still apply.

2.3.2 PAVEMENT FRICTION MANAGEMENT PROGRAMS

PFMPs are a proactive and systematic approach to measuring and monitoring pavement friction and crash risks (wet and dry) of roadways, such that pavement surfaces in need of remedial action (e.g., friction improvement with HFST) can be readily identified and treated (AASHTO 2008, de León Izeppi et al. 2019).

FHWA Technical Advisory R 5040.38 provides general guidance on what should be considered in a PFMP, and the AASHTO Guide for Pavement Friction provides additional detail on the various aspects of a PFMP. However, it should be noted that while the FHWA Technical Advisory generally focuses on wet-weather crash locations, numerous studies have found that HFST also helps reduce dry pavement crashes. Current efforts to develop PFMPs recommend the following steps for implementation (de León Izeppi 2019):

1) **Pavement Network Definition**—The roadway network is divided into distinct pavement sections based on friction demand categories. Factors affecting friction demand categories include: roadway alignment (horizontal and vertical), roadway features/environment or "events" (ramps, driveways, intersections, median type, urban vs. rural setting, etc.), traffic characteristics (traffic volume, composition, and speed), and driver/vehicle characteristics.

2) **Network-Level Data Collection and Processing**—Agencies establish field testing procedures for collecting friction, texture, and geometric data. Friction testing parameters agencies need to define include: season for testing, test speed, test lane and wheelpath, and ambient conditions. Agencies also collect and use crash data, traffic data, and pavement condition data (e.g., distress, smoothness, etc.) in the safety analysis.

   For friction measurement, continuous pavement friction measurement (CPFM) methods provide a more comprehensive "map" of pavement friction, as opposed to spot measurements representing only a short section of pavement from a locked-wheel skid trailer test which will only measure 1-2 percent of the pavement surface (de León Izeppi et al. 2019). This allows agencies to identify variations in friction, which may occur within a given pavement section. This is particularly common for sections with high friction demand due to accelerated wear of the surface (e.g., horizontal curves, intersection approaches, steep grades, etc.). These sections commonly have the worst-case friction condition and may not traditionally be measured due to safety concerns for data collectors. Recent evaluations have demonstrated the benefits of CPFM for PFMPs, and there are several CPFM devices currently available for collecting continuous friction data (de León Izeppi et al. 2016a). Most modern friction measurement devices also collect texture and roadway data simultaneously (FHWA 2021b).

3) **Threshold Analysis**—Friction, roadway characteristics, and crash data are analyzed to help define friction demand categories and to determine appropriate ILs for friction. The IL is considered a desirable level of friction (based on site characteristics/friction demand) and if friction falls below this value, further investigation of a location should be performed. These thresholds can be determined from an evaluation of crash rates and historical pavement friction measurements for each friction demand category (AASHTO 2008). These friction thresholds will be specific to the device used to measure friction unless measurements from different devices have been harmonized.
4) **Safety Analysis**—Agencies use SPFs and the EB methodology to analyze crash data and determine the expected crash counts based on friction demand categories. As an agency's PFMP evolves, they can develop SPFs that consider friction or CMFs that consider friction change from various treatment types for better estimation of the impact of pavement friction on crashes.
5) **Network Screening**—Agencies screen network-level friction data to identify pavement sections that fall below the ILs for potential friction treatments.
6) **Benefit-Cost Analysis for Selection of Friction Treatments**—In this step, agencies use the EB approach to predict the potential crash reduction and compute the crash reduction savings. Agencies then use the cost of various treatments and anticipated life to compute a B/C for each treatment to facilitate treatment selection and prioritize treatment locations.

This process is then repeated annually to help further refine friction demand categories, friction ILs, SPFs, and B/C ratios for different treatments.

A significant benefit of a comprehensive PFMP is that friction data can be used to potentially identify all friction-related crashes in a network, rather than just wet pavement crashes (de León Izeppi et al. 2016a). While wet pavement crashes are typically used as a network screening criterion to identify HFST candidate sites, HFST is also effective at reducing dry pavement crashes. Further, the benefits of a PFMP can far outweigh the costs and effort to develop and deploy such a program. A pilot PFMP study from Virginia found that the potential economic savings from crash reduction realized through the deployment of a comprehensive

PFMP would offset the costs, including the equipment necessary for data collection using CPFM and the cost of friction treatments (de León Izeppi et al. 2016a).

2.4 SPEED DIFFERENTIALS FOR CURVES

For horizontal curves, speed differential is defined as the difference between the tangential posted regulatory speed limit (e.g., at the approach to a curve) and the curve advisory speed, or more importantly, the speed at which drivers navigate a curve (i.e., 85th percentile curve speed). Speed differential can be a good indicator of the usefulness of an HFST treatment as side friction demand increases with increasing speed reduction due to deceleration as vehicles enter a curve (Bonneson 2007). As figure 4 illustrates, for a given curve radius and curve speed (85th percentile speed), speed differential increases with the 85th percentile tangent speed (Pratt et al. 2014). Under wet weather or low pavement friction conditions, friction supply may be inadequate for this increased side friction demand, and skidding or a RwD crash may result. HFST provides additional friction to allow motorists to break and navigate successfully without losing control.

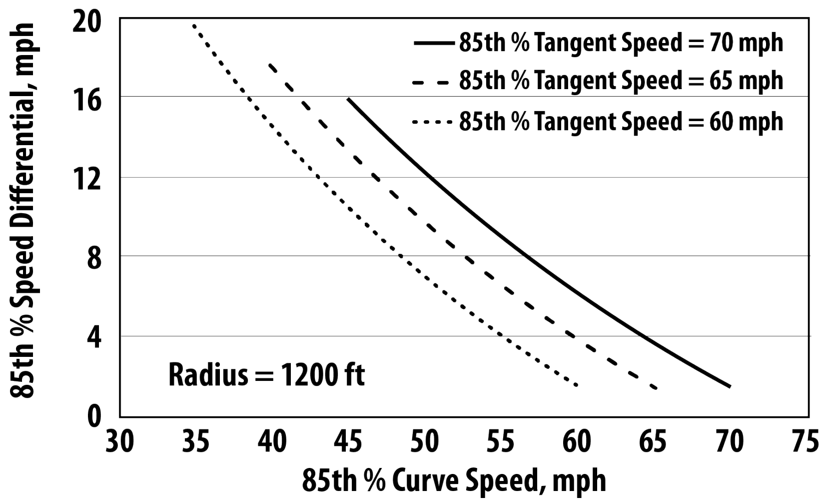

Figure 4. Graphic. Increase in speed differential (Pratt et al. 2014).

Studies have linked curve radii to crash likelihood, with crash rate increasing with a decrease in curve radius, particularly below 1,000 ft. Since a smaller curve radius corresponds to a lower advisory speed and a greater speed differential, radius and speed differential can be deductively linked in many cases. In addition to curve radius, other studies have examined the relationship between the length of tangent upstream and downstream from a curve. Although not defined explicitly in terms of tangent length, longer upstream and downstream tangents result in a higher number of RwD crashes, while shorter upstream and downstream tangents result in lower RwD crashes (Donnell et al. 2019).

2.5 ROADWAY GEOMETRY

Superelevation and roadway grade are other geometric factors that affect friction demand and the potential need for HFST. Superelevation is accounted for in the AASHTO Green Book equation for friction demand (AASHTO 2018a). A lack of superelevation increases friction demand and is commonly found in the first and last portions of most curves where superelevation is not fully developed. Increasing friction using HFST can help counteract a lack of superelevation. Roadway downhill grade greater than four percent has been reported to have an impact on ROR crashes on sharp curves (Tsai et al. 2018). To account for roadway grade, a modified version of the AASHTO Green Book friction demand equation which accounts for grade is proposed by Pratt et al. and incorporated into the margin of safety tool discussed previously (Pratt et al. 2014).

Roadway geometry can also impact friction demand at intersection approaches. Intersections at the bottom of a downward grade, for example, require additional braking distance. Limited sight distance at an intersection approach, likewise, can increase friction demand as drivers react suddenly to a stoplight or stop sign. Increasing friction supply through the use of HFST can counteract increased friction demand at these critical locations (FHWA 2020a).

Roadway Characteristics Site Selection Processes

Recognizing the importance of roadway geometry and the interaction of friction, superelevation, curve radius, and speed, Georgia DOT used a ballbank indicator (BBI) to help identify curves with potential high friction demand as part of their systemic deployment of HFST, regardless of crash history. Current efforts are underway to use curve characteristics data measured using automated data collection methods to identify high-risk locations based on these characteristics (Tsai et al. 2018).

TTI's TCMS tool also accounts for speed differentials and roadway characteristics in computing margin of safety for HFST curve candidate locations (Pratt et al. 2014, Pratt et al. 2018a, Pratt et al. 2018b, Pratt et al. 2020).

CHAPTER 3—FIELD VERIFICATION AND DESIGN

Once an agency identifies, either through crash history or systemic site selection processes, HFST candidate locations the next step is field verification and determining whether HFST should be implemented at a given location. Field verification helps to identify site factors that are not readily apparent from the crash data analysis or roadway characteristics information used for site selection. Field verification may even help identify the need for safety countermeasures other than or in addition to HFST. In addition to helping assess the suitability of a candidate location, field verification also helps to identify design factors that can impact the cost of the HFST installation.

3.1 FIELD VERIFICATION

Key factors which should be included and addressed as part of the field verification process are discussed below. Consideration should be given to conducting the field review during the timeframe or conditions of collision patterns (e.g., time of day, season, light conditions, pavement condition). Agencies should collect copious notes, accompanied by photos and videos, during the field visit, particularly if they are reviewing numerous sites.

1) **Pavement Friction**—Because HFST is specifically used to enhance pavement friction, verification of a "friction issue" at an HFST candidate location is one of the most critical aspects of field verification. If an agency uses data from a PFMP to screen and identify HFST candidates, confirmation testing may not be necessary. Agencies can perform additional testing for locations where PFMP or routine network-level friction data are unavailable. Verification testing should include the limits of the treatment area as well as surrounding (upstream and downstream) pavement to identify variations in friction at the candidate location.

   As discussed in chapter 2, CPFM provides a better indication of friction variation through a curve or at an intersection approach than spot friction. Spot friction tests may not adequately capture differences in friction through the treatment area.

   Assessment of whether there is a friction issue will depend on the friction demand for the location. Chapter 2 describes methods for assessing friction demand in more detail. If an agency determines that the pavement friction is adequate, they may investigate other potential causes of the crashes.

2) **Pavement Condition**—The condition of the pavement surface where the HFST is to be installed has a major impact on the longevity of the treatment. Highly distressed pavements will diminish the lifespan of HFST, regardless of the integrity of the HFST itself as HFST does not provide any pavement preservation benefit.

   With experience, agencies should establish pavement distress criteria for which HFST will not be permitted until the structural integrity of the existing pavement has been restored. Pennsylvania DOT (PennDOT) does not allow placement of HFST over structurally inadequate pavement, and has guidelines on whether HFST should be installed based on pavement condition, as shown in table 5 and table 6 (PennDOT 2019).

Table 5. PennDOT guidelines for HFST usage on asphalt pavements.

Existing Asphalt Pavement Condition	HFST Allowable Usage
Project Length ≤ 1,500 feet	YES
Project Length > 1,500 feet	MAYBE
Low Severity Rutting (1/8 inch or less)	YES
Medium Severity Rutting	NO
High Severity Rutting	NO
Low Severity Fatigue Cracking (hairline or smaller)	YES
Fatigue Cracking	NO
Low Severity Edge Deterioration	YES
Permanent Asphalt Patching (Less than 1%)	YES
Non-Permanent Asphalt Patching	NO
Bleeding	NO
Raveling	NO
Raveling or Weathering	NO

Table 6. PennDOT guidelines for HFST usage on concrete pavements.

Existing Concrete Pavement Condition	HFST Allowable Usage
Project Length ≤ 1,500 feet	YES
Project Length > 1,500 feet	MAYBE
Permanent Concrete Patching	YES
Non-permanent Concrete Patching	NO
Low Severity Cracking (hairline or smaller)	YES
Low Severity Joint Spalling (1 inch or less)	YES
Joint Spalling	NO
Broken Slabs	NO
Faulted Joints	NO

While many agencies maintain annual pavement condition surveys on primary roadways which could be used for an initial screening of pavement condition, current condition information is likely not available for secondary and local roadways. Regardless of the availability of pavement condition data, field verification is always a recommended practice.

In addition to pavement distress, an additional pavement condition issue is subsurface moisture migration. Poor subsurface drainage can result in moisture migrating upward from beneath the pavement. This condition could impact installation of HFST as resin binders do not bond well to saturated pavement surfaces and could also lead to a shortened pavement life as the HFST may serve to trap moisture in the underlying pavement surface layer. This issue (if suspected to be present) will need to be verified through a field visit and possibly also through discussions with local maintenance personnel.

3) **Physically Locating Crashes**—Physically locating crashes within a given curve, ramp, or intersection candidate location will help provide a better understanding of potential contributing factors to observed crashes and will also help establish the necessary HFST treatment limits. Bringing a populated crash report diagram to the field review will help to locate these crashes in relation to the treatment area such that an assessment can be made as to whether there are factors other than pavement friction that are contributing to the crashes.

4) **Roadway Characteristics and Confounding Factors**—While many agencies maintain databases of roadway characteristics (shoulders, median, geometry, signage, etc.) a field review will help assess whether these characteristics could be contributing factors to the observed crashes. Confounding factors, such as driveways or intersections, horizontal and vertical site distances, roadside clearance, inadequate cross slope, and surface drainage issues can be noted as other potential contributors. The presence and condition of other safety countermeasures (guardrail, signage, pavement markings, crosswalks, etc.) should also be noted. If a high percentage of crashes are occurring at night, consider performing the field review at night to observe lighting conditions and retroreflectivity of pavement markings and warning signs. If surface drainage is suspected to be a contributing factor (e.g., due to inadequate cross slope, ponding of water, etc.), consider a field review during rainy conditions.

5) **Traffic Characteristics and Driver Behavior**—While most agencies maintain traffic counts for their networks, these counts do not always provide the whole picture, such as hourly distribution and vehicle type mix. A field review scheduled to coincide with the timeframe of observed crash patterns may provide insight as to the impact of traffic characteristics on crashes.

   Additionally, observation of driver behavior may provide additional insight into potential causes of crashes at the site as well as information useful for the project design (e.g., establishment of treatment limits). Observing where vehicles begin to brake or how they navigate a curve, for example, may provide a better understanding of where HFST treatment should be applied. Observing speed differentials between posted/advisory and typical vehicle speeds may provide additional insight.

3.2 DESIGN

Many factors can affect the cost of HFST projects. These factors should be captured in as much detail as practical during the design stage of an HFST project, particularly for larger projects with multiple installations bundled together. Below is a summary of key factors for consideration in HFST design.

1) **HFST Treatment Limits**—Treatment limits dictate how much HFST material will be installed and will also impact the time necessary for installation. While there are anecdotal guidelines for treatment limits, the final decision for a particular site should be as data-driven as possible.
   - *Curve Locations*
     - A recent survey of 26 State DOTs that use HFST for curve treatment revealed that nearly half of agencies select treatment limits based on a predetermined relationship to curve geometry, approximately one quarter determine treatment limits from in-person site observations, and the remaining States determine limits from crash diagrams, engineering judgment, and other factors (Wilson and Saca 2021).
     - While a common practice has been to assume treatment from the PC to PT, this may be overly-conservative if most crashes are occurring at a specific location at the middle or at one end of the curve or the other. Conversely, the assumption may be unconservative if crashes are occurring prior to the PC or beyond the PT. Many agencies have adopted policies of extending the treatment 100-300-ft prior to the PC and 100-300-ft beyond the PT, in recognition that drivers typically begin braking prior to the PC. The TTI developed general guidelines for the distance to begin treatment prior to the PC based on approach speed (e.g., posted or operating) and curve advisory speed, as shown in table 7.

Table 7. Recommended distance upstream of curve PC to begin HFST application (Brimley and Carlson 2012).

Approach Speed (mph)	Curve Speed (mph)						
	30	35	40	45	50	55	60
35	35	-	-	-	-	-	-
40	76	41	-	-	-	-	-
45	122	86	46	-	-	-	-
50	173	138	97	51	-	-	-
55	230	194	154	108	57	-	-
60	292	257	216	170	119	62	-
65	359	324	284	238	186	130	68

  - Physically locating crashes and observing driver behavior during a field review will help with establishment of the necessary treatment limits and whether they should begin prior to the PC, extend beyond the PT, or be limited to a specific part of a curve.
  - CPFM will help identify changes in friction leading up to, through, and away from the curve such that agencies can adjust treatment limits based on pavement friction. Note that CPFM provides a "map" of pavement friction, typically at 1-ft intervals, versus locked-wheel skid tester data which only provides a friction value for approximately 60 ft of pavement (FHWA 2021b).
  - Agencies can use a curve margin of safety assessment to help establish treatment limits based on site conditions.
- *Intersection Locations*
  - The common practice among agencies is to treat anywhere from 200-1,000 ft of approach to the intersection (e.g., up to the stop bar or crosswalk), depending on where crashes are occurring. Agencies may also desire to continue the treatment through the intersection as well as beyond the intersection, however this is not common practice.
  - Physically locating crashes, observing driver behavior (braking and stopping behavior approaching the intersection), and monitoring traffic queues at the intersection will help determine the length of approach that needs to be treated and whether the intersection itself and/or the departure side of the intersection should be treated.
  - Continuous friction measurement of the intersection approach, the intersection itself, and departure side of the intersection will help identify any variations in friction and establish the limits of the treatment.
- *Ramp Locations*
  - Treatment limits for curved ramps can be established using similar processes as curve locations. Likewise, agencies can establish treatment limits for ramps terminating at an intersection using similar processes as intersection locations.
  - Agencies may also consider additional ramp treatments (i.e., acceleration, deceleration, and merging behavior). Physically locating crashes and observing driver behavior during a field review will help determine the necessary treatment limits based on these additional considerations.
- Some additional general considerations for treatment limits include:
- **Treatment of only one lane or direction.** If crashes are predominantly occurring in only one direction (e.g., on a two-lane road), or in one lane on a multi-

lane roadway, it may not be necessary to treat both lanes or the entire roadway width. This is a more likely scenario at locations with significant grade where vehicles have a tendency to lose control going downhill rather than uphill. Crash data on undivided roadways may not always capture or accurately capture vehicle direction, and therefore agencies should make their decision based on sound data.

- **Treatment of adjacent paved shoulders.** While this will add additional cost to a project, if there is evidence from the crash data that additional friction on a paved shoulder would increase the likelihood of recovery from lane departure and decrease the likelihood of RwD, consideration can be given to treating paved shoulders.
- **Continuous treatment of S-curves or multiple curves.** If an S-curve or multiple consecutive curves are to be treated, consider a continuous treatment of the S-curve or multiple curves, rather than leaving short areas (e.g., < 500 ft) of untreated pavement between them, even if crashes are not occurring in these areas. Changes in friction and surface appearance may alter driver behavior when such short areas are left untreated between treated sections.

2) **Pavement Type and Texture**—Certain pavement types, such as open graded friction course, may need special consideration in the design process. Installation on open graded pavement is generally not recommended as it will require significantly more resin binder to fill voids in the surface, leading to a thick resin binder layer which can increase problems with thermal compatibility between the HFST and underlying pavement. Florida DOT (FDOT) does not allow installation on open graded friction course pavements, requiring placement of a new dense-graded asphalt prior to HFST installation (FDOT 2021).

   Pavement type will also impact the required surface preparation prior to HFST application. Shotblasting is a required surface preparation for concrete pavements in all known State and AASHTO specifications (AASHTO 2019). For asphalt pavements, shotblasting may or may not be required, depending on agency specifications.

   Pavement texture, regardless of pavement type, can have a significant impact on project cost as resin binder demand to achieve the desired mil thickness increases with macrotexture depth. If possible, measurement of macrotexture should be completed during a field review or using network-level texture data from pavement management systems. An agency can provide this information in the bidding documents so installers can appropriately adjust the resin binder quantities. Alternatively, an agency can specify the necessary resin binder coverage rate for the project based on pavement macrotexture so that all bidders would be estimating the correct resin binder quantity. The Virginia DOT, as shown in table 8, has used this approach by specifying the minimum resin binder application rate based on the measurement of pavement macrotexture depth.

Table 8. Virginia DOT resin binder application rate adjustment based on pavement macrotexture.

Macro-Texture Depth, in (ASTM E 965)	Minimum Resin Binder Application Rate, mils
<0.04	50
0.04 – 0.06	75
>0.06	2 applications @50

***Note:* Application rate mil thickness should be measured over a flat/smooth plate, not the textured surface.**

3) **Pavement Condition**—Existing pavement condition may necessitate treatment of minor distresses, minor rehabilitation, or complete repaving prior to HFST installation. These can add significant cost to HFST projects and may be considered in the design stage.

In addition to the PennDOT pavement condition guidelines shown in table 5 and table 6, FHWA notes the following conditions that will require minor rehabilitation or complete replacement (Wilson et al. 2020):

Asphalt Pavement

- Moderate-severity cracking (more than six percent of cracking in or outside the wheelpaths).
- Widespread rutting greater than 0.25-inches deep.
- Raveling.
- Flushed or bleeding surface (typically associated with chip seals/sealcoat).
- Areas where layer debonding or subsurface stripping is suspected.

Concrete Pavement

- Moderate or severe transverse cracking, longitudinal cracking, spalling, or corner cracking.
- Shattered slab in more than three pieces.

Treatment of minor distresses typically includes crack sealing prior to HFST installation, particularly for wider "working" cracks that may be sources for water infiltration beneath the HFST if not sealed.

Minor rehabilitation may include patching or small repairs of potholes, spalls, or highly distressed areas (if the rest of the pavement is in satisfactory condition). Minor rehabilitation may also include filling of ruts, depending on the pavement condition assessment and whether the rutting is not the result of a major structural deficiency.

Repaving should be considered if the majority of the area to be treated is heavily distressed to the point that it would impact the longevity of the HFST. If repaving is needed, a minimum of 30 days of cure time is typically required before HFST can be installed over the new surface (AASHTO 2019, RTSA 2017).

Note that consideration should be given to the potential for further pavement condition degradation if there will be a significant time lag (e.g., more than one year) between project design and construction.

Consideration should also be given to the current pavement rehabilitation cycle for the site. If the site is scheduled for repaving within 1 to 2 years after HFST installation, consider delaying treatment until after repaving, or plan on a short re-application timeframe (e.g., short lifespan) for the HFST.

4) **Striping or Pavement Marking Removal and Replacement**—Consideration may be given to the cost of replacing any striping, pavement markings (e.g., arrows, lettering, crosswalks, etc.), and pavement markers (e.g., raised pavement markers) as this can be significant for thermoplastic striping/lettering or high performance tape products. While it is not advisable to place HFST "around" any in-lane markings, masking off lane striping will eliminate the need to remove and replace this striping after installation. Exceptions would be for installations where the treatment is to extend out into the shoulders (in the case of a curve or ramp) or through a crosswalk (in the case of an intersection). When striping removal and replacement is needed, consideration may be given to the cost of new striping. KYTC, for example, includes a special note in HFST project specifications advising contractors that multiple applications may be needed for waterborne striping of HFST.

5) **Maintenance of Traffic**—Maintenance of traffic during installation can impact project cost. Agencies may consider full (e.g., detour necessary) or partial (e.g., single lane traffic) closures for installation, and whether closures will be limited to certain hours of the day or night.

   Note that restriction to nighttime installation may create potential delays in installation as most HFST resin binder materials are temperature-sensitive with minimum temperature requirements for installation.

6) **Construction Staging**—Agencies may also consider the practical limitations on staging of construction equipment and materials during installation. Rural roads with limited potential locations for equipment and materials staging may require the installer to travel miles for reloading materials into the installation vehicle. This could impact the length of time required for installation. Agencies should complete a general assessment of staging opportunities during the field review.

CHAPTER 4—HFST MATERIALS

HFST is a non-conventional pavement surface treatment that incorporates materials not commonly used by the paving industry. As such, there are requirements and considerations specific to the two components of HFST: surface aggregate and polymer resin binder. While the aggregate provides the actual skid resistance, the resin binder bonds the aggregate to the underlying pavement surface.

HFST systems used in the United States are considered "cold applied" systems where the resin binder is applied to the pavement surface first followed by broadcasting of aggregate into the resin binder. This is in contrast to "hot applied" systems commonly used in the United Kingdom where the resin binder and aggregate are mixed together and heated in a boiler at a high temperature to achieve a consistency that can be spread onto the pavement surface (RSTA ADEPT 2017).

4.1 AGGREGATE

HFST aggregate provides the actual frictional properties for the treatment through a combination of microtexture and macrotexture (figure 5). Microtexture is the smaller-scale texture that can be thought of as the roughness of the surface of the aggregate particles. Microtexture contributes to friction through adhesion, or the small-scale bonding between the aggregate particles and vehicle tire rubber. Macrotexture is the larger, more visible texture created by the aggrege particles themselves and the spaces between aggregate particles. Macrotexture is critical for skid resistance at higher speeds and wet conditions as it provides a path for water to evacuate from beneath a vehicle tire, such that the tire makes contact with the aggregate. Macrotexture also provides the hysteresis component of friction under wet or dry conditions as the vehicle tire interacts with the aggregate particles (AASHTO 2008). Without adequate macrotexture, microtexture cannot engage vehicle tires in wet conditions at higher speeds, thereby reducing friction.

While macrotexture can be measured directly through a number of different methods, microtexture generally cannot be measured outside of a laboratory setting. As such, microtexture is generally not measured directly, but assessed indirectly through friction testing methods and accelerated polishing tests. Because maintaining micro- and macrotexture is so important for pavement friction, HFST aggregate must be polish and abrasion resistant so that these properties are sustained under vehicle wear over the life of the treatment.

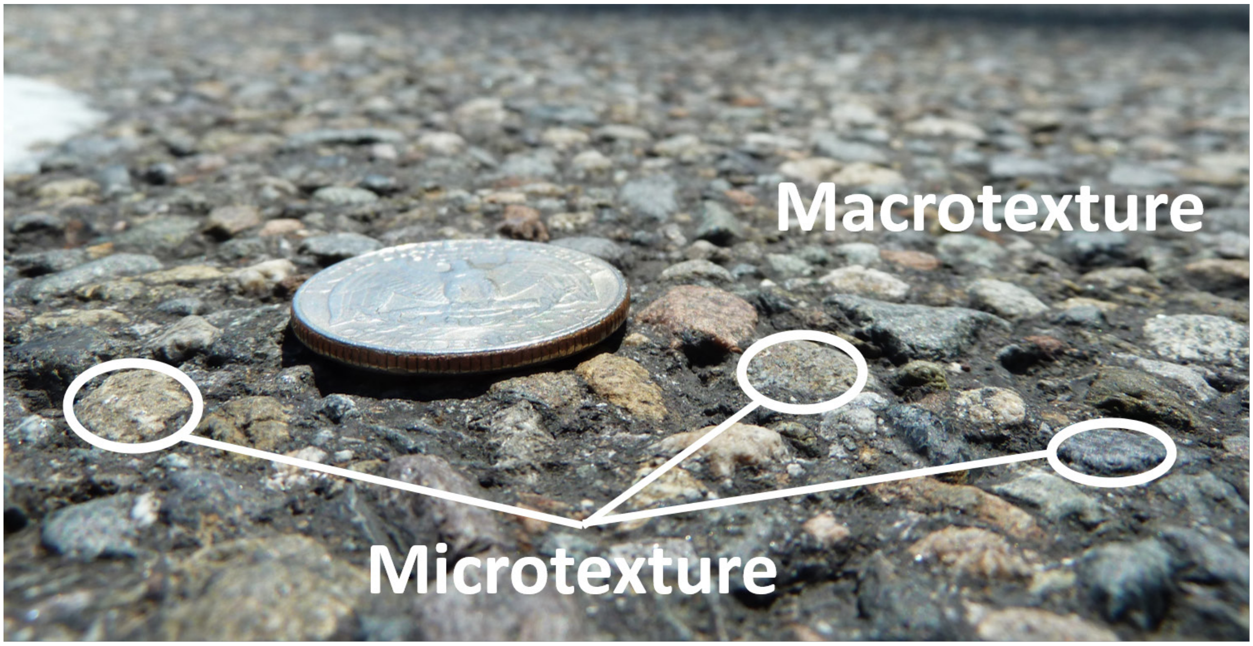

Figure 5. Graphic. Illustration of pavement microtexture and macrotexture.

Calcined bauxite has a decades-long proven track record of providing exceptional polish and abrasion resistance properties necessary for HFST. Calcined bauxite is the only aggregate permitted for HFST under the current AASHTO specification, virtually all State specifications, and in other counties with significant HFST usage, such as the United Kingdom and New Zealand (Highways England 2019, NZTA 2011). A 2017 article from researchers in the United Kingdom which reviewed 50 years of road trial data and laboratory investigation of HFST aggregates concluded that, "calcined bauxite is the only aggregate to consistently offer the highest levels of performance for the longest period of time" (Woodward and Friel 2017 p.14).

Refractory-grade calcined bauxite is raw bauxite that is calcined at temperatures of 2,900 to 3,000°F, producing a dense, high purity, stable aggregate. Refractory-grade has a high alumina content (≥ 87 percent) and a very low alkali content (≤ 0.4 percent) with low impurities and a bulk density ≥ 3.1.

In response to concerns over the cost of calcined bauxite and the need to import it from overseas, numerous laboratory and small-scale field evaluations of alternative (domestically sourced) aggregates have been performed (Heitzman et al. 2015; Wilson and Mukhopadhyay 2016, Heitzman and Moore 2017, Pratt 2018b, Li et al. 2017, Li et al. 2019). These evaluations as well as evaluation from the United Kingdom (Woodward and Friel 2017) have revealed that no other material provides the high level of long-term friction performance of calcined bauxite. It should be noted, however, that these alternative aggregates (including flint, steel slag, basalt, granite, emery, and taconite) may still provide satisfactory frictional properties for applications such as bridge deck overlays with lower friction demand. It should also be noted that there is now a domestic source of calcined bauxite. Other sources of refractory-grade calcined bauxite suitable for HFST include: China, India, and Guyana. Key physical properties of HFST aggregate and associated test methods include:

- **Aggregate Size/Gradation**—HFST aggregate has a nominal maximum aggregate size of 3-4 mm, with most particles between 1 and 3 mm in size, as show in figure 6. Chapter 5 provides the specific gradation required in the current AASHTO specification and most agency specifications.

Figure 6. Photograph. Calcined bauxite aggregate for HFST.

- **Abrasion and Polish Resistance**—Abrasion resistance is typically measured using the AASHTO T 96/ASTM C 131 Los Angeles Machine abrasion test (AASHTO 2020a). However, this test can be difficult to perform accurately for such a small aggregate site, and alternatives such as ASTM D 7428 Micro-Deval Apparatus (MDA) have been evaluated as a more suitable alternative (ASTM 2015a). The MDA is also known to provide some indication of polish resistance (Eluri 2018). Figure 7 shows an example of MDA results from testing of calcined bauxite versus other conventional pavement aggregates (Wilson and Mukhopadhyay 2016). Similar results have been reported by Heitzman et al. (2015) and Li et al. (2017, 2019).

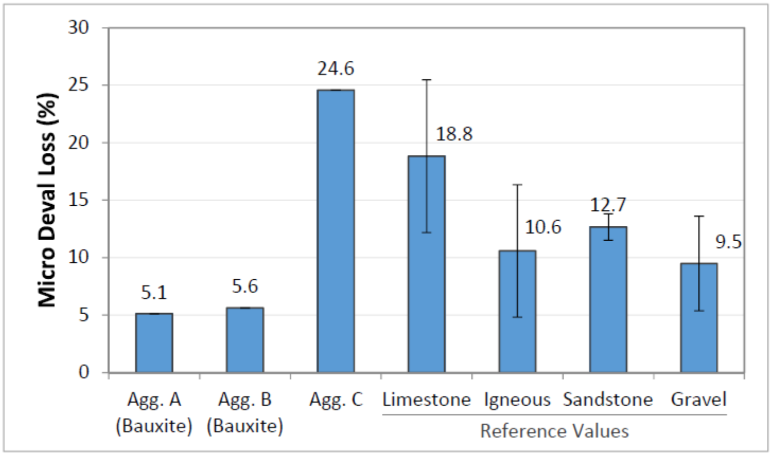

Figure 7. Graph. Micro-Deval loss from testing of calcined bauxite and other reference aggregates (Wilson and Mukhopadhyay 2016).

Polish resistance is most commonly assessed with the ASTM D 3319 (ASTM 2017) British Wheel and ASTM E303 British Pendulum Tester. This test is also not well suited for such a small aggregate size, primarily due to difficulty in fabricating test coupons, but is currently specified by some agencies for lack of a suitable alternative. The NCAT Three Wheel Polishing Test is another option for measuring polish resistance and wear, but is more suitable for testing the HFST system (resin binder and aggregate) as the test is performed on a sample of HFST placed on a test slab (Heitzman et al. 2015).

- **Aluminum Oxide Content**—Aluminum oxide (alumina) content indicates the grade of calcined bauxite. HFST requires refractory-grade calcined bauxite with a minimum aluminum oxide content of 87 percent. Testing for aluminum oxide content is performed in the laboratory using x-ray fluorescence spectrometry (see section 5.2.1).
- **Macrotexture**—While macrotexture is a property of the HFST system and not the aggregate itself, it is most impacted by the aggregate and wear of the aggregate over time. Macrotexture is typically assessed with a volumetric technique such as ASTM E965 (ASTM 2019b) to compute mean texture depth (MTD) or using laser-based measurement to compute a mean profile depth (MPD) in accordance with ASTM E1845 (ASTM 2015b). In general, HFST should maintain an MPD or MTD of at least 1.0 over the life of the treatment.
- **Microtexture**—Currently aggregate microtexture can only be measured and fully characterized directly in the laboratory using specialty laser surface scanning equipment. However, agencies can use friction tests in a laboratory such as the ASTM E303 British Pendulum Tester (ASTM 2018b) and ASTM E 1911 Dynamic Friction Tester (ASTM 2019a) as surrogate measures of microtexture.
- **Cleanliness**—Cleanliness of HFST aggregate is critical for HFST performance. Cleanliness includes contaminants in the aggregate stockpile as well as cleanliness (e.g., dust content) of

the aggregates themselves. Currently, only subjective assessment is used to determine aggregate cleanliness.

4.2 RESIN BINDER

The polymer resin binder bonds the aggregate particles to the underlying pavement surface. As such, it must be compatible with both the aggregate and the underlying pavement surface and must be able to securely hold the aggregate in place under high shear stresses from traffic under a potentially wide range of temperatures over the life of the treatment.

The most common resin binder materials for HFST in the United States are epoxy resin and polyester resin, although agencies have used methyl methacrylate (MMA) on a very limited basis. These multi-component, thermosetting, exothermic resin binders are considered high strength, low modulus materials that are chemical and ultraviolet light resistant and moisture sensitive during curing.

Epoxy Resin is the most commonly used HFST resin binder in the United States. Epoxy resin is typically a two-component system (commonly mixed at a 1:1 ratio by volume) with one component being a resin with a portion of dilutants or other proprietary ingredients (to achieve specified material properties), and the other component being the curing agent or hardener (de Leon Izeppi et al. 2010). Epoxy resin is a thermosetting material which cures under an exothermic reaction. As such there are minimum temperature requirements for using epoxy resin, typically 50°F and above. Cure times can be adjusted (per manufacturer recommendations) to account for higher or lower temperature conditions.

Agencies across the United States have also used *polyester resin* for HFST. Polyester resin is a two-component material (although mixed at a much different ratio than epoxy resin) but an accelerator can also be added to shorten cure time. The primary advantage of this material is that it can cure under a wide range of temperatures (below 40°F), which is beneficial for cooler weather installations.

Other resin binders that have been used internationally (for hot applied systems in particular) but are not common in the United States are polyurethane resin, acrylic resin, and rosin ester.

Key physical properties for the resin binder which will affect installation and performance of the finished surface include:

- **Viscosity**—Viscosity is a measure of resistance to flow or how "thick" or "thin" the resin binder is. Viscosity affects how the material flows when deposited and spread onto the pavement surface. Lower viscosity resin binder will more readily flow down into the pore structure of the pavement, however, it also tends to run across superelevation or down pavement grade if the aggregate is not applied immediately after the resin binder to help hold it in place. Higher viscosity resin binder may not blend as easily or spread as easily, potentially leaving a non-uniform or uneven surface. It will also not penetrate the pavement pore structure as well and may resist penetration of aggregate when broadcast onto the resin binder.

While requirements for viscosity are outlined in agency specifications, these requirements are for laboratory conditions (standard temperature). During installation, resin binder viscosity is highly affected by ambient and pavement temperatures. In general, the warmer the temperature, the lower the viscosity, although resin binder manufacturers may be able to adjust these properties by varying component proportions. Conversely, the cooler the temperature, the higher the viscosity, unless the manufacturer provides recommendations to adjust proportioning to account for cooler temperatures. Resin binder manufacturer recommendations for material temperatures and proportioning should always be followed very carefully based on ambient and surface temperatures during installation and the equipment used to apply resin binder to the pavement surface.

The effect of temperature on resin binder viscosity and associated "drain down" (i.e., how quickly the resin binder drains down into the pavement pore structure) was measured in the laboratory by researchers from TTI, and is illustrated in figure 8 (Wilson and Mukhopadhyay 2016). Researchers observed that for the same asphalt pavement surface (FC-5), resin binder film thickness decreased much quicker at higher temperature (95°F) than at moderate temperatures (65-72°F) Note however that for an actual HFST installation, application of aggregate immediately after the resin binder causes a capillary rise or wicking action that can easily offset this drain down.

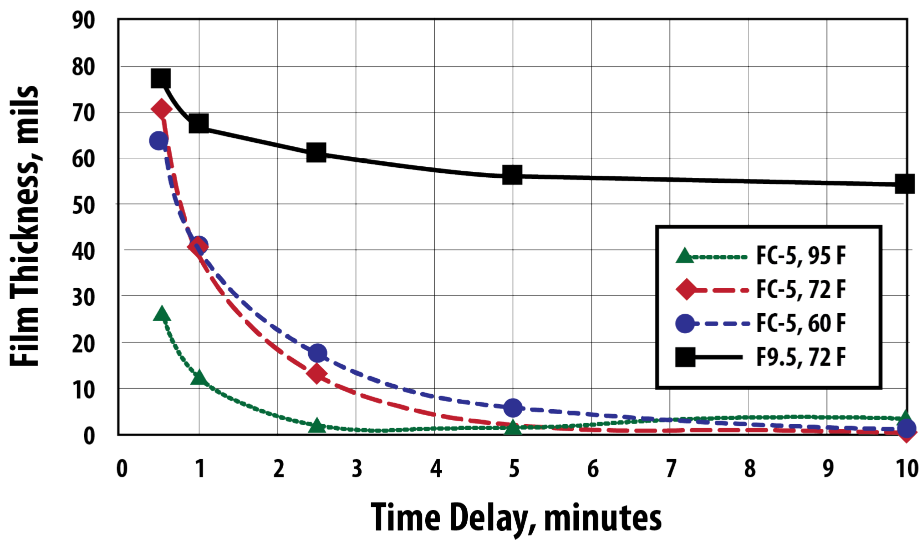

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Figure 8. Graph. Impact of pavement temperature and resin binder viscosity on resin binder film thickness due to drain down (Wilson and Mukhopadhyay 2016).

- **Gel Time**—Thin-film gel time is the time from the application of the liquid material onto the pavement surface until it begins to thicken (gel) and no longer flows. Gel time affects the amount of time available to spread the resin binder on the pavement surface, and more importantly, the amount of time before aggregate must be broadcast onto the resin binder. As resin binder materials begin to gel, they will resist penetration of the aggregate, which can lead to aggregates not fully embedded in the resin binder. Like viscosity, gel time is highly affected by temperature for most resin binder materials and installers should always refer to resin binder manufacturer recommendations regarding gel time.

- **Cure Rate**—Cure rate is how quickly the resin binder material cures or hardens to the point that excess aggregate can be swept and the surface can be opened to traffic. Note that cure time for sweeping will likely be different from that for opening to traffic. While there is generally not a problem with resin binder curing quickly (assuming aggregates are broadcast onto the surface before gel), a slower cure rate will delay sweeping and opening to traffic. Similar to viscosity and gel time, cure rate is highly dependent up on temperature. In general, the warmer the temperature, the shorter the cure time. Resin binder manufacturers provide guidance for the cure time of their product, typically based on temperature, similar to the product label shown in table 9.

Table 9. Resin binder product label showing minimum curing time based on temperature.

Average Temperature	Cure Time (hours)
60-64°F (16-18°C)	5-6
65-69°F (19-21°C)	5
70-74°F (22-23°C)	4
75-79°F (24-26°C)	3
80-84°F (27-29°C)	3
85+°F (29+°C)	3

- **Adhesion**—Adhesion is a measure of how well the resin binder adheres to the underlying pavement surface. The most common test for adhesion is the ASTM C1583 pull-off tensile strength test (2020c). This test is not commonly specified for HFST acceptance in the field due to the destructive and specialized nature of the test, however, a few agencies require the test for acceptance of the resin binder based on laboratory testing (Wilson and Saca 2021). It should be noted, however, that because the test method is designed for concrete, the 100 percent substrate mode of failure will vary when performed on an asphalt pavement.

- **Thermal Compatibility**—Thermal compatibility is a measure of how well the resin binder remains bonded to the underlying pavement surface under temperature cycling. Thermal compatibility considers the difference in the coefficient of thermal expansion (CTE) between the HFST and underlying pavement surface. In general, the greater the difference in the coefficient of thermal expansion between the HFST and underlying pavement, the higher the shear stresses at the HFST-pavement interface or within the underlying pavement, which can lead to delamination or cohesive failure within the pavement itself. Despite large differences in CTE between HFST and concrete/asphalt surfaces, failure due to thermal compatibility issues generally only occurs when the HFST is placed too thick (i.e., due to high pavement porosity) or when HFST is placed over a weak asphalt pavement. While laboratory testing of this property is included in many agency specifications (in accordance with ASTM C884), the test protocol calls for placement of the resin binder over a concrete substrate, which may not be representative of placement over asphalt surface (ASTM 2016). The Nevada DOT is currently investigating thermal compatibility and developing appropriate specifications (Nevada DOT n.d.).

While it is ultimately the installer's decision on which resin binder to use (assuming it meets agency specification requirements), resin binder selection based on the specifics of a given project is critical. Resin binder should be appropriate (or appropriately proportioned) for:

- **Site Conditions**—Site conditions include pavement type (specifically pavement texture and/or porosity), roadway cross-slope/superelevation, and grade.
- **Installation Conditions**—Installation Conditions include the ambient and pavement temperature during installation (with consideration given to nighttime vs. daytime installation) and lane closure restrictions/opening to traffic requirements.
- **Installation Methods**—Installation methods are the equipment for blending and applying the resin binder. This also includes equipment and timing of aggregate placement.

CHAPTER 5—SPECIFICATIONS AND INSTALLATION

This chapter discusses specifications and installation considerations for HFST. The list below summarizes key factors based on lessons learned from early implementation and agencies with mature HFST programs.

5.1 KEY COMPONENTS OF HFST INSTALLATION

The following are key components of an HFST installation which agencies should cover through HFST specifications, a quality control plan (QCP), and inspection practices, and will be discussed in greater detail throughout this Chapter.

- **Material Handling and Testing**—As non-conventional materials, there are special considerations for handling and testing of HFST resin binder and aggregate materials.
    - Resin binder component material storage in accordance with manufacturer recommendations.
    - Aggregate material storage to keep the material clean and dry.
    - Verification that the materials for use on-site are approved for use and the same as those called for by the installer in the QCP.
    - Verification testing of materials, if required by the agency, in lieu of or in addition to certified test results from the installer.
    - Staging of materials in advance of and during installation to help prevent delays during installation for refilling installation vehicles.
- **Surface Preparation**—Preparation of the underlying pavement surface is critical for the installation and long-term performance of HFST. Key aspects of surface preparation include:
    - Pavement repairs—patching of distressed areas, removal of rutting, sealing and/or filling of wide (working) cracks.
    - Striping and pavement marking—removal or masking of striping and pavement markings as required.
    - Cleaning and roughening—processes used to thoroughly clean and roughen the pavement surface to help ensure bond between the resin binder and pavement surface.
    - Protection of joints and drainage structures—protection of working joints (e.g., concrete pavement or at bridge abutments) and drainage inlets to prevent intrusion of HFST materials during installation.

- **Application Methods and Equipment**—Methods and equipment for metering, blending, and applying the resin binder, and processes and equipment for applying the aggregate.
- **Aggregate Removal and Reclamation**—Removal of excess aggregate and requirements for reclamation, if permitted.
- **Preparation for Opening to Traffic**—Final inspection and preparation of the finished surface for opening to traffic, including replacement of striping.
- **Acceptance Testing**—Acceptance testing typically consists of friction testing after opening to traffic to give the surface an initial wear-in period (typically 30 to 60 days after opening to traffic), but may also include macrotexture testing and bond testing, depending on agency requirements.
- **Early-Age Monitoring**—Monitoring the treatment over the first few days and weeks after opening to traffic will help identify any potential materials and workmanship-related issues. Monitoring should also include a re-sweep of the treated area and adjacent lanes or shoulders to remove aggregate that is naturally shed under traffic wear during the first few weeks.

5.2 HFST SPECIFICATIONS

AASHTO MP 41-19 *Standard Specification for High Friction Surface Treatment for Asphalt and Concrete Pavements Using Calcined Bauxite* is the current version of the AASHTO specification for HFST developed through an agency-industry consensus process (AASHTO 2019). This specification is intended to provide guidance to agencies seeking to develop their own specification but can also be used as-is by agencies. Agencies with mature HFST programs have developed their own specifications with agency-specific requirements for materials and installation practices. Highlighted below are key elements of an HFST specification based on the AASHTO specification and other agency specifications. Specific requirements (e.g., resin binder physical properties) from the current AASHTO specification are shown, but not those from other agencies as there is a wide range of variations. (*Note that the AASHTO specification is currently being revised and split into two specifications, one for materials and one for installation*).

5.2.1 PHYSICAL PROPERTY REQUIREMENTS FOR MATERIALS

- Many agencies require pre-approval of resin binder and aggregate materials before use on a project. Qualified product lists (QPLs) help ensure that only materials meeting specification requirements will be used on the project without the need to test the material ahead of installation (unless project-level verification tests are required). As part of pre-approval, agencies may also require that HFST products be evaluated through the AASHTO National Transportation Product Evaluation Program (NTPEP) for High Friction and Thin Overlays (AASHTO n.d.). Tennessee DOT, for example, has a QPL for HFST, and part of the pre-approval process is conformance with the AASHTO HFST specification requirements for resin binder and submission of test data from an AASHTO NTPEP evaluation (Tennessee DOT 2021a, Tennessee DOT 2021b).

- Agencies may also allow material suppliers to submit a certification that materials meet the specified requirements in lieu of separate testing by the installer or agency prior to construction. The certification includes independent laboratory test results that satisfy agency specification requirements.

Physical requirements for polymer resin materials may include some or all of those shown in table 10, depending on the agency. Note that many agencies have their own test methods for these properties. The AASHTO specification and several agency specifications provide separate requirements for epoxy, polyester, and MMA resin binders.

Table 10. Physical property requirements for HFST resin binder materials.

Resin Binder Property	AASHTO/ASTM Test Method	AASHTO Specification Requirement
Viscosity	ASTM D2556 (spindle and speed selection based on ASTM D2556-11)	1,000 cP min. (epoxy and polyester) 1,500-2,500 cP min. (MMA)
Flash Point	ASTM D3278 (see Note 3 of D3278)	See Safety Data Sheet (SDS)
Gel Time	ASTM C881/AASHTO M235	10 minutes min (epoxy and polyester) 15 minutes min (MMA)
Compressive Modulus	ASTM D695	130,000 psi max. @ 7 days (epoxy and MMA)
Compressive Strength	ASTM C579 (Test Method B for epoxy and polyester)	1,000 psi min. @ 3 hr., 3,000 psi min. @ 24 hr. (epoxy and polyester) 1,500-3,000 psi @ 7 days (MMA)
Tensile Strength	ASTM D638 Type I	2,000-5,000 psi @ 7 days (epoxy and polyester) 500-1,000 psi @7 days (MMA)
Tensile Elongation	ASTM D638 Type I	30% min. (epoxy and polyester) 50% min. (MMA)
Absorption	ASTM D570	1% max.
Type D Hardness	ASTM D2240 (cure specimen for 7 days ± 6 hr.)	60-80 (epoxy and polyester) 50-60 (MMA)
Thermal Compatibility	ASTM C884	PASS
Infrared Spectrum	ASTM E573/Section 7.1.11	Combined & Components
Cure Rate (at 75°F)	ASTM D1640	Typical: 3 hours max. *Not Included in AASHTO*
Adhesive Strength (at 24 hours)	ASTM C1583	Typical: 250 psi min. or 100% substrate failure *Not Included in AASHTO*
Chloride Permeability	AASHTO T 277	Typical: < 100 coulombs @ 28 days *Not Included in AASHTO*

- Based on discussions with resin binder manufacturers, Wilson and Saca noted that current resin binder specifications place too much emphasis on high strength and high modulus criteria, when the focus should be on toughness or resilience. The resin binder should hold the aggregate well and adhere to the underlying pavement well, but also be as flexible as possible (Wilson and Saca 2021). Ongoing research by Nevada DOT should help with refinement of specifications for this purpose (Nevada DOT n.d.).

Physical requirements for aggregate materials may include some or all of those shown in table 11, depending on the agency.

Table 11. Physical property requirements for HFST aggregate materials.

Aggregate Property	AASHTO/ASTM Test Method	AASHTO Specification Requirement
Los Angeles Abrasion (LAA)	AASHTO T 96 (Grading D)	20% max.
MDA	ASTM D 7428	5% max.
British Wheel	ASTM D3319 AASHTO T 279	Typical: 38 min. *Not Included in AASHTO*
Aluminum Oxide	ASTM E 1621	87±2%
Gradation	AASHTO T 27	No. 4 sieve: 100% passing No. 6 sieve: 95-100% passing No. 16 sieve: 0-5% passing No. 30 sieve: 0-0.2% passing
Soundness	AASHTO T104	Typical: 12-15% max. *Not Included in AASHTO*
Moisture Content	AASHT T255	0.2% max.

- Note that the LAA test method is marginally appropriate for HFST due to the small-size aggregate which will require a substantial sample size to achieve the requirements for Grading D. Some agencies require this test to be performed on the parent aggregate (e.g., larger size before crushing).
- The MDA test has been noted to provide an indication of both abrasion and polish resistance and therefore some agencies only require this test and not a separate polishing test. MDA is more appropriate for smaller aggregates (even though HFST gradation is still marginal for the standard) than LAA. It is possible that modifications to ASTM D7428 (ASTM 2015a) will be developed for testing HFST aggregates.
- Aluminum oxide content reflects the hardness of the aggregate. Some have questioned the 87 percent aluminum oxide content and whether a lower grade would still provide the desired performance. There is currently not enough data to justify a lower requirement, although at least one State (FDOT) has lowered their requirement to 86 percent, and the next revision of the AASHTO specification will set this as 85 percent minimum
- FDOT is also exploring an alternative method of X-ray fluorescence for measuring aluminum oxide content using ASTM C 1271 (ASTM 2020d), but this has not yet been adopted into practice (Wilson and Saca 2021). ASTM E1621, "Standard Guide for Elemental Analysis by Wavelength Dispersive X-Ray Fluorescence Spectrometry" (ASTM 2021) is currently being considered for the AASHTO HFST specification.
- Research from Indiana DOT reported that specific gravity and water absorption may indicate if the raw bauxite is fully calcined, which may be another indicator of the quality of

the material (Li et al. 2017. However, this has not been confirmed through further investigation.

- Freeze-thaw soundness, in accordance with AASHTO T 103, has been specified in at least one agency specification, but is not common and not included in the AASHTO specification.

5.2.2 QUALIFICATIONS OF THE INSTALLER

Many agency specifications require that the installer have prior experience with HFST installation and submit proof of prior experience for a specified minimum number of projects or SY of HFST installation. Proof of prior experience may permit an installer to forgo installation of a test strip (described below). The AASHTO specification calls for a minimum of three projects with a cumulative minimum of 10,000 SY of HFST in the past 3 years, and documentation of friction numbers from those projects (AASHTO 2019).

5.2.3 QUALITY CONTROL PLANS

QCPs require the installer detail every aspect of their plan for installation of HFST. QCPs, which must be approved by the agency, allow the agency to provide input on various aspects of the installation before construction begins, and allows the agency to hold an installer accountable for practices outlined in the plan. While not exhaustive, key items commonly found in QCPs include:

- Identification of a Plan Administrator or Project Superintendent who has full authority to institute any action necessary for the successful operation of the plan, and other key personnel, such as an on-site Lead Technician.
- Documentation of resin binder and aggregate sources and materials certifications.
- Procedures for storage of stockpiled and on-site materials.
- Plan for on-site representation by the resin binder material supplier during initial installation.
- Proposed methods for surface preparation (distress treatment, striping/pavement marking treatment, cleaning/roughening, sweeping, etc.).
- Plan for documenting material quantities used for verification of application rate of resin binder and aggregate.
- Moisture control methods for aggregate.
- Procedures and equipment to be used for: resin binder proportioning, blending, and application; aggregate application and removal.
- Equipment calibration records for all metering and application monitoring devices.
- Plan for monitoring and recording of ambient conditions (air temperature, surface temperature, relative humidity).
- Plan for corrective actions for unsatisfactory construction practices and deviations from project specifications.
- Sampling and testing plan for acceptance.

- Methods for determination of time for sweeping and opening to traffic.
- Plan for replacement of pavement markings.

5.2.4 APPLICATION REQUIREMENTS

Most agencies currently require fully-automated continuous application installation methods capable of covering a full lane width in a single pass in their specifications (Wilson and Saca 2021). The purpose for this requirement is to help ensure consistency and uniformity of the finished surface through accurate proportioning, thorough blending, and uniform application of resin binder and aggregate materials. A recent survey of 26 States with HFST programs revealed that approximately 70 percent had problems with manual application often or sometimes versus only 30 percent with fully-automated application (Wilson and Saca 2021). In addition to requiring fully-automated application, Delaware DOT and West Virginia DOT further require real time data reporting of installation information, including resin binder quantity and thickness, aggregate quantity, and ambient temperatures. Agencies which require fully automated installation will also permit manual installation methods for smaller and/or irregular areas/lane widths, typically less than 200-300 SY, where automated installation is not practical.

Many agencies also specify requirements for the timing and method of aggregate application. Georgia DOT, for example, limits the height from which aggregate can be dropped onto the resin binder to 24 inches, while Illinois DOT, West Virginia DOT, and Delaware DOT limit this to 12 inches. Tennessee DOT and Caltrans require aggregate to be applied within 3 minutes after placement of the resin binder, while KYTC specifies within 2 minutes; FDOT and Delaware DOT require application within 30 seconds, and West Virginia DOT requires application within 3 seconds. The purpose of these requirements is to ensure that the resin binder is not displaced when the aggregate is applied and to confirm that the aggregate is applied well within the gel time of the resin binder.

Agencies typically specify limitations on application temperatures, depending on material requirements. As noted in chapter 4, epoxy resin binders will typically not cure (or cure very slowly) below 50°F, and most resin binders will gel too quickly at higher temperatures (e.g., above 100°F). Typical temperature limitations are a minimum of 50°F surface temperature and maximum of 110°F ambient temperature, but as noted in chapter 4, this is highly dependent on the limitations of the particular resin binder that is used. Most agencies will allow placement outside of these limits if permitted by the manufacturer. Installation over wet or damp surfaces is always prohibited, with some agencies requiring a moisture test such as ASTM D 4263, "Indicating Moisture in Concrete by the Plastic Sheet Method" (ASTM 2018a) at the discretion of the engineer if surface moisture is questionable. Many agencies further restrict installation when there is more than a 50-percent probability of rain in the forecast.

5.2.5 APPLICATION RATE

For resin binder application rate, the goal is to achieve a thickness that will provide approximately 50-percent embedment of the aggregate particles, as illustrated in figure 9. If the resin binder layer is too thin, aggregate particles are more likely to ravel or pull out of the resin binder under traffic wear. If the resin binder layer is too thick, resin binder material is wasted, and the finished surface will not have the desired macrotexture to ensure the frictional properties.

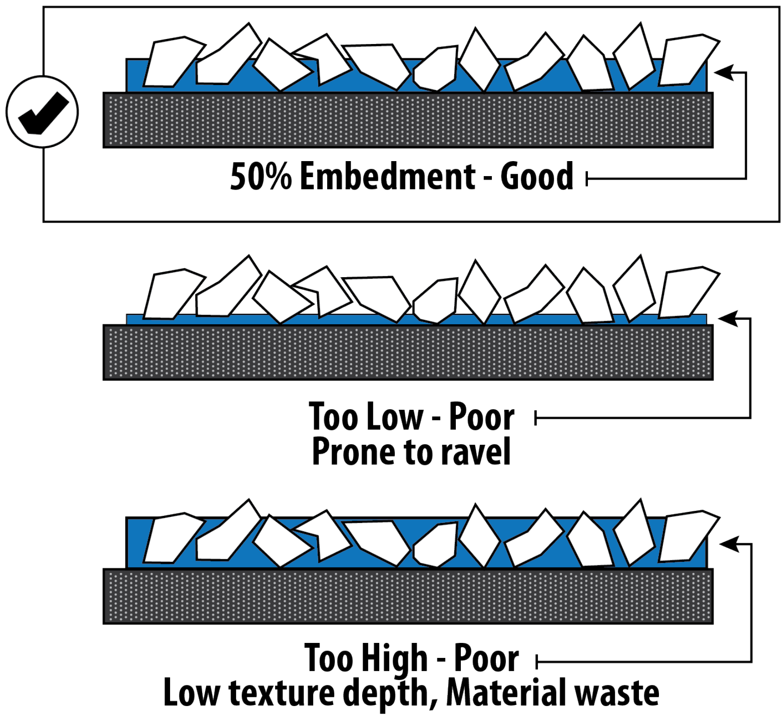

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Figure 9. Graphic. Illustration of aggregate embedment in resin binder layer (FDOT 2021).

Agencies typically specify a minimum resin binder mil thickness of 50-65 mils. This is the thickness of resin binder required to achieve approximately 50 percent embedment of a 3-4 mm sized HFST aggregate over a perfectly smooth and flat surface. Accounting for displacement of resin binder by the aggregate particles, this mil thickness should still provide the 50 percent embedment over typical pavement textures. As discussed in Chapter 3, however, the coverage rate (e.g., gallons per SY) required to achieve 50 percent embedment is highly dependent on the level of macrotexture in the underlying pavement. To account for this Virginia DOT, for example, adjusts the required mil thickness based on pavement macrotexture depth (table 8) from which the installer can determine the necessary coverage rate. Agencies can use figure 10 and figure 11 to estimate the required coverage rate based on the desired resin binder mil thickness.

Coverage rate (gallons/SY) = mil thickness x 0.0056

Figure 10. Equation. Calculation of coverage rate in gallons per square yard based on mil thickness.

Coverage rate (SY/gallon) = 178.6 ÷ mil thickness

Figure 11. Equation. Calculation of coverage rate as SY per gallon based on mil thickness

Verification of mil thickness during installation using a wet film thickness gage can be very difficult, particularly on coarse textured pavements. For this reason, agencies should compare actual material usage to the required coverage rate to achieve the desired mil thickness for the pavement texture as part of inspection. Louisiana DOTD, for example, requires the installer to report the quantity of materials used per unit area (e.g., 1,000-ft sections), along with measurements of mil thickness obtained during installation.

Aggregate application rate is typically specified as 12-15 lb/SY or "to refusal" as additional aggregate may be necessary to completely cover all resin binder. This application rate varies slightly by agency with ranges from 11 to 20 lb/SY. Automated aggregate application processes tend to be more efficient in optimizing material usage than manual processes, and therefore actual material usage may vary from this range. The main concern is that all resin binder is completely covered by aggregate, similar to that shown in figure 12.

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Figure 12. Photograph. Example of a uniform application of aggregate with no resin binder visible.

5.2.6 TEST SECTIONS

Most agencies require installers to complete an initial test section before beginning full-scale production application. The purpose of a test section is for the installer to demonstrate competence in HFST placement and to verify that the installed surface meets agency acceptance requirements (e.g., friction and texture) and can be opened to traffic on schedule. Test section requirements vary widely but are typically at least one lane wide by 20 to 200 ft in length. Most agencies will allow the test section to be placed as part of the actual site location and left in place if it meets acceptance criteria. For large projects with multiple installation locations, the test section is typically only required for the first installation.

5.2.7 SURFACE PREPARATION

Typical minimum surface preparation requirements for cleaning and roughening of the underlying pavement include:

- **Asphalt/Bituminous Surfaces**—air wash with a minimum 180 cubic feet/minute of clean and dry compressed air. Agencies may also require shotblasting of bituminous surfaces to remove bleeding/flushing (on seal coat/chip seal surfaces, in particular) fog seal, or to open up the pore structure on a dense-graded asphalt surface, but this should be followed by a compressed air wash.
- **Concrete Surfaces**—shotblasting to a minimum concrete surface profile (CSP) of 5 but no more than 7 (Winkler 2014). Shotblasting should always be followed with an air wash (similar to asphalt surface requirements) to ensure all latent dust from the shotblasting process has been removed.

Agency requirements vary on treatment of distresses prior to HFST application. In general, highly distressed pavements should be removed and replaced prior to HFST installation to ensure long-term performance. However, if there are budget limitations and a shorter HFST lifespan can be tolerated for the sake of an immediate safety improvement, HFST can still be placed, though this is not recommended. Agencies can remove minor rutting and seal wider working cracks using crack sealant materials that are compatible with HFST resin binder. Note that crack sealant should be kept below the top of pavement surface and not overbanded onto the pavement surface. Most agencies specify that cracks wider and deeper than 0.25 inches be pre-treated with HFST resin binder or binder/aggregate slurry just prior to HFST placement. Agencies can also mask off joints in concrete pavements, as well as bridge approach joints. Drainage inlets and manhole covers should also be covered.

If repaving is required prior to HFST installation, most agencies require a 30-day cure period for both asphalt or concrete pavements prior to application of HFST.

Most agencies require removal of any in-lane pavement markings, particularly if they are thermoplastic as HFST will not bond well to these. Raised or recessed pavement markers can be masked off to reduce the cost of replacement, at the discretion of the agency. Whether striping can be masked off or must be removed and replaced is at the discretion of the agency.

In general, lane-dividing striping should be removed and replaced so that HFST is uniform across the width of the roadway, but shoulder striping can be masked if HFST will not be placed out into paved shoulders, at the discretion of the agency. KYTC adds a note to project plans indicating that multiple lifts of paint may be required (particularly for waterborne paint) over HFST when replacing striping to ensure the installer accounts for this in their estimate.

5.2.8 AGGREGATE REMOVAL, RECLAMATION, AND RE-SWEEPING

Most agencies require removal of excess aggregate (after the HFST has cured) using a vacuum truck or power broom at the discretion of the installer. Requirements for aggregate removal are that the resin binder is adequately cured before beginning removal and that all loose material is removed prior to opening to traffic. Some agencies will allow excess aggregate to be swept from the edge of the roadway onto native shoulders on rural roadways, but in an urban environment or when paved shoulders are present, vacuum sweeping is generally necessary.

Many agencies do not permit the reuse of aggregate recovered from a previous placement. Reclaimed aggregate tends to have a different gradation (i.e., finer gradation) from virgin material and may also have significant dust content from the vacuuming process used to recover it. Agencies which do permit reclaimed aggregate to be used require that it be remixed with virgin aggregate at a minimum ratio of two (or three) parts of virgin material to one part reclaimed aggregate.

Because HFST naturally sheds aggregate under traffic wear during the first few days and weeks after initial installation, most agencies require re-sweeping of the surface within 30 days after installation. Shed aggregate tends to accumulate on the edges of a lane and on paved shoulders or adjacent lanes, which can create a safety hazard if not removed through re-sweeping.

5.2.9 ACCEPTANCE AND OPENING TO TRAFFIC REQUIREMENTS

Typical acceptance criteria include a subjective assessment of the finished surface to ensure all resin binder has cured and all loose aggregate has been removed, friction testing, and for a few agencies, macrotexture testing.

Friction testing should be performed sometime after the surface has been opened to traffic to allow a wear-in period as friction values immediately after installation may be artificially high. Friction testing is typically performed with an ASTM E 274/AASHTO T 242 locked-wheel skid tester (LWST) (ASTM, 2020b, AASHTO 2018b) or ASTM E1911 Dynamic Friction Tester (DFT) (ASTM 2019a). From a recent survey of State DOTs with HFST programs, approximately two-thirds require LWST testing, approximately one quarter require DFT testing, and less than 10 percent require other methods (Wilson and Saca 2021).

- LWST testing is typically performed using either an ASTM E501 ribbed tire (AASHTO, KY, LA, WV, TX, TN, IL, FL, MO) or ASTM E524 smooth tread tire (PA, VA), depending on agency standard practices. Testing is typically performed and reported at 40 mph, but speed corrections can be used if it is necessary to test at a lower speed due to roadway geometry or traffic conditions. The number of LWST tests will depend on the length of the treatment, with 1 to 3 tests typically required. For shorter sections, this may require multiple passes with the LWST. The AASHTO specification requires FN40R = 65 for acceptance, while agency-specific values range from FN40R of 65-75 and FN40S of 55-70.

- The DFT is a stationary test device requiring a lane closure to perform the test. Many agencies specify this test in lieu of the LWST due to concerns with safety and the validity of LWST measurements on sharp curves. The DFT provides a friction reading over a range of speeds from the specified test speed (typically 80 kph) down to 0 kph. Most agencies require reporting of the friction value at 60 kph or 20 kph. The number of test locations is variable with some agencies requiring only one test per location and others requiring testing as frequently as every 200 ft. The AASHTO specification does not provide a friction requirement based on DFT testing. Agency-specific values range from DFT(60 kph) of 0.75 to 0.90.

Agency requirements for timing of initial friction testing range from immediately after installation to 90 days after installation, with many agencies requiring additional testing anywhere from 90 days to 12 months after installation. Some agencies will allow for a reduced pay factor for a lower initial friction value rather than requiring removal and replacement. PennDOT, for example, requires FN40S = 70 for full payment, reduces payment to 90 percent for FN40S of 65-69, and requires removal and replacement below FN40S of 65.

Several agencies (DE, IL, IN, LA, MD, NC, TN, and VA) require macrotexture testing in addition to friction testing. Macrotexture testing is typically specified as the mean texture depth (MTD) in mm based on the ASTM E 965 volumetric method (ASTM 2019b) or as MPD in mm, based on the ASTM E2157 circular track meter device. The acceptance requirement for macrotexture (whether MTD or MPD) is typically a minimum 1.0 mm.

5.2.10 WARRANTY AND PERFORMANCE GUARANTEES

Warranties and performance guarantees are not common practice for HFST in the United States. However, a few agencies include some form of these (typically for a one-year performance period) in their specifications which require the installer to address early-age performance issues that could be related to materials and workmanship.

- FDOT requires a one-year warranty period against loss of friction below the acceptance threshold (FN40R = 65) and latent surface defects. These defects, which require remedial work if more than 10 percent of any given 100 SY of HFST application area, include (FDOT 2017):
    - Surface cracking (Class 1B or greater)—requires removal and replacement of distressed areas to the full distressed depth and to a minimum surface area of 150 percent of each distressed area.

    - Raveling and/or Delamination—requires grinding and replacement of distressed areas to the full distressed depth and to a minimum surface area of 150 percent of each distressed area.
    - Soft Spots/Bleeding—requires grinding and replacement of distressed areas to the full distressed depth and to a minimum surface area of 150 percent of each distressed area.

- Delaware DOT includes a one-year warranty against surface defects, although specific defects are not identified.
- Louisiana DOTD requires a performance guarantee with performance measures including: skid resistance and delaminations or more than 50-percent aggregate loss on more than 0.1 percent of installation area or on more than 10 contiguous ft^2 of overlay area.

Longer warranty periods are more common for HFST internationally.

- Highways England specifies a two-year performance guarantee to address the following performance criteria: skid resistance, erosion index, overall system loss, fatting-up, texture depth, cracking, tensile adhesion, scuffing test, and visual assessment (Highways England 2019, BBA 2017).
- The New Zealand Transport Agency (NZTA) specifies a two-year performance guarantee which covers: skid resistance, macrotexture, binder and aggregate retention/loss, visual appearance, and loose aggregate (NZTA 2011).

5.2.11 INSTALLATION AND INSPECTION TRAINING

Many agencies require the installer to schedule training for project inspectors and installer personnel in advance of the actual installation. The purpose of the training is to provide an overview of the installation process and highlight key items for inspection as HFST materials and installation practices are different from traditional paving or surface treatments. Currently the American Traffic Safety Services Association (ATSSA) provides a comprehensive HFST inspection and installation training course (ATSSA n.d.), FHWA also offers a training course, and a few agencies may have their own training.

5.3 APPLICATION METHODS

The two primary methods for HFST application are fully-automated and manual methods. As noted previously, most agencies require fully-automated HFST installation, with manual application permitted for smaller or irregular areas (less than 200-300 SY) where automated installation is impractical. Installations where lane width varies over the treatment section (e.g., ramps which may vary from 12 ft at the ends to 14-15 ft in the middle) or irregular areas at tapers or turn pockets are examples where manual application may need to supplement automated installation.

5.3.1 MANUAL APPLICATION

Manual application consists substantially of manual processes for resin binder proportioning, resin binder blending, resin binder application, and aggregate application. While manual installations may utilize components, such as automated proportioning and blending of resin binder or mechanically-assisted placement of aggregate, application of the resin binder is typically performed with manual labor using notched squeegees to spread the resin binder on the pavement surface, as shown in figure 13. Aggregate placement, whether broadcast manually (figure 14) or with mechanically-assisted methods such as venturi blowers (figure 15) typically lags several minutes behind resin binder application. Additional detail on the various components of manual application are provided in chapter 6.

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Figure 13. Photograph. Example of mechanically-assisted manual resin binder application.

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Figure 14. Photograph. Example of manual application of aggregate, broadcast by hand.

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Figure 15. Photograph. Example of mechanically-assisted manual aggregate application using a venturi blower.

5.3.2 FULLY-AUTOMATED APPLICATION

While there is no formal definition of fully-automated application, in general terms it consists of a single vehicle which is capable of placing HFST in a single pass with minimal manual effort. All materials are contained on the vehicle, and automated systems for conditioning (pre-heating), metering, blending, and placing the resin binder and aggregate materials are utilized for application of HFST. These vehicles allow for on-the-fly adjustment of resin binder thickness and aggregate application rate. They are typically set up for a fixed width at the beginning of a placement and can usually place 2,000-3,000 SY of HFST before refilling materials. Only a minimal (e.g., 2-3 person) crew is typically necessary to operate these vehicles, and they are capable of installing HFST at a rate of 40-50 ft per minute (or more), one lane wide. Most modern, fully-automated vehicles automatically track material usage and provide this information in real-time during installation. Figure 16 shows an example of a fully-automated installation vehicle and figure 17 shows a closeup of the resin binder and aggregate placement for a fully-automated installation vehicle. Additional information on fully-automated application is provided in chapter 6.

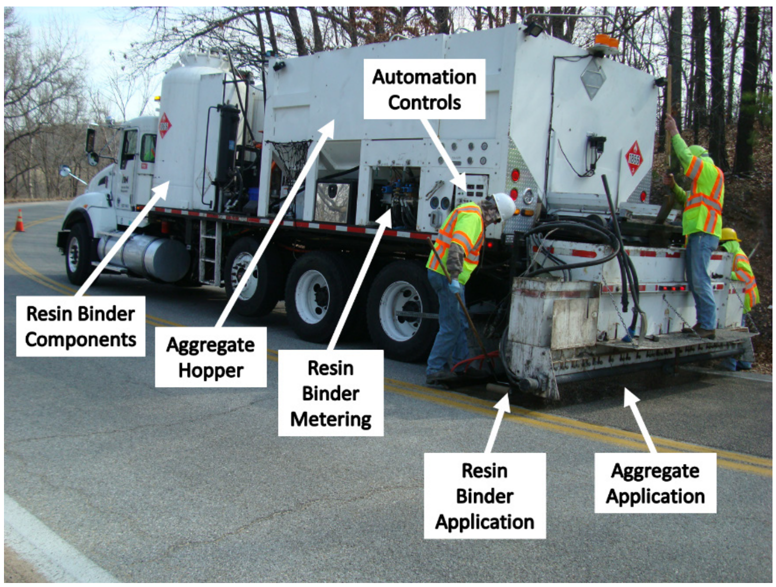

Figure 16. Photograph. Example of a fully-automated installation vehicle.

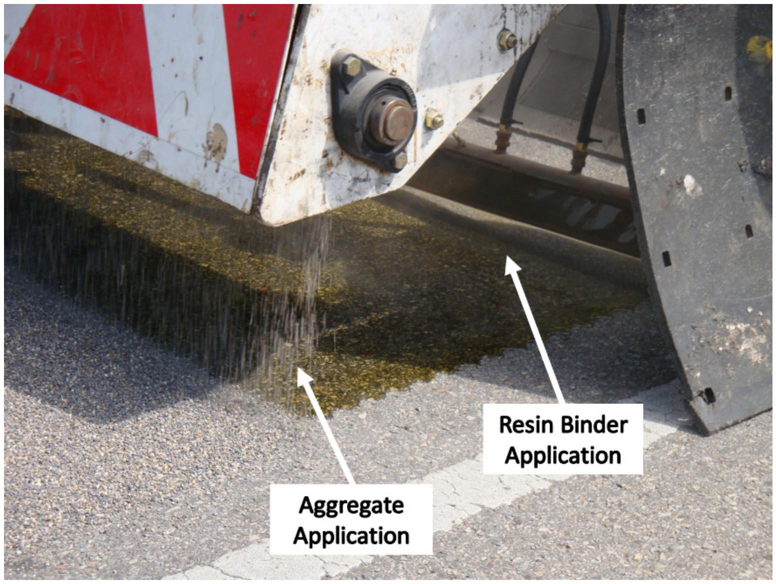

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Figure 17. Photograph. Example of resin binder and aggregate placement on a fully-automated installation vehicle.

5.3.3 COMPARISON OF APPLICATION METHODS

Table 12 highlights some of the key advantages and disadvantages of manual and fully-automated application methods. When it comes to HFST installation, the most critical elements affecting HFST performance are: ensuring that the resin binder is properly conditioned and proportioned (to manufacturer recommendations), confirming it is thoroughly blended and placed to the proper mil thickness (to achieve 50 percent aggregate embedment), and that the aggregate is applied as soon as possible after resin binder application. With manual application methods, each of these processes offers potential for human error and a poor installation. Fully automated application seeks to eliminate much of the opportunity for human error, although there is still potential for human error in the setup and operation of fully-automated vehicles.

Table 12. Key advantages and disadvantages of application methods.

Fully-Automated	Manual
Advantages	**Advantages**
• Automated conditioning, metering, blending, and application of resin binder • Real-time adjustment of resin binder component ratio and application rate • Uniform mil thickness of resin binder to eliminate high points and uneven wear on the finished surface • Immediate and automated application of aggregate onto the resin binder layer • Automated metering and real-time adjustment of aggregate placement • Smaller installation crew and faster application (reduced exposure of workers and quick re-opening to traffic) • Automated recording of material usage and options for real-time reporting during installation	• Minimal initial cost for tools and equipment • Flexibility of placement (to accommodate varying withs and irregular areas) • Few opportunities for equipment breakdown (if using mechanically-assisted methods) and manual methods can be used as a backup
Disadvantages	**Disadvantages**
• May be difficult to navigate tight curves and confined installations • Generally fixed installation width • High initial cost and maintenance cost of equipment • High mobilization cost • No backup if equipment breaks down	• Potential variability in binder proportioning and blending (using manual methods) • Variability in resin binder thickness • Slower installation • Larger installation crew required • Delayed placement of aggregate after resin binder

5.4 SPECIAL CIRCUMSTANCES AND CONSIDERATIONS

Open Graded Friction Course (OGFC)—Many States regularly use OGFC or permeable friction course surfaces due to the surface drainage and friction benefits they provide in areas with high amounts of rainfall. However, placement of HFST over open graded surfaces is **not recommended** for the following reasons:

- **Resin binder demand**—Resin binder will drain down into porous pavement surfaces, requiring significantly more resin binder to achieve the 50-65 mil thickness for the surface aggregate. If placement over an open graded surface cannot be avoided, a double layer HFST may be considered, but may lead to thermal compatibility issues.
- **Issues with thermal compatibility**—As resin binder fills the pores of an open graded surface, it effectively creates a very thick layer (i.e., equal to the thickness of the open graded layer) of HFST resin binder, which will have different thermal properties than the underlying asphalt pavement. This can lead to delamination of the open-graded layer and HFST from the underlying asphalt or cohesive failure within the underlying asphalt pavement during thermal cycling.

- **Poor performance of past applications**—After poor performance of several projects, FDOT no longer permits HFST to be installed over OGFC. FDOT requires that any OGFC be removed (using milling) and replaced with dense-graded asphalt mix prior to HFST installation within the HFST treatment limits.

Double Layer HFST—A double layer HFST has been used by some agencies for very high traffic volume locations where there is a higher likelihood a single layer application will wear off faster (e.g., urban mainline locations on interstates or State highways). However, a double layer HFST comes with certain risks which should be carefully weighed, including:

- A two-layer HFST is much less flexible than a single layer system due to the thickness of the resin binder. This can increase shear forces at the bond interface due to differing thermal properties from the underlying pavement, potentially leading to delamination or substrate failure.
- A two-layer HFST is less permeable than a single layer system, which increases vapor pressure between the HFST and underlying pavement. This can increase the potential for stripping of underlying bituminous pavement surfaces and eventual failure.

CHAPTER 6—HFST INSPECTION GUIDE

This chapter provides a guide for HFST installation inspection using either the manual or full-automated methods discussed in chapter 5. Key elements of each aspect of a typical HFST installation will be discussed, although this information will vary based on agency-specific requirements. An inspection checklist is provided in Appendix C, and a pocket guide is available for download from FHWA for use on mobile devices (FHWA, forthcoming).

6.1 OVERVIEW OF HFST

HFST is a pavement surface treatment used specifically to dramatically increase the skid resistance of virtually any pavement surface for the purpose of reducing friction-related crashes. HFST is installed by spreading a thin layer of polymeric resin binder (typically epoxy or polyester) over the pavement surface, then broadcasting or dropping a 1-3 mm nominal-size polish and abrasion-resistant aggregate onto the resin layer. The finished surface is a thin, superficial, pavement surface treatment that can be applied during a short closure of the roadway. Figure 18 shows an HFST placed over a conventional asphalt pavement surface.

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Figure 18. Photograph. HFST placed over a conventional asphalt pavement surface (Merritt et al. 2020a).

6.2 PRE-CONSTRUCTION

Key considerations for HFST inspection to verify prior to construction include:

1) Review of contractor/installer QCP to verify:
    - Schedule for the test strip and full-scale/production of HFST placement (if test strip is to be completed separately).
    - Description of equipment for placing HFST.
    - Methods for conditioning, metering, blending, and applying resin binder.
    - Methods for applying aggregate, including timing of placement onto resin binder.
    - Methods for monitoring and documenting material usage.
    - Method for protecting areas that will not receive HFST.
    - Description of acceptable environmental conditions (temperature and precipitation) for placing HFST.
    - Cure time and time to opening to traffic estimates for HFST.
    - Storage and handling of HFST materials.
    - Disposal and recycling of excess HFST and containers.
    - Contingency plan for possible failure during the HFST application.
    - Name of the certified independent testing laboratory.
    - Key personnel and contact information.
    - All project certifications and test results.
2) Verify name and contact information for contractor QCP administrator.
3) Check that materials supplied to the project meet specification requirements (through agency testing or from certified test results from the installer).
4) Verify that a resin binder manufacturer's representative is present for initial/test strip installation.

6.3 HFST MATERIALS INSPECTION

HFST consists of two materials, polymeric resin binder and calcined bauxite aggregate. The following are key considerations for inspecting these materials.

6.3.1 RESIN BINDER

- Verify that resin binder type and brand supplied to the project site is what was specified in the QCP and approved for use.
- Verify that resin binder conforms to agency specifications if certified test results were provided by the installer in lieu of agency testing.
- Verify proper storage of materials for ambient conditions:
    - Resin binder components should be stored in sealed, watertight containers.
    - Resin binder should be stored as recommended by manufacturer (heated/cooled/shaded locations as required).

- Verify resin binder component containers are clearly labeled with: resin component (e.g., Part A, Part B, etc.), brand name, name of manufacturer, lot or batch number, temperature range for storage, expiration date, and quantity of material in container.
- Sample materials for verification testing on-site as required by specification.
- Verify that adequate quantities of resin binder components for the intended installation are on-site or accessible near the project site.

6.3.2 CALCINED BAUXITE AGGREGATE

- Verify that aggregate packaging is clearly labeled with: type of aggregate, manufacturer, and location of processing.
- Verify that aggregate conforms to agency specifications if certified test results were provided by the installer in lieu of agency testing.
- Verify that aggregate is packaged and stored in such a way to protect it from rain.
- Verify that adequate quantity of aggregate for the intended installation is on-site or accessible near the project site.
- Sample materials for verification testing on-site as required by specification.
- Assess aggregate cleanliness:
    - Examine aggregate material in packaging or installation vehicle for presence of foreign matter.
    - Observe loading of aggregate into installation vehicle to check for segregation and assess cleanliness (dust generation).
- Verify aggregate is dry and there is no visible moisture on the stockpile or within the stockpile when sampled by hand. Sample and test for moisture if questionable.
- If reclaimed aggregate is permitted, verify that reclaimed material has been remixed with virgin material at the specified minimum ratio (typically 2:1 or 3:1 virgin to reclaimed).

6.4 SURFACE PREPARATION INSPECTION

The various aspects of surface preparation prior to HFST application are discussed below.

6.4.1 TREATMENT OF PAVEMENT DISTRESSES

The types of underlying pavement distresses to be addressed prior to HFST application should be clearly outlined in the project plans and specifications. Note that some distresses will require patching or the complete removal and replacement of pavement surfaces, which typically require 30 days of cure time before HFST can be applied. Most agency specifications require pre-treatment of non-working cracks wider than 0.25 inches with HFST resin binder, which can be completed just prior to HFST application.

- Verify that all distresses identified for treatment in the project plans have been addressed or will be addressed during installation.

- Note that crack sealing using bituminous crack sealant should be flush with or slightly recessed from the top surface of the pavement (figure 19) and not overbanded onto the pavement surface.
- Bituminous crack sealant should be allowed to cure for at least 30 days prior to HFST application.

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Figure 19. Photo. Example of bituminous crack sealant in asphalt pavement recessed from the top surface of the pavement.

6.4.2 CLEANING AND ROUGHENING OF THE PAVEMENT SURFACE

- Verify that compressed air wash is completed in accordance with specifications (AASHTO Specification: minimum 180 CFM with tip of lance within 12 inches of surface) and that the surface is fully covered by the air wash (figure 20).
- For concrete pavement, verify that the specified CSP (AASHTO Specification: minimum 5) has been achieved with the shotblasting process (figure 21, figure 22). Verify that entire surface to receive HFST has been shotblasted. Ensure that a compressed air wash has been used to remove latent dust and verify that the prepared surface is free from dust.
- If a power broom or vacuum truck are used to clean the surface, ensure that these are not generating additional dust and are followed by a compressed air wash to remove latent dust.
- For a double layer HFST, verify that all loose aggregate has been removed from the first layer before application of second layer.

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Figure 20. Photo. Example of compressed air wash surface preparation.

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Figure 21. Photo. Shotblast surface preparation showing overlap between successive passes.

Figure 22. Photo. Shotblast concrete surface with CSP = 5.

6.4.3 STRIPING AND PAVEMENT MARKING REMOVAL AND MASKING

- Verify complete removal of any pavement striping or markings as required in the project plans and specifications.
- Check the integrity of the pavement surface where the striping/markings were removed to verify that there is no damage (e.g., raveling) from the removal process (figure 23).
- Verify that any pavement striping or markers to be left in place have been properly masked off as required in the project plans and specifications.

Figure 23. Photo. Example of pavement striping removal using milling which has not damaged the underlying pavement.

6.4.4 PROTECTION OF JOINTS AND DRAINAGE STRUCTURES

- Verify that any pavement joints (e.g., concrete pavement joints, bridge approach joints, etc.) have been masked off as required in project plans and specifications.
- Verify that any drainage structures (e.g., inlets, manholes, etc.) have been properly masked off as required in project plans and specifications (figure 24).

Figure 24. Photo. Example of masking of drainage structures near HFST application.

6.4.5 PROTECTION OF THE PREPARED SURFACE PRIOR TO APPLICATION

- Verify that the surface is clean and dry prior to HFST application. If the surface has been opened to traffic after cleaning and roughening, verify that the surface has not been affected by traffic.
- Check cracks, joints, and surface pores for dirt and moisture.
- Check moisture content of surface if required in project specifications. ASTM D 4263, "Indicating Moisture in Concrete by the Plastic Sheet Method," modified to a two-hour test can be used for this purpose.
- Monitor prepared surface prior to and during installation for any contaminants from installation vehicles (oil, hydraulic fluid, air conditioner condensate, etc.).

6.5 HFST APPLICATION INSPECTION

This section will address application methods and provide inspection guidance on key aspects of various application practices for both manual application and fully-automated methods. General principles for HFST application inspection, regardless of the method include:

- Ensure resin binder is properly proportioned to manufacturer specifications for installation conditions (pavement and air temperature) and thoroughly blended such that it fully cures after application.
- Ensure resin binder is applied to the required mil thickness, verified using a wet film thickness gage (if appropriate, figure 25) and through a comparison of anticipated to actual coverage rate.
- Ensure aggregate is applied to the resin binder before it gels and that all resin binder is covered.
- Prevent vehicular traffic on the HFST surface before it has cured.

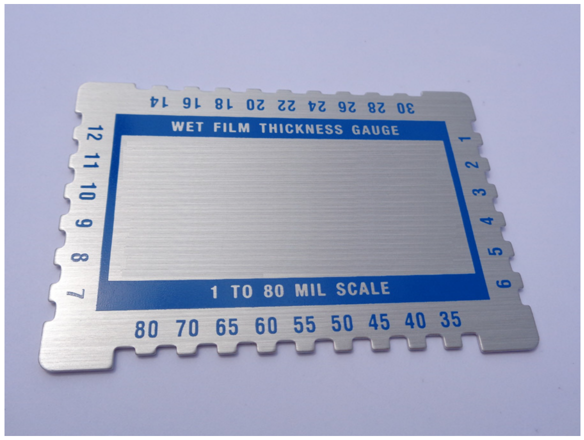


Figure 25. Photo. Wet film thickness gage used to measure resin binder thickness during application.

6.5.1 MANUAL APPLICATION

Resin Binder Proportioning and Blending

The following is a general list of tools and equipment for manual resin binder proportioning and blending (figure 26).

- Tarps/plastic sheeting to protect work area.
- Nozzles for resin totes.
- Clean measuring containers (resin type dependent).
- Variable speed drill (primary and backup).
- Generator for mixing drill.
- “Jiffy” style mixer for blending.
- Timer for resin blending.
- Clean mixing container (with wheels if using for transport).
- Rags for clean-up and cleaning spills.
- For mechanically assisted resin binder proportioning and blending.

For inspection of manual resin binder proportioning and blending:

- For manual proportioning and blending, verify that resin binder components are proportioned to the correct ratio.
- For mechanically-assisted proportioning and blending, verify the metering process used to proportion the resin binder components to the proper ratio.
- Routinely sample the blended material to ensure that it cures/hardens.

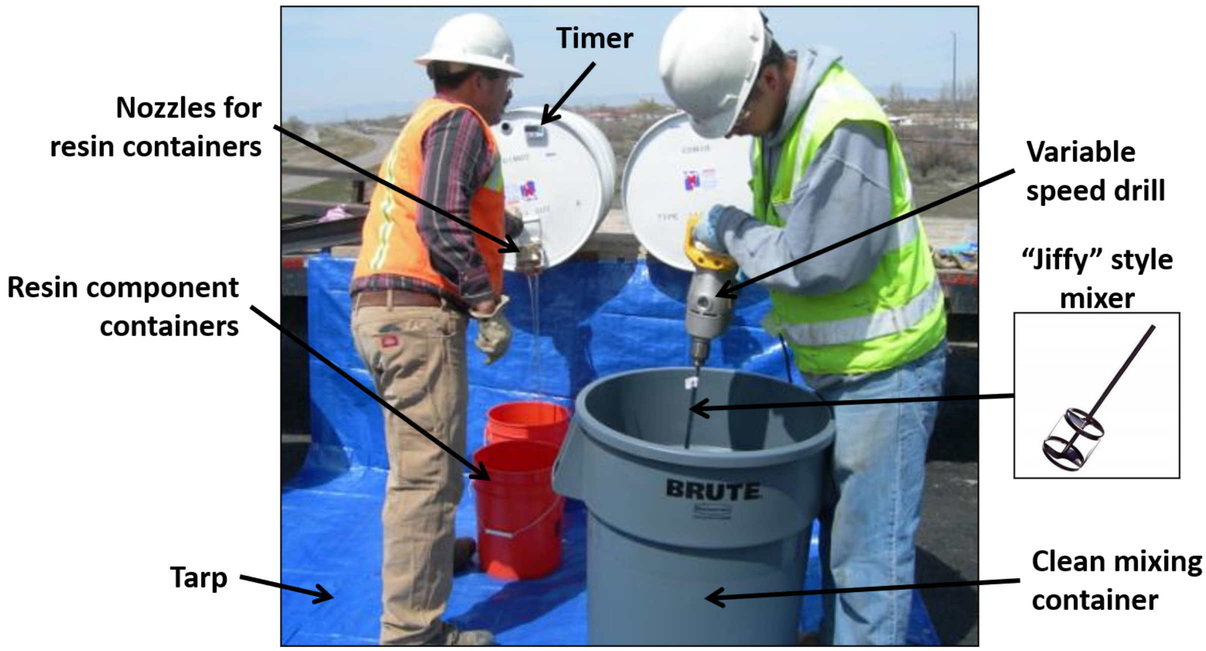


Figure 26. Photo. Typical tools and equipment for resin binder proportioning and mixing for manual application.

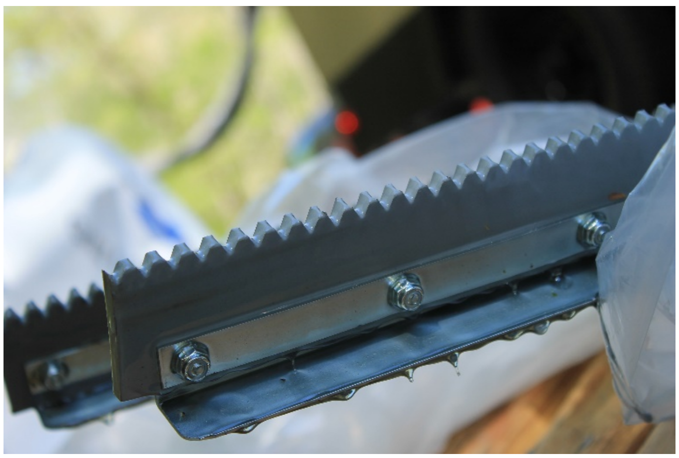
Resin Binder Application

The following is a general list of tools and equipment for manual resin binder application:

- Duct tape/tar paper to form start/end joint.
- Wheelbarrow or wheeled mixing container for transporting resin from blending to placement location (may not be necessary for mechanically-assisted reason binder proportioning and blending).
- Spiked shoes for squeegee operator to prevent shoeprints in resin binder (figure 27).
- Notched rubber squeegee for spreading resin binder with provision of additional squeegees for replacement when notches/serrations become worn (figure 28).
- Wet film thickness gauge (figure 25).

Source: FHWA

Figure 27. Photo. Example of spiked shoes worn by squeegee operator.



Source: FHWA

Figure 28. Photo. Notched rubber squeegee for spreading resin binder during manual application.

The following is a general list of checks for inspection of manual resin binder application (figure 29):

- Note ambient and pavement surface temperatures regularly during application.
- Verify use of tar paper (or similar) masking to create clean construction joints at the beginning and end of the placement.
- Note resin binder viscosity and if it appears too thick or too thin.
    - If resin binder is too thick, it may be difficult to spready uniformly.
    - If resin binder is too thin, watch for resin binder sheeting across the lane or down the pavement grade leaving deficient thickness at the high side.
- Watch for resin binder running off the lane, potentially leaving inadequate thickness.
- Verify complete coverage of the treated area with resin binder before aggregate application.

- Note the method used to operate the squeegee. Squeegees should be pulled towards the operator rather than pushed.
- Note any changes in color or consistency of resin binder throughout application and watch for contaminants (e.g., deleterious materials or residual hardened resin binder) as resin binder is deposited onto the pavement surface.
- Verify resin binder mil thickness with a wet film thickness gage at the frequency prescribed in the specifications.
- Verify total material quantity usage at the end of placement for comparison with expected usage based on required mil thickness.

Figure 29. Photo. Example of manual resin binder application.

Aggregate Application

The following is a general list of tools and equipment for manual aggregate application.

- Wheelbarrows (2-wheeled preferred).
- Shovels (flat head preferred).
- 5-gallon buckets.
- For mechanically-assisted aggregate application, only 5-gallon buckets may be necessary.

The following is a general list of checks for inspection of manual aggregate application (figure 30):

- Verify that aggregate is applied using a method that does not disturb (shove) the resin binder, ideally from the shoulder or adjacent lane.
- Watch for foreign material and significant dust content in aggregate as it is applied.
- Verify that aggregate is applied to the wet resin binder before gelling occurs and within the prescribed timing from project specifications or manufacturer recommendations.
- Verify that all resin binder is completely covered such that no "wet" areas of resin binder show through the aggregate before resin gels.

- Verify that aggregate application remains behind resin binder application such there is no aggregate on the pavement surface before the resin binder.
- Verify uniform thickness of aggregate application.
- Verify total material quantity usage at the end of placement for comparison with expected usage from project specifications.

Figure 30. Photo. Example of manual application of HFST aggregate.

6.5.2 FULLY-AUTOMATED APPLICATION

Resin Binder Application

- Verify functionality of resin binder component metering system and proportioning to the required blending ratio.
- Routinely sample blended material to ensure that it cures/hardens.
- Note ambient and pavement surface temperatures regularly during application.
- Verify use of tar paper (or similar) masking to create clean construction joints at the beginning and end of the placement.
- Observe resin binder application, noting any issues with consistency of the material or uniformity of coverage (figure 31).
- Note any excessive use of rollers and squeegees to correct automated application issues.
- Verify resin binder mil thickness with a wet film thickness gage, if possible, at the frequency prescribed in the specifications.
- Verify total material quantity usage at the end of placement for comparison with expected usage based on required mil thickness.

Aggregate Application

- Verify that aggregate application method does not interfere with resin binder application or disturb (shove) the resin binder.
- Watch for foreign material and significant dust content in aggregate as it is deposited.
- Observe aggregate application, noting any issues with uniformity of coverage (figure 31).
- Verify that all resin binder is completely covered such that no "wet" areas of resin binder show through the aggregate before resin gels, using manual aggregate application to cover these areas as needed.
- Verify total material quantity usage at the end of placement for comparison with expected usage from project specifications.

© Florida DOT

Figure 31. Photo. Example of fully automated resin binder application followed by automated aggregate application demonstrating uniformity of coverage.

6.6 INSPECTION OF AGGREGATE REMOVAL

The primary purpose of aggregate removal is to remove the loose excess aggregate from the HFST after the resin binder has cured. A secondary purpose is to loosen and remove lightly-bonded aggregate to help minimize the amount of shedding over the first few days and weeks after opening to traffic.

6.6.1 METHODS

Removal of excess aggregate is generally always completed using some form of a power broom (figure 32), vacuum sweeper (figure 33), or combination broom-vacuum. Power brooms tend to be most effective and efficient, generally only requiring 1 to 2 passes, but may not be possible to use if there is risk of sweeping aggregate into adjacent lanes. Whenever broom methods are used, only non-metallic, less aggressive broom bristles should be permitted. If aggregate reuse is permitted, vacuum sweepers are generally the most efficient method for reclaiming aggregate. However, because vacuum sweepers do not agitate the surface like power brooms, 3 to 4 passes may be necessary to remove all loose aggregate. Agencies may have requirements for dust mitigation that will require one method over another.

Figure 32. Photo. Example of aggregate removal using a power broom.

Figure 33. Photo. Example of aggregate removal using a vacuum truck.

6.6.2 TIMING

Timing of aggregate removal is critical. If sweeping/vacuuming begins before the resin has adequately cured, there is risk of pulling aggregate out of the resin binder, potentially diminishing the frictional properties of the finished surface. Timing of aggregate removal will be dictated by resin binder manufacturer guidelines based the cure time requirements and ambient temperature at placement. Deformability of the resin binder is typically used to determine timing of sweeping in the field. Note that cure time required before sweeping may be different from that required before opening to traffic.

6.6.3 RECLAMATION

If reuse of aggregate is permitted, reclaimed aggregate should be stored separately from virgin aggregate such that they can be remixed in the proper proportions for future application.

6.6.4 INSPECTION

- Verify that the sweeping time is in accordance with the resin binder manufacturer recommendations, and resin cure has been verified before sweeping begins.
- Note any areas where sweeping exposes the resin binder or underlying pavement (figure 34). These areas will require repair or replacement.
- Verify that all loose aggregate has been removed from the surface of the HFST before opening to traffic.
- Verify that all aggregate which has migrated onto adjacent lanes, paved shoulders, or pavement adjacent to the beginning or end of the HFST section has been removed (figure 35).
- Verify that reclaimed aggregate is stored separately from virgin aggregate.

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Figure 34. Photo. Example of exposure of underlying pavement after sweeping.

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Figure 35. Photo. Example of loose aggregate migration onto adjacent lanes and shoulders.

6.7 INSPECTION OF FINISHED SURFACE

Before opening to traffic, the finished surface should receive a final visual inspection. Visual inspection should include:

- Verify that there is no loose aggregate on the HFST surface or adjacent surfaces.
- Verify that there are no areas of discoloration that could indicate uncured resin or moisture beneath the treatment (figure 36).
- Verify that all masking of striping, pavement markers, joints, drainage structures, etc. has been removed.
- Identify any areas where HFST is missing (figure 37) or will need to be removed and replaced for non-conformance.
    - Verify that the surface is safe to open to traffic before these repairs are made.
    - If surface is not safe to open to traffic, discuss mitigation and repair/replacement plan with installer.
- Verify that all striping has been replaced with temporary or permanent markings in accordance with project plans and specifications.

Figure 36. Photo. Example of discoloration indicating uncured resin binder.

Figure 37. Photo. Example of areas where HFST is missing and will require repair.

6.8 ACCEPTANCE TESTING

Acceptance testing is specific to agency requirements. In addition to the visual inspection of the finished surface discussed above, acceptance testing typically includes friction testing, but may include macrotexture testing and pull-off testing.

6.8.1 FRICTION TESTING

Friction testing may be required before opening to traffic but is most commonly required 14 to 90 days after opening to traffic to allow a wear-in period. Agencies with performance guarantee requirements may also require testing during or at the end of the performance period.

The most common methods for friction testing are, ASTM E274/AASHTO T 242 LWST (ASTM 2020b, AASHTO 2018b), which can be performed under traffic, and ASTM E 1911 DFT (ASTM 2019a), which will require a lane closure.

- Verify the test requirements in the project specifications, including timing, number of tests required, test speed, friction value for acceptance.
- Verify that the test is performed in accordance with project specifications and any ASTM/AASHTO/agency-specific procedures.

6.8.2 MACROTEXTURE TESTING

Macrotexture testing is typically completed at the same time as friction testing. The two most common methods for macrotexture testing are stationary methods that will require a lane closure. The ASTM E 965 "Sand Patch" method uses a known volume of sand or glass beads to estimate macrotexture depth, reported as MTD (ASTM 2019b). The ASTM E2157 Circular Track Meter measures macrotexture over a circular path and reports it as MPD.

- Verify the test requirements in the project specifications, including timing, number of tests required, and friction value for acceptance.
- Verify that the test is performed in accordance with project specifications and any ASTM/AASHTO/agency-specific procedures.

6.8.3 OTHER TESTS

Some agencies may have additional acceptance testing requirements, such as the ASTM C1583 pull-off tensile strength test to verify adhesion between the HFST and underlying pavement (ASTM 2020c). This is also a stationary test which will require a lane closure but can typically be performed after installation, before opening to traffic.

6.9 EARLY-AGE MONITORING

Early-age monitoring will help identify any issues related to materials and installation workmanship. These issues will typically develop within the first 30 to 60 days after installation. Summarized below are potential early-age items to monitor.

6.9.1 UNCURED RESIN BINDER

Uncured resin binder will normally appear as isolated areas where the HFST is discolored (figure 36) and soft, and will lead to aggregate loss or flushing of the resin binder on the HFST surface. This may not appear immediately and may develop over the first few days after installation. Agencies may investigate discoloration and determine the limits of the resin binder failure as it may not affect the entire application.

Agencies may remove and reapply the HFST in the affected area(s) to correct the resin binder failure.

6.9.2 AGGREGATE LOSS AND RE-SWEEPING

HFST will naturally shed aggregate that is only lightly bonded to the resin binder under traffic wear. Normal shedding will generally be heaviest during the first 24 to 72 hours, tapering off over time, depending on traffic volume. Shed aggregate will generally accumulate along the edges of the lane and possibly in adjacent lanes and paved shoulders (figure 38). Re-sweeping is typically required in project specifications to remove this loose material within the first 2 to 4 weeks of installation.

If significant aggregate loss continues beyond the first 30 to 60 days, this may indicate an issue with materials and installation and the cause should be investigated further, particularly if the resin binder or underlying pavement becomes exposed.

Corrective action for aggregate loss is removal and reapplication of the affected area(s).

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Figure 38. Photo. Example of aggregate shedding and accumulation along lane edge and on paved shoulder.

6.9.3 DELAMINATION

Delamination is the separation of the HFST from the underlying pavement due to a lack of bond. Delamination generally manifests as “sheets” of HFST peeling away from the surface, commonly in small localized areas, but can spread to much larger areas (figure 39).

Delamination is not obvious until the HFST peels away, leaving exposed pavement, but may still be occurring. Sounding techniques can be used to identify delamination if there is evidence that this may be occurring.

Corrective action for delamination is removal of all affected areas and reapplication of HFST. Widespread delamination may necessitate complete removal and reapplication, ensuring that any possible causes of the delamination (e.g., surface preparation) are addressed before reapplication.

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Figure 39. Photo. Example of delamination of HFST from underlying pavement surface.

6.9.4 AGGREGATE POLISHING

Aggregate polishing is the result of aggregate particles being worn away under traffic, leaving a smooth HFST surface where the aggregate may be worn flush with the resin binder (figure 40). While this should not occur if calcined bauxite aggregate meeting specification requirements is used, if it does occur, the aggregate should be further investigated with laboratory testing.

Corrective action for aggregate polishing will be removal and reapplication of the HFST.

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Figure 40. Photo. Example of polished HFST surface in wheelpaths.

6.9.5 DISCOLORATION

Discoloration is a visible difference in color of localized areas of HFST from the surrounding surface (figure 41). Discoloration does not necessarily indicate a problem with the HFST, but may be an indicator of the presence of moisture trapped beneath the HFST. Monitoring should continue over time to note any changes in discoloration or appearance of localized distresses. Corrective action would only be necessary if it leads to distresses.

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Figure 41. Photo. Example of HFST discoloration likely caused by moisture.

6.9.6 SURFACE WEAR LOSS OF HFST

Surface wear loss of HFST occurs when both the aggregate and resin binder wear off under traffic. This generally occurs when the aggregate polishes or breaks away from the resin binder, exposing the resin binder which quickly wears off, exposing underlying pavement (figure 42). While wear-off is expected at the end of HFST service life, premature wear-off is a cause for concern and should be investigated further, as it may indicate that the resin binder layer was placed too thin.

Corrective action for wear-off is reapplication of HFST either over the existing surface (if recommended by the resin binder manufacturer) or after removal of the worn layer.

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Figure 42. Photo. Example of HFST worn off in the wheelpaths.

6.9.7 FRICTION LOSS

Friction loss is defined as a sustained decrease in friction over time. While there will naturally be some loss of friction over the first year after installation as the surface is worn in under traffic, continued loss of friction (e.g., 10 percent or more) year after year, should be investigated further. Generally, this condition is caused by polishing or loss of aggregate.

Corrective action for friction loss is reapplication of HFST either over the existing surface (if recommended by the resin binder manufacturer) or after removal of the existing surface.

6.9.8 FAILURE OF UNDERLYING PAVEMENT

Failure of the underlying pavement will cause a loss of HFST. Failures typically manifest as small isolated areas (e.g., potholes) which can progress to much larger areas (figure 43). This type of failure is more common in asphalt pavements and may be the result of a cohesive failure within a weak asphalt layer or due to stripping of the asphalt layer due to trapped moisture.

Corrective action for failure of the underlying pavement will require removal of the affected area, proper repair of the underlying pavement, and reapplication of HFST.

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Figure 43. Photo. Example of failure of underlying pavement leading to isolated failures (potholes) of HFST.

6.10 INSPECTION CHECKLIST

Appendix C provides an example of an inspection checklist covering the various inspection items discussed above. This checklist provides a quick verification that each of these items are addressed during installation by the inspector. An editable Microsoft Word version of this checklist along with a stand-alone inspection guide is available for download from FHWA.

CHAPTER 7—PERFORMANCE MONITORING AND REPLACEMENT

Monitoring the performance of HFST installations is important for the further refinement of specifications and site selection processes for future implementation. This chapter will discuss common causes of HFST failure followed by consideration for performance monitoring and additional considerations for the removal and replacement of HFST.

7.1 CAUSES OF HFST FAILURE

When discussing HFST failure, a distinction is made between premature failure and terminal failure. Premature failure is typically related to the site conditions (e.g., underlying pavement integrity), materials, or installation practices. Terminal failure is typically characterized by a loss of pavement friction due to aggregate loss under traffic wear over time. While there are likely a number of other failure mechanisms, summarized below are some of the most common. Proper site screening (chapter 3), materials (chapter 4), specifications (chapter 5), and installation practices (chapter 6) will help prevent premature failure of HFST.

- **Resin binder formulation and blending—**Improperly formulated resin binders or resin binders which are not properly blended before application can result in a resin binder that will not have the desired properties necessary to bond to the pavement surface or securely hold the aggregate in place. Virtually all resin binders are two (or more) part materials that must be blended in the proper proportions to ensure proper curing. Soft or uncured areas of resin binder after application are an indication of improper formulation or improper blending (figure 44 and figure 45).

© FDOT

Figure 44. Photograph. Example of localized failures due to poor binder mixing (FDOT 2021).

Figure 45. Photograph. Example of soft areas in resin binder shortly after construction (FDOT 2021).

- **Inadequate resin binder thickness**—The target embedment depth for HFST aggregate in the resin binder is 50 percent of the nominal aggregate size. If the resin binder layer is too thin, aggregate particles will be more easily be dislodged from the resin binder during sweeping (figure 34 and figure 46) or under traffic wear, leaving only the resin binder which provides no frictional benefit. Inadequate thickness typically results from an inadequate coverage rate for the pavement macrotexture. Specifications for resin binder coverage rate should account for pavement macrotexture, ensuring adequate resin binder material for the level of macrotexture in the pavement surface to be treated. Low viscosity of the resin binder is another cause of inadequate thickness. If the material lacks viscosity, it will flow or run down the pavement slope, leaving inadequate thickness at the higher points.

Figure 46. Photograph. Example exposure of underlying pavement due to inadequate resin binder thickness.

- **Improper aggregate application**—If the aggregate is not broadcast onto the resin binder before it begins to gel, the resin binder will resist penetration and bond of the aggregate and the aggregate will more easily be dislodged during sweeping or under traffic wear, leaving only the resin binder. Figure 47 shows a photo of resin binder with only minimal aggregate embedded as a result of delayed application of the aggregate. While the timing of aggregate application will vary with resin binder and temperature, best practice is to apply the aggregate immediately after the resin binder application. Dirty aggregate can be another source of premature aggregate loss as the aggregate does not properly bond to the resin binder and can become dislodged under traffic wear.

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Figure 47. Photograph. HFST with inadequate aggregate coverage due to delayed aggregate application.

- **Delamination due to lack of macrotexture on existing pavement or improper surface preparation**—Resin binder bond to the pavement surface is partly mechanical, meaning the resin binder interlocks with the pavement surface through macrotexture. If a pavement surface lacks adequate macrotexture, this mechanical bond is diminished. A poor bond can also be the result of improper surface preparation when the surface is not thoroughly cleaned, leaving latent dust that inhibits the bond between the resin binder and pavement surface. The result of either condition is typically a delamination of the HFST from the pavement surface, as shown in figure 39 and figure 48. This issue is more common with smooth concrete surfaces that have not been shotblasted or with bituminous surfaces exhibiting bleeding or flushing. Shotblast surface preparation helps to ensure adequate macrotexture, and thorough air wash helps to remove latent dust.

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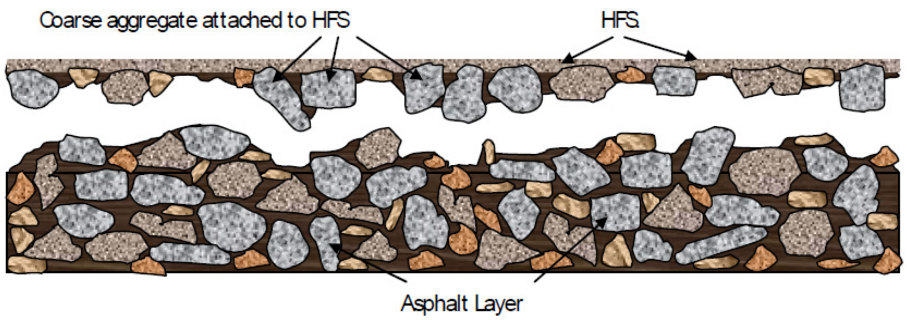
Figure 48. Photo. Example of an area of HFST delamination from the underlying pavement surface.

- **Failure of underlying pavement**—If the underlying pavement is in poor condition, or if moisture becomes trapped in the underlying pavement (e.g., from subsurface moisture migration or surface intrusion at cracks leading to asphalt stripping), the pavement can fail and cause failure of the HFST as well. Underlying pavement failures typically manifest as isolated distresses (potholes) in the HFST as shown in figure 43 and figure 49. While these may remain isolated failures, they can spread to much larger areas.

Source: FHWA

Figure 49. Photograph. Example failure of underlying pavement (delamination of surface layer) resulting in failure of HFST.

Failure of the underlying pavement can also be the result of high shear stresses in the underlying pavement, resulting in a cohesive failure (figure 50). The HFST remains bonded to the underlying pavement, but failure occurs within the pavement itself. This type of failure is typically caused by a weak asphalt layer and may be exacerbated by thermal incompatibility between the HFST and underlying pavement which increases these shear stresses under thermal cycling, as well as by vehicle-induced shear stresses (FDOT 2021, Waters 2011).



© Waters

Figure 50. Graphic. Cohesive failure of underlying pavement (Waters 2011).

7.2 PERFORMANCE MONITORING

As with the implementation of any safety countermeasure, performance monitoring includes regular evaluations of safety performance (e.g., crash reduction). For HFST, however, performance monitoring also includes regular evaluation of functional performance (e.g., friction and treatment deterioration). Section 7.2.1 provides considerations and methods for monitoring HFST safety performance and Section 7.2.2 provides considerations and methods for monitoring HFST functional performance.

7.2.1 SAFETY PERFORMANCE

Monitoring safety performance of HFST installations will allow an agency to optimize deployment of this safety countermeasure through refinement of site selection processes and an improved understanding of the B/C for HFST. In general, there are three levels of safety performance evaluation: project, countermeasure, and program (Gross 2017).

- **Project-level evaluation**—The purpose is to evaluate individual projects over time to assess changes in crash frequency and severity against the before condition.
- **Countermeasure-level evaluation**—The purpose is to evaluate groups of similar projects to determine the effectiveness in changes to crash frequency and severity with the intention of developing a CMF. This includes identifying factors associated with HFST being more or less effective to inform future decision-making.
- **Program-level evaluation**—The purpose is to evaluate the overall HFST program to measure the effectiveness with respect to changes in crash frequency and severity by crash type at the system level. This evaluation level helps to demonstrate the value of

the HFST program. Agencies can also use program evaluations to identify opportunities to improve processes and procedures.

There are several techniques available for conducting evaluations at each level. The HSIP Evaluation Guide provides details specific to each with a separate chapter devoted to each evaluation level (Gross 2017). However, the analytical methods are relatively similar for each level and should be determined based on data availability, sample size, and the desired level of confidence in the results. Table 13 provides an overview of potential analytical methods and when each may be most appropriately applied.

Table 13. Safety Performance Evaluation Methods

Evaluation Method	Advantage	Potential Biases/ Implementation Issues	Data Needs	Most appropriate for
Simple before-after	Straightforward application	Regression-to-mean Traffic volume changes Time trends	Crashes before and after	Project evaluation Not looking for generalized effectiveness Volume data unavailable
Before-after with traffic volume correction	Straightforward application Accounts for traffic volume	Regression-to-mean Assumes linear crash rate Time trends	Volume and crashes before and after	Project evaluation Not looking for generalized effectiveness
Before-after with comparison group	Accounts for several biases Does not require SPFs	Regression-to-mean Assumes a linear crash rate	Appropriate comparison sites Volume and crashes before and after	Countermeasure evaluation Limited sample of sites SPFs unavailable
Empirical Bayes before-after study	Accounts for most biases	Requires reference group for SPF development or calibration	Reference sites or calibrated SPF Volume and crashes before and after	Countermeasure or program evaluation
Cross-sectional study	Installation date not needed Study can be conducted immediately	Potential confounding across sites Does not compare before to after	Volume and crashes before and after Confounding factors to reduce omitted variable bias	Countermeasure or program evaluation when installation dates unknown
Shift of proportions	Useful when traffic volume changes suspected but unavailable	Provides proportion, not change in frequency	Crashes before and after by type or severity	Evaluating changes to target crash type or severity Volume data unavailable

A key factor in all evaluation methods is that HFST project installations must be tracked for location, and for nearly all methods, the date of installation is required. Additionally, analysts should further consider the site selection method prior to evaluating safety performance.

In general, the methods for evaluating HFST installed based on a site-specific approach and a systemic approach are the same. The data needs are the same, including the need for project details (installation locations and dates), traffic volume data, and crash data before and after installation. There is also a chance of regression-to-the-mean (RTM) bias when evaluating both site-specific and systemic applications, but potentially in opposite directions. RTM (or return to average) is the natural variation in crashes over time where sites with an abnormally high number of crashes in the past will likely experience a reduction in crashes in the future and vice versa even with no other changes to the site. The following are related challenges in evaluating site-specific and systemic HFST applications:

- **Site-specific**—When evaluating HFST at sites selected based on crash history, there is the potential for RTM to inflate the estimated effectiveness (i.e., crashes would have gone down even without treatment). While more reliable methods can help to account for RTM when evaluating the performance of individual projects, this is typically not done for a number of reasons. First, the focus of project evaluations is on whether or not the observed crash problem still exists at a specific location. Second, the results of individual projects may not be representative of all sites and agencies tend not to use the results of individual projects to make future decisions. Instead, agencies combine the results from multiple projects to estimate the general effectiveness of a countermeasure. When evaluating HFST to estimate countermeasure effectiveness and develop CMFs, analysts should use more reliable methods (e.g., EB before-after) to account for RTM and separate the natural variation in crashes from the effectiveness of HFST.
- **Systemic**—When evaluating systemic HFST applications, there are challenges in accounting for sites that were treated but did not have any crashes in the recent past. If these sites experience even a single crash in the post-implementation study period, then a simple before-after method would indicate the HFST was ineffective. More reliable methods (e.g., EB before-after) that incorporate predicted crash frequency provide a better indicator of the change in safety performance. Additionally, a shift in proportions or other analytical method may provide further insight. The HSIP Evaluation Guide and NCHRP Report 955 provide further details and options for evaluating the safety performance of a systemic approach (Gross 2017; Torbic et al. 2020).

To support performance monitoring and future decision-making, agencies can consider developing robust agency-specific CMFs and B/C ratios. This can help to justify the general deployment of HFST and to better target the use of HFST to address friction-related safety issues. While there are several CMFs for HFST in the CMF Clearinghouse, these were generated from a limited number of jurisdictions (FHWA 2021a) that do not necessarily account for all of the possible conditions (e.g., climate, geography, traffic characteristics, etc.) in the United States. Agency-specific CMFs will further improve the reliability of the crash reduction potential of HFST for jurisdiction-specific conditions. Gross et al. (2010) and Carter et al. (2012) provide insights on developing high-quality CMFs as well as a discussion of considerations for improving the completeness and consistency in CMF reporting.

7.2.2 FUNCTIONAL PERFORMANCE

The two primary indicators of functional performance of HFST are friction performance and treatment condition.

Friction Performance

As a treatment used specifically to enhance pavement friction, monitoring HFST friction performance, or changes in friction over time, is critical. Routine friction testing (e.g., on an annual basis), preferably as part of a comprehensive PFMP, is recommended for proactively monitoring HFST friction performance, as opposed to waiting for issues (e.g., increased crashes) to manifest before checking friction.

If tested under a routine PFMP regime, HFST sections should be specifically identified in the PFMP database such that an appropriate investigatory/intervention level of friction specific to HFST is assigned to those segments.

A sudden or rapid decrease in the friction of HFST is typically caused by aggregate polishing or aggregate loss. Assuming the proper aggregate materials were specified and verified during installation, the latter condition is more common. Aggregate loss can be caused by a number of issues related to the resin binder, discussed above.

Pavement friction testing methods should remain consistent such that results can be readily compared year-to-year (assuming annual testing). Alternatively, different friction thresholds can be established based on the potential devices used to measure friction. Furthermore, the use of CPFM is desirable as it can help identify variations in friction within the length of the treatment itself since friction may be lower at points of the highest friction demand. CPFM devices are also generally able to operate at locations (sharp curves and intersections) where other devices cannot.

Initial friction requirements (test type and friction threshold) are defined by each agency. While the initial version of the AASHTO HFST specification (PP 79-14) called for FN40R = 65 for acceptance (which is very conservative for HFST) the current version leaves this to individual agencies. Chapter 5 provides examples of friction requirements for acceptance.

While there is no codified standard for what would be considered an intervention friction value for HFST, several studies have examined both field and laboratory performance of HFST under normal traffic wear and accelerated wear to help determine what long-term friction values should be expected, as summarized in table 14. These studies reveal that HFST should maintain a friction value (FN40R) of at least 57-66 over time. The TCMS tool for evaluating margin of safety based on friction supply and friction demand uses a friction prediction curve which assumes an initial friction value and a fairly rapid decay to a terminal value within a year where it remains over the life of the treatment (Pratt et al. 2018a, Pratt et al. 2018b).

Table 14. Long-term friction performance of HFST.

Source	Friction Values
TCMS Tool Development, Pratt 2018b) • Field data from Florida and Texas HFST sites. • Laboratory testing of samples subjected to accelerated wear with the three-wheel polishing test. • Modelling based on Aggregate Imaging System of aggregates subjected so accelerated wear using Micro-Deval.	Field Testing: Initial: FN40R = 83 (based on SN50S = 70) Terminal: FN40R = 57 (based on SN50S = 50) Modelled: Initial: FN40R = 86 (based on SN50S = 73) Terminal: FN40R = 67 (based on SN50S = 58) TCMS Model: Initial: FN40R = 76 (based on SN50S = 65) Terminal: FN40R = 66 (based on SN50S = 57)
Field data from Florida HFST sites, (Wilson and Mukhopadhyay 2016)	Initial FN40R = 80 Long-Term (≤ 6 years) FN40R = 63
Field data from FHWA study to develop crash modification factors for HFST, (Merritt et al. 2020a).	Long-Term (6 to 10 years) FN40R = 57-73 (based on HFT(40) = 0.8-1.0)
NCAT Test Track, (Heitzman et al. 2015)	Long-Term (>10M ESAL applications): FN40R = 63

Treatment Condition

HFST condition should be routinely monitored as part of regular network-level pavement management condition surveys for distress and deterioration. If treatments are installed on rural roadways which do not receive regular (e.g., annual) condition assessment, agencies may need to perform project-level assessments. HFST sections should be clearly delineated in pavement management system databases such that they are not assessed with the same criteria as conventional pavement surfaces. It is important to note that the presence of distresses in HFST does not indicate a failed treatment. As long as the surface is still providing the desired level of friction, distresses should not be the primary indicator of a functional failure of an HFST unless the distresses are extensive and leading to potential safety hazards or maintenance liabilities. As such, project level condition surveys or field reviews of HFST sections should be performed if routine performance monitoring indicates a high level of distress.

Common distresses and their potential impact on HFST performance are summarized below:

- **Cracking**—Any cracking or joints in underlying pavement (even if sealed prior to HFST application) will eventually reflect through into the HFST surface (figure 51). However, experience has shown that this does not necessarily affect performance of HFST unless the underlying pavement begins to fail. In general, cracks in HFST should not be sealed as part of routine maintenance as the sealant can affect the skid resistance of the surface.

Figure 51. Photograph. Example of cracking in underlying pavement reflecting through HFST.

- **Aggregate Loss**—Also sometimes referred to as raveling, HFST aggregate loss (figure 42 and figure 52) will lead to a loss of friction and can be caused by a number of factors discussed previously. Unfortunately, there are no established methods quantifying aggregate loss aside from visual subjective inspection. While automated pavement condition assessment continues to improve, the only metric which appears to correlate to some degree with aggregate loss is macrotexture, or MPD.

Figure 52. Photograph. Example of aggregate loss under traffic wear.

- **Aggregate Polishing**—While it may be possible to visually identify aggregate polishing (figure 40), or to detect it through a loss of macrotexture, friction testing will a more reliable indicator of aggregate polishing issues.
- **Delamination**—Delamination is the separation of the HFST from the underlying pavement due to a lack of bond to the underlying surface. Condition surveys may not detect delamination until the HFST begins to peel away (figure 39 and figure 48). Sounding techniques, however, can help identify delaminated areas during a project-level survey if delamination has been observed and there is suspicion of additional delamination.
- **Discoloration**—Discoloration of HFST is not necessarily a problem but may indicate the presence of moisture trapped beneath the HFST (figure 41) or possibly some issue with the resin binder (figure 44 and figure 45). A project-level assessment can help to determine whether discoloration is indicative of other issues.

7.3 REMOVAL AND REPLACEMENT

HFST removal may be necessary due to premature failure of the treatment, replacement of the treatment once it has reached the end of its useful life, or as part of capital improvement for the roadway (e.g., repaving).

Milling or cold planing is the most common method for removal of HFST. If only the HFST is to be removed and not the underlying pavement, micromilling is preferred. It is important to protect the integrity of the underlying pavement if it will remain in place or if HFST will be reapplied. Micromilling tends to be less destructive to underlying asphalt and concrete than standard milling. Diamond grinding is another option for removal, and may be more appropriate for concrete than milling, but tends to be a slower and more costly process.

Note that while it may appear that all HFST has been removed, it is possible that residual resin binder still remains in the pore structure of the underlying pavement left in place. This may inhibit the bond of any new HFST installed over the same surface as there is reduced opportunity for the resin binder to "soak into" the pavement surface. A simple test to determine if there is residual resin binder is to pour water on the surface. If the water beads or pools on the surface and does not soak into the pavement, there may be residual resin binder. If the water soaks into the pavement surface, the resin binder has likely all been removed. If resin binder remains, it should be removed to the greatest extent possible using techniques such as shotblasting.

When removing HFST along with the underlying pavement, there have not been any reported issues with the HFST being blended with asphalt millings. However, if the asphalt is to be recycled for a surface-grade asphalt pavement, it may be preferred to mill the HFST off first, separately from the asphalt.

If HFST is to be reapplied, installation should follow similar practices to those outlined for a new treatment in previous chapters. If applied to the existing surface, special attention should be given to the integrity and macrotexture of the surface, particularly after milling. If milling led to raveling or other distresses in the remaining the surface, this should be repaired prior to placing new HFST. Note also that milling processes generate substantial dust and laitance, so special attention should be given to removing this latent dust with a compressed air wash.

CHAPTER 8—COST ESTIMATION AND FUNDING

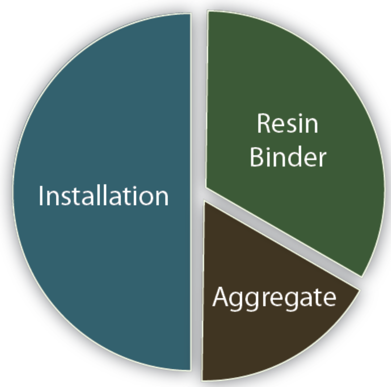
This chapter will discuss the cost of HFST and B/C estimation based on crash reduction benefits. Additional discussion is provided on potential options for funding HFST implementation.

8.1 HFST COST

HFST cost (unit cost, installed) has traditionally been highly variable due to a number of factors related to agency contracting mechanisms, materials, and installation.

Figure 53 shows a generalized breakdown of the unit cost of HFST. Installation (mobilization, labor, etc.) accounts for roughly half of the unit cost, while the materials account for the other half. Of the material costs, resin binder accounts for roughly two-thirds of the material cost and aggregate one-third.

Materials—Material prices (and associated supply volatility), are a key factor, particularly for calcined bauxite aggregate which is normally imported (although domestic suppliers are now available) and resin binder which is a specialty material with a limited number of suppliers. While the cost of imported calcined bauxite aggregate is often thought to be the primary contributor to materials cost, this is not necessarily the case.



Source: FHWA

Figure 53. Graphic. Approximate breakdown of HFST cost (Atkinson et al. 2016).

Installation—Installation-related factors that affect HFST cost include the size of a given project, project requirements, and the contracting mechanisms. Economies of scale can significantly impact unit cost, and in general the larger a project (which may consist of several HFST installation locations), the lower the unit cost. The proximity of HFST installations to one another under a given project will also affect cost, as will any restrictions on scheduling of installation (e.g., seasonal or nighttime or weekend only work). Many agencies will let projects with multiple installations bundled together by District/Region or county to reduce cost (Wilson and Saca 2021). Some agencies have set up on-call master agreements with negotiated fixed costs for HFST installation on an as-needed basis. Specification requirements can be another factor impacting cost as requirements for traffic control, installation methods, surface preparation, materials testing, and finished product testing outlined in project specifications can all impact HFST cost. Contracting mechanisms and availability of competition is another factor. Agencies with multiple bidders will typically see more favorable unit prices, and projects where HFST installers are able to bid the work directly, rather than as a subcontractor to a general contractor, will generally be lower in cost.

Current unit prices for HFST used by agencies for project estimation purposes range from $20 to $37 per square yard for the treatment itself (FDOT 2021, Wilson and Saca 2021). A 2018 PennDOT study of 47 locations (from 7 different contracts) in the State revealed a total unit cost just over $36/SY which included materials and installation costs, inspection costs, and construction survey costs. This was for an average area of 1,805 SY per location which equates to approximately 680 ft treatment length for two lanes (Hershock 2020). FDOT reports a comprehensive HFST unit cost, which includes all related construction costs, ranging from $36 to $113/SY, with an average of $59/SY (FDOT 2021). As usage of HFST continues to grow, material costs are likely to continue to decrease, and more installers will likely enter the market thereby also decreasing installation cost.

8.2 B/C RATIOS

Published B/C ratios for HFST vary widely, based primarily on the process used for site selection. HFST used at very high crash locations (e.g., Wisconsin and California examples from chapter 1), particularly locations with high percentages of injury or fatal crashes will produce very high B/C ratios. Conversely, HFST deployed through a systemic implementation will likely produce very low B/C ratios, particularly if the site selection is risk-based and the B/C analysis is based on observed crashes, as there is typically a high cost to deploy the treatment on a large scale to prevent crashes which are spread over a large area. To refine B/C estimates for both site-specific and systemic-based HFST installations, there is an opportunity to employ the EB method to serve as the basis for the benefit analysis.

PennDOT closely tracks project costs and regularly computes B/C ratios for HFST. From a 2018 evaluation of 47 locations which had been in place for 3 to 5 years, PennDOT reported a B/C of 14.28 for all crashes and 8.97 for wet road crashes using crash costs associated with the KABCO scale, and 5.5 for all crashes and 2.04 for wet road when just considering fatal and various levels of injury crashes (PennDOT 2018; Hershock 2020). This is perhaps the most granular B/C ratio evaluation as PennDOT used actual HFST cost data for the analysis.

KYTC documents HFST B/C ratios on an annual basis in the HSIP Annual Report. While initial years revealed very promising B/C ratios from 9 to 44, after 2 years of lower B/C ratios (less than 4), KYTC reevaluated their site selection process to ensure that non-friction-related crashes were filtered out for the network screening. This refinement of their site selection process has led to B/C > 30 for the past 2 years.

FDOT has reported an average 5-year B/C ratio of 24.5 on tight curves using the KABCO method, but no calculable B/C for wide curves and intersections (FDOT 2021).

Louisiana DOTD, which implemented a systemic deployment reported a B/C ratio of 0.5. This is not entirely unexpected for systemic deployment of HFST as the crash reduction benefits may take many years to be fully realized and Louisiana DOTD analysis is based on less than 3 years of after period crash data.

The FHWA study on CMFs for HFST reported B/C ratios for HFST for curve and ramp locations based on treatments in six States. Using an assumed conservative unit cost of $35/SY for HFST, and very conservative service life of five years, B/C ratios ranged from 6.00 for curves to 18.74 for ramps based on the crash reduction computed from an EB before-after evaluation (Merritt et al. 2020b). Actual B/Cs for many of these locations would likely be much higher with a lower unit cost and longer service life.

B/C ratios should ideally be calculated using the most accurate cost data available, preferably actual cost data if the evaluation is performed on a project already in place. Crash costs, likewise, should be calculated based on the most accurate crash data which differentiates fatal, injury (including various levels of injury crashes), and property damage only crashes. If an agency does not have defined crash unit costs, national crash unit costs (based on KABCO scale) are available (Harmon et al. 2018). Realistic service life estimates should also be used, particularly when comparing HFST to an alternative countermeasure. As discussed previously, a service life of at least 7 to 10 years can be expected from a properly installed HFST.

Tools such as FHWA's Highway Safety Benefit-Cost Analysis spreadsheet and TCMS program (Pratt et al. 2018a) can be used for B/C ratio computation. The TCMS tool will compute B/C ratios specifically for different types of friction treatment on curves, including HFST, using predictive models for crash frequency based on change in pavement friction. As with any evaluation, B/C ratios should be continually verified with actual performance data and refined as needed.

8.3 FUNDING

HFST qualifies for Federal funding under the HSIP, which is geared toward reducing fatalities and serious injuries on all public roads. Historically, FHWA has matched HFST project costs through a 90/10 split utilizing HSIP funds. While each State's process varies, local agencies can apply to receive funding for HFST projects within their jurisdiction.

CHAPTER 9—CONCLUSION

HFST is a highly-effective safety countermeasure for reducing both wet and dry friction-related crashes. When applied at appropriately selected locations and installed properly, exceptional B/C ratios can be realized. The majority of HFST installations are on curves and ramps, but a number of agencies are also implementing HFST at intersection locations. Summarized below are key practices based on successful implementation of HFST in the United States.

Site Selection—Site-specific (crash history) approaches to site selection will provide the most immediate benefit in terms of crash reduction. However, systemic deployment of HFST should also be considered as a necessary strategy to help address the rare and random friction-related crashes on rural roadways. Predictive methodologies using SPFs and EB, and margin-of-safety analysis are data-driven methods for site selection which are readily available. Several high-quality CMFs are available for curve and ramp HFST sites. Verification of candidate locations through field reviews and friction testing will help ensure HFST is applied at appropriate locations and that all issues related to project design and cost are addressed.

Materials and Specifications—There is an excellent understanding of HFST material properties that will help ensure long-term performance. Critical properties of polymer resin binders have been identified and research continues to improve and establish appropriate limits for these properties. Although many alternative aggregate materials have been evaluated, only calcined bauxite has a demonstrated track record of providing exceptional skid resistance, maintained over the life of the HFST. AASHTO as well as a number of agencies with mature HFST programs have developed specifications which others can use as guidance to develop a specification.

Installation and Inspection—There is an excellent understanding of HFST installation practices and inspection procedures that will help to eliminate premature failure of HFST due to improper installation. Training of inspectors is a key element to a successful installation.

Performance Monitoring—HFST performance should be continually monitored through regular evaluations of safety performance, regular friction testing, and regular monitoring of treatment condition. Performance monitoring will help agencies further refine site selection processes and installation specifications. PFMPs are an important tool for HFST deployment as they can help identify areas of deficient friction such that they can be treated proactively before crashes occur, as well as to monitor HFST friction performance over time.

The agencies which have realized the greatest benefit from HFST deployment as a safety countermeasure:

- Utilize data-driven approaches for HFST site selection. These data-driven approaches utilize statistically rigorous predictive methodologies such as SPFs and EB to identify and prioritize treatment locations.
- Perform friction testing and project-level reviews of candidate installation locations to ensure each location is suitable for installation.

- Bundle multiple installations in a single contract and/or utilize on-call contracting mechanisms to reduce unit cost of deployment.
- Require the use of advanced installation methods such as fully-automated systems to ensure proper conditioning, proportioning, and blending of resin binder materials, uniform application of resin binder to the specified mil thickness, and timely and uniform application of aggregate to the resin binder.
- Continually monitor the performance of existing installations to document both safety performance and functional performance for the purposes of improving deployment programs.
- Regularly review and update the B/C ratio of existing HFST installations for the purpose of improving the efficiency of HFST deployment.
- Regularly review and revise as needed the site selection practices as well as materials and installation specifications to continue to optimize deployment of HFST.
- Do not compromise on HFST material quality or performance requirements for the sake of reducing cost.

CHAPTER 10—ADDITIONAL RESOURCES

FHWA Frequently Asked Questions for HFST
https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/faqs_links_other/hfst_faqs/

FHWA Technical Advisory for Pavement Friction Management (T 5040.38)
https://www.fhwa.dot.gov/pavement/t504038.cfm

FHWA Office of Safety HFST website
https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/high_friction/

FHWA/ATSSA Videos
6 min. version: https://www.youtube.com/watch?v=HVzS-VkABPE
20 min. version: https://www.youtube.com/watch?v=V860pC6ncAY

ATSSA HFST Technical Services
https://www.atssa.com/Technical-Services/High-Friction-Surface-Treatment

ATSSA HFST Inspection and Installation Training Course
https://www.atssa.com/Training/Find-a-Course/High-Friction-Surface-Treatment-Inspection-and-Installation#/qbeld/Web_HFS_Events

Pennsylvania DOT HFST Videos
https://www.youtube.com/watch?v=YE5N8WiAp24
https://www.youtube.com/watch?v=Sn34DAynjCE

Oklahoma DOT HFST Video
https://www.youtube.com/watch?v=gWajb4Vz38Q

Florida DOT High Friction Surface Treatment Guidelines
https://www.fdot.gov/docs/default-source/materials/pavement/performance/ndt/documents/hfstguidelines.pdf

APPENDIX A: OTHER POTENTIAL HFST APPLICATIONS

Summarized below are some non-conventional but viable applications for HFST. Case studies are also highlighted for these applications when available.

HFST AS AN ALTERNATIVE TO GEOMETRIC MODIFICATIONS

Friction demand can be reduced with roadway geometric modification such as increasing superelevation or reducing curve radius. However, these modifications may be cost prohibitive or not even possible due to site constraints (environmental restrictions, right-of-way limitations, etc.). HFST offers a lower-cost solution for increasing pavement friction supply to counteract higher friction demand at these locations.

In 2012 Caltrans installed HFST on a curve along US 199 in Del Norte County as an alternative to curve realignment after they had not seen the desired crash reduction from multiple safety countermeasures (figure 54). Installation of HFST saved at least 2 to 5 years of total project time which would have been required for curve realignment (due to design and environmental review), saved nearly 6 months of construction time (along with a 100 mile detour during construction), and potentially saved nearly $14 million in total project cost. Crashes decreased from approximately nine crashes per year to no crashes since installation (FHWA 2015).

Source: FHWA

Figure 54. Photograph. Example of HFST as an alternative to curve realignment (FHWA 2015).

HFST AS AN ALTERNATIVE TO INCREASED ROADSIDE CLEAR ZONES

Roadside clear zones help to reduce crash severity or the consequences of RwD crashes. Tree removal is a common requirement in increase clear zones. However, environmental concerns may not allow for tree removal at all locations. HFST provides a lower-cost treatment that can help to prevent RwD crashes and the associated consequences from roadside obstacles at these locations.

PennDOT used HFST for this particular application after they determined it was not possible to remove mature, culturally-significant trees that were contributing to crashes due to shielding of the roadway along Route 147 in Dauphin County. HFST was applied to help keep vehicles on the roadway, rather than removing the trees. In the 4 years since HFST was applied, fatal and injury crashes were completely eliminated.

HFST FOR TANGENT APPLICATIONS

In some instances, HFST may be a solution to inadequate friction on tangent roadway sections. In Illinois, for example, a tangent section of Interstate 74 had a very high percentage (77 percent) of RwD crashes highway, with more than 50 percent being tractor trailer semis, and more than 50 percent of the crashes occurring under wet conditions. Illinois DOT determined that high crosswinds were causing semi-trucks to lose control, and inadequate pavement friction reduced the ability of these vehicles to regain control. HFST was applied to this tangent section of interstate, dramatically reducing crashes. In the five years prior to HFST application, there were eight passenger vehicle and 50 tractor trailer semi-truck crashes involving slick pavement and/or strong crosswinds. In the nearly four years following HFST application, there were six passenger vehicle crashes but zero tractor trailer crashes involving slick pavements and/or wind.

HFST FOR TUNNELS

Tunnels offer little margin for error for RwD crashes, and HFST offers a solution to help keep vehicles in their lane. While wet-weather crashes would not be expected in a tunnel unless a drainage problem existed, a decrease in friction over time would not be unexpected as oil and rubber deposits that are normally washed away with precipitation will continue to accumulate unless the surface is regularly washed. While there is no published information on the benefits of HFST for crash reduction in tunnels, a noted benefit of a buff-colored calcined bauxite used for HFST in tunnels in Germany is improved visibility in tunnels due to the lighter-colored pavement surface reflecting vehicle and tunnel lighting (figure 55 and figure 56).

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Figure 55. Photograph. Example of HFST used for tunnel application.

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Figure 56. Photograph. Example of light reflectance off of a light-colored HFST tunnel.

HFST FOR STEEP GRADES

Steep downhill grades, particularly at intersection approaches are key applications with high friction demand. The City of Bellevue, Washington applied HFST to a curved downhill intersection approach in 2004 to reduce crashes attributed to grade, skidding, and driving too fast for conditions (figure 57). After applying HFST, crashes decreased by 78 percent and costs associated with crashes by 83 percent (FHWA 2016).

Figure 57. Photograph. HFST application for steep grade at intersection approach (FHWA 2016).

Source: FHWA

COLORED SURFACES

Colored pavement surfaces are another application where HFST or a similar thin polymer overlay can be utilized. Colored pavement surfaces are typically used for demarcation purposes and may require FHWA approval if used for an application not included in the Manual of Uniform Traffic Control Devices (MUTCD). Depending on the application, these surfaces may or may not have the same level of friction demand as typical HFST applications for curves, ramps, and intersections. To achieve the desired color, tinted resin binder and/or dyed aggregate can be used, or alternatively, aggregates with natural coloration (e.g., red granite). Resin binder materials and installation methods are generally similar to conventional HFST, with the exception of overlay materials where the resin binder and aggregate are mixed together before application. Color-fastness of these surfaces under UV exposure is critical for ensuring they will continue to provide the intended demarcation over the life of the treatment. Some examples colored surface applications include:

- Lane Demarcation (figure 58 thru figure 62)
- Bicycle Lanes (figure 63)
- Pedestrian Crossings (figure 61)
- Railroad Crossings (figure 64)

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Figure 58. Photograph. Lane demarcation with two colors of polymer overlay.

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Figure 59. Photograph. Example of HFST used for demarcation at an intersection approach.

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Figure 60. Photograph. Example of HFST used for bus lane demarcation.

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Figure 61. Photograph. Example of HFST used for pedestrian crossing.

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Figure 62. Photograph. Example of HFST used for roundabout demarcation.

© DBi

Figure 63. Photograph. Green bicycle lane application.

© Traffic Calming USA

Figure 64. Photograph. Railroad crossing application.

Bridge decks were the original application for HFST in the United States, dating back to the 1950s (Cheung and Julian 2016). Typically referred to as thin or multi-layer polymer overlays or broom and seed overlays, applications to bridge decks serve two purposes: to seal and preserve bridge decks from chloride ingress, and to increase friction on surfaces which will freeze before the surrounding pavement in colder climates. Bridge decks are not necessarily considered locations with high friction demand, unless they are part of a curved ramp or overpass. As such, the frictional properties are less critical for this application and alternative aggregates such as flint, granite, taconite, slag, etc. are typically used. However, the resin binder materials and processes used to apply bridge deck overlays are the same. It is not uncommon for a double-layer application to be used as well (figure 65).

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Figure 65. Photograph. Manual application of HFST to bridge deck.

STEEL PLATE TRENCH COVERS

Steel plates used to cover trenches from utility cuts in the pavement surface can be very slick, particularly in wet conditions. Many times, these plates are used in or near intersections where friction demand is high with vehicle braking. Many agencies require that these plates have a skid-resistant surface. The New York City DOT, for example, specifically requires that, "All plating and decking shall have a skid-resistant surface equal to or greater than the adjacent existing street or roadway surface. The whole surface area of all plating and decking must be skid-resistant." (NYCDOT 2019). MoDOT, likewise, requires that steel plates used for trench covers be treated for skid resistance using either surface deformation or from a friction course (MoDOT 2021).

While there are no known studies on safety impacts of skid resistant surfaces on trench plates, HFST provides a simple solution. Most common HFST resin binder materials should adhere well to properly prepared (e.g., sandblast/shotblast) steel plates (figure 66).

© Heaton Manufacturing

Figure 66. Photograph. HFST with calcined bauxite on steel trench plates (Heaton Manufacturing n.d.).

APPENDIX B: EXAMPLES OF SYSTEMIC DEPLOYMENT OF HFST

Four examples of criteria used for systemic deployment of HFST are described below. It should be noted that most agencies will typically apply more than one countermeasure at these locations. As such, an evaluation of the effectiveness of HFST (by itself) in reducing rural roadway curve crashes can be very difficult.

LOUISIANA

Louisiana DOTD used a statewide systemic approach for HFST deployment beginning in 2015. The target roadway classification was two-lane rural roads which accounted for 43 percent of fatalities from 2010 to 2012 and the target crash type was RwD crashes which accounted for nearly 90 percent of the fatalities (McRae 2020). Risk factors identified for site selection included:

- Traffic (AADT): 2,500 to 7,500 vehicles per day.
- Lane width: 12 ft or greater.
- Shoulder width: 2 to 6 ft.
- Degree of curvature: > 3.5 (radius < 1,640 ft).

Based on these criteria, 282 curves were initially identified statewide for safety improvements including HFST and other low-cost countermeasures. HFST was ultimately installed on roughly 150 curves statewide, playing a key role in countermeasure deployment. A formal before-after analysis has not yet been completed to assess the effectiveness of this approach with respect to crash reduction.

GEORGIA

Georgia DOT used a systemic approach to HFST deployment beginning in 2014. Georgia DOT's two-step process began with identification of roadway corridors with a high number of segments with a high severity index which represents the average damage (based on fatal and serious injury crashes) resulting from crashes along the corridor. The second step was to collect ball bank measurements (at posted speed) on all curves along the selected corridor segments, and to identify any curve with a BBI value greater than 12 for treatment (Tsai et al. 2018). The majority of corridors selected for HFST installation through this process were rural two-lane roads.

Georgia DOT is currently refining their site selection process, moving away from a systemic process using BBI values towards a more systemic data-driven process utilizing automated roadway data collection methods to identify HFST candidates based on roadway characteristics. A thorough before-after analysis of Georgia DOT's initial systemic deployment of HFST has not yet been completed.

THURSTON COUNTY

Thurston County in Washington State utilized a systemic approach to HFST deployment for reducing RwD crashes on local roads. HFST candidate sites were identified from 0.2-mile roadway sections with more than three skidding/out-of-control crashes under wet and icy conditions. Risk factors were used to rank candidate sites for potential treatment, and included (Torbic et al. 2020, Tsai et al. 2018):

- Roadway class: arterial and collector roads.
- Posted speed of 50 mph.
- Traffic volume of 5,000 to 8,000 AADT (high confidence), 3,000 to 5,000 AADT (low confidence).
- Paved shoulders 4 or 8 ft in width or native shoulders of 2, 3, 7, or 8 ft in width,
- Presence of a vertical curve.
- Consecutive horizontal curves.
- Speed differential between posted speed and curve advisory speed of 0, 5, and 10 mph.
- Presence of a visual trap (i.e., a minor road on the tangent extended).

DELAWARE

Delaware DOT implemented a systemic site selection process after a successful HFST demonstration project in 2013. Delaware DOT used this process to address RwD crashes which accounted for 47 percent of all fatal crashes. The target roadway classification was collector and local roadways and the target crash type was wet weather RwD crashes at curves. For the initial installation, Delaware treated 15 high crash curves. In 2016, Delaware treated an additional eight locations. Preliminary results from these 23 locations indicated that RwD crashes decreased at 83 percent of the locations by an overall average of 56 percent (Americas Transportation Awards n.d.).

APPENDIX C: HFST INSPECTION CHECKLIST

Item	Item description	Status
1. Pre-Construction		
1.1	Review contractor Quality Control Plan (QCP) to verify requirements for: a) Test strip and full-scale/production of HFST placement schedule (if test strip is to be completed separately). b) Description of equipment for placing HFST. c) Methods for conditioning, metering, blending, and applying resin binder. d) Methods for applying aggregate, including timing of placement onto resin binder. e) Methods for monitoring and documenting material usage. f) Method for protecting areas that will not receive HFST. g) Description of acceptable environmental conditions (temperature and precipitation) for placing HFST. h) Cure time and time to opening to traffic estimates for HFST. i) Storage and handling of HFST materials. j) Disposal and recycling of excess HFST and containers. k) Contingency plan for possible failure during the HFST application. l) Name of the certified independent testing laboratory. m) Key personnel and contact information. n) All project certifications and test results.	
1.2	Verify name and contact information for contractor QCP administrator.	
1.3	Check that materials supplied to the project meet specification requirements (through agency testing or from certified test results from the installer).	
1.4	Verify that a resin binder manufacturer's representative is present for initial/test strip installation.	
2. Materials		
2.1	Check that resin binder is type and brand specified in the QCP.	
2.2	Check that aggregate material is type and brand specified in QCP.	
2.3	For reclaimed aggregate only: verify that reclaimed material had been blended with new/virgin material at the specified ratio (e.g., two parts new to one part reclaimed).	
2.4	Check resin binder and aggregate stockpiles to verify proper packaging and storage of materials.	
2.5	Check that aggregate is clean (minimal dust content and no foreign materials) and dry (subjective assessment).	
2.6	Check that adequate quantities of resin binder and aggregate materials for the intended installation area are on-site or accessible near the project site.	
2.7	Sample materials for verification testing on-site as required by specification.	

Item	Item description	Status
3. Surface Preparation		
3.1	Check that all distresses identified for pre-treatment in the project plans have been addressed.	
3.2	Check that all striping and pavement markings have been removed or masked as required in project plans and specifications.	
3.3	Check that all drainage inlets, manhole and valve covers, and other utilities and structures have been masked as required in project plans and specifications.	
3.4	Shotblasting: Verify that surface has been shotblast to concrete surface profile (CSP) of 5, as required in project specifications, followed by compressed air wash.	
3.5	Check that entire surface has been cleaned with a mechanical sweeper and/or a compressed air wash as required in the project plans.	
3.6	Check that all pavement surfaces to be covered with HFST are dry and free of oils, grease, dust (including latent dust from shotblasting) and foreign material prior to HFST placement.	
4. Pre-Application		
4.1	Verify test strip placement procedure (i.e., separate test strip or as part of initial production installation).	
4.2	Check that equipment for placing HFST is as outlined in the QCP.	
4.3	Document width of placement based on installation vehicle setup.	
4.4	Check for masked-off areas at beginning and end of placement to ensure clean termination joints.	
4.5	Verify that resin binder metering devices are fully functional.	
4.6	Document ambient and surface temperatures at start and end of application (minimum) and routinely throughout application if necessary.	
5. Resin Binder Application		
5.1	Check for changes in coloration and consistency of resin binder throughout application.	
5.2	Check uniformity of resin binder film across the lane (e.g., no gaps or tearing of the film or variations in thickness).	
5.3	Check thickness of resin binder on pavement surface as it is placed using a mil thickness gage as required in project specifications.	

Item	Item description	Status
5.4	Document total quantity of material used from metering devices on installation vehicle. Verify if quantity of material used corresponds to anticipated quantity based on placement area and mil thickness requirement.	
5.5	Manual application of small areas: a) Check that resin binder is properly proportioned and thoroughly blended before being deposited on pavement surface. b) Check that resin binder is spread with notched squeegees to the required, uniform thickness over the placement area. c) Check that resin binder is not sheeting or running across the lane or down the pavement grade before aggregate is applied. d) Check that no foot traffic other than spiked shoes are allowed on uncovered resin binder.	
5.6	Check that no vehicular traffic is allowed onto the surface prior to curing of the resin binder.	
6. Aggregate Application		
6.1	Check that aggregate is applied onto the resin binder within the time required in the project specifications.	
6.2	Check that aggregate is applied in a manner that it does not disturb the resin binder	
6.3	Check for dryness and cleanliness (substantially free of dust and foreign matter) of aggregate as it is deposited.	
6.4	Check for uniformity of placement across the lane.	
6.5	Check for aggregate placement until refusal over resin binder.	
6.6	Check that any exposed resin binder and "wet" areas that appear are covered.	
6.7	Document total quantity of material used from installer records. Verify if quantity of material used corresponds to anticipated quantity based on placement area.	
6.8	Manual Placement of small areas: a) Check that aggregate is deposited onto the exposed resin binder within the time required in the project specifications. b) Check that aggregate is broadcast such that it does not disturb the resin binder.	
7. Aggregate Removal		
7.1	Check that resin binder has reached adequate cure prior to sweeping (verify that resin binder is not soft and that aggregate does not pull out of resin binder).	
7.2	Document timing of aggregate removal with respect to completion of HFST placement.	

Item	Item description	Status
7.3	Check that aggregate removal using a vacuum or power brooms is not damaging the HFST surface and exposing the underlying pavement.	
7.4	Check that surface is free of loose aggregate after completion of all aggregate removal.	
7.5	Check for and document any areas where underlying pavement is exposed after aggregate removal.	
8. Opening to Traffic and Acceptance Testing		
8.1	Check for any remaining loose aggregate.	
8.2	Check for any "soft" areas in the HFST surface where resin binder may not have fully cured.	
8.3	Check for and document any discolored areas in HFST surface.	
8.4	Check for and document any areas where HFST is missing and needs to be patched.	
8.5	Check for replacement of pavement markings (temporary or permanent) as required in the project plans and specifications.	
8.6	Verify that masking has been removed from drainage inlets, manhole and valve covers.	
8.7	Check for loose aggregate on any adjacent untreated lanes and paved shoulders, and untreated pavement before and after the treated area.	
8.8	Verify the plan for acceptance testing and check that acceptance testing is performed in accordance with project specifications.	
8.9	Check acceptance testing result for conformance with specification requirements.	
9. Post-Installation		
9.1	Monitor aggregate shedding over the first several days after installation and note any excessive build-up of loose aggregate within the treated lanes or on adjacent surfaces. Ensure loose aggregate is promptly removed if it presents a safety hazard.	
9.2	Check that surface is re-swept within two weeks after initial placement to remove loose aggregate.	
9.3	Monitor the HFST surface for discoloration, delamination, cracking, and other distresses.	

REFERENCES

AASHTO. (n.d.) National Transportation Product Evaluation Program website. https://ntpep.transportation.org/, last accessed May 1, 2021.

AASHTO. (2008). *Guide for Pavement Friction*. Washington, D.C.

AASHTO. (2018a). *A Policy on Geometric Design of Highways and Streets*. Washington, D.C.

AASHTO. (2018b). *Standard Method of Test for Frictional Properties of Paved Surfaces Using a Full-Scale Tire*. AASHTO T 242-18. Washington, D.C.

AASHTO. (2019). *Standard Specification for High Friction Surface Treatment for Asphalt and Concrete Pavements using Calcined Bauxite*. MP 41-19. Washington, D.C.

America's Transportation Awards. (n.d.). "Delaware Department of Transportation -High Friction Surface Treatment". https://americastransportationawards.org/delaware-department-of-transportation-high-friction-surface-treatment/, last accessed May 1, 2021.

ATSSA. (n.d.). *High Friction Surface Treatment Inspection and Installation Training Course*. American Traffic Safety Services Association. https://www.atssa.com/Training/Find-a-Course/High-Friction-Surface-Treatment-Inspection-and-Installation#/qbeld/Web_HFS_Events, last accessed October 29, 2020.

ASTM. (2015). *Standard Test Method for Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus*. ASTM D7428-15. ASTM International. West Conshohocken, PA.

ASTM. (2015b). *Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth*. ASTM E1845-15. ASTM International. West Conshohocken, PA.

ASTM (2016). *Standard Test Method for Thermal Compatibility Between Concrete and an Epoxy-Resin Overlay*. ASTM C884/C884M-16. ASTM International. West Conshohocken, PA.

ASTM (2017). *Standard Practice for the Accelerated polishing of Aggregates using the British Wheel.* ASTM D 3319-11 (2017). ASTM International. West Conshohocken, PA.

ASTM. (2018a). *Standard Test Method for Indicating Moisture in Concrete by the Plastic Sheet Method*. ASTM D4263-83(2018). ASTM International. West Conshohocken, PA.

ASTM. (2018b). *Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester*. ASTM E303-93. ASTM International. West Conshohocken, PA.

ASTM. (2019a). *Standard Test Method for Measuring Surface Frictional Properties Using the Dynamic Friction Tester*. ASTM E1911-20. ASTM International. West Conshohocken, PA.

ASTM. (2019b). *Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique*. ASTM E965-15. ASTM International. West Conshohocken, PA.

ASTM. (2020a). *Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Lose Angeles Machine*. ASTM C131/C131M-20. ASTM International. West Conshohocken, PA.

ASTM. (2020b). *Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire.* ASTM E274/E274M-15. ASTM International. West Conshohocken, PA.

ASTM. (2020c). *Standard Test Method for Tensile Strength of Concrete Surfaces and the Bond Strength or Tensile Strength of Concrete Repair and Overlay Materials by Direct Tension (Pull-off Method).* ASTM C1583/C1583M-20. ASTM International. West Conshohocken, PA.

ASTM. (2020d). *Standard Test Method for X-ray Spectrometric Analysis of Lime and Limestone.* ASTM C1271-99. ASTM International. West Conshohocken, PA.

ASTM. (2021). *Standard Guide for Elemental Analysis by Wavelength Dispersive X-Ray Fluorescence Spectrometry.* ASTM E1621-21. ASTM International. West Conshohocken, PA

Atkinson, J., Clark, J., and Ercisli, S. (2016). *High Friction Surface Treatment Curve Selection and Installation Guide*. Federal Highway Administration FHWA Report No. FHWA-SA-16-034. Washington, D.C.

BBA. (2017). *Guidelines Document for the Assessment and Certification of High-Friction Surfacing for Highways*. British Board of Agrément.

Bonneson, J., Pratt, M., Miles, J., and Carlson, P. (2007). Development of Guidelines for Establishing Curve Advisory Speeds. Texas A&M Transportation Institute Research Report No. FHWA/TX-07/0-5439-1. College Station, TX.

Brimley, B. and Carlson, P. (2012). *Using High Friction Surface Treatments to Improve Safety at Horizontal Curves*. Texas A&M Transportation Institute. College Station, TX.

Carter, D., Srinivasan, R., Gross, F., and Council, F. (2012). Recommended Protocols for Developing Crash Modification Factors. TRB, Washington DC.

Cheung, J. and Julian, F. (2016). "'Curve' Appeal: High Friction Surface Treatments Key to Safer Pavements." *Pavement Preservation Journal*, Vo. 9, No. 2. Okemos, MI.

Davis, S. (2014). "High Friction Surface Site Selection Analysis." EDC Exchange for Local and Tribal Agencies, Washington, D.C.

de León Izeppi, E. D., Flintsch, G. W., and McGhee, K. K. (2010). *Field Performance of High Friction Surfaces*. VTRC Report 10-CR6. Virginia Department of Transportation. Richmond, VA.

de León Izeppi, E., Katicha, S. W., Flintsch, G. W., and McGhee, K. K. (2016a). Pioneering use of continuous pavement friction measurements to develop safety performance functions, improve crash count prediction, and evaluate treatments for Virginia roads. *Transportation Research Record*, *2583*, pp. 81–90, Washington, D.C.

de León Izeppi, E. D. L., Katicha, S. W., Flintsch, G. W., Mccarthy, R., and McGhee, K. K. (2016b). *Continuous Friction Measurement Equipment As a Tool for Improving Crash Rate Prediction: A Pilot Study*. VTRC Report 16-R8. Virginia Department of Transportation. Richmond, VA.

de León Izeppi, E. de L., Flintsch, G., Katicha, S., McGhee, K., McCarthy, R., and Smith, K. (2019). Pavement *Friction Management Program utilizing Continuous Friction Measurement Equipment and State-of-the-Practice Safety Analysis Demonstration Project – Final.* Federal Highway Administration Report No. FHWA-RC-20-0009. McLean, VA.

Donnell, E., Porter, R., Lingyu, L., Hamilton, I., Himes, S., and Wood, J. (2019). *Reducing Roadway Departure Crashes at Horizontal Curve Sections on Two-lane Rural Highways*. Federal Highway Administration Report No. FHWA-SA-19-005. Washington, D.C.

Eluri, Z. (2018) *Modified Micro-Deval Procedure for Polishing of Fine Asphalt Mix Aggregates*. Research Report No. FHWA-ICT-18-006. Illinois Center for Transportation. Urbana, IL.

FDOT. (2017). *High Friction Surface Treatment*, Developmental Specification Section 333. Florida Department of Transportation. Gainesville, FL

FDOT. (2021). *High Friction Surface Treatment Guidelines*, Project Selection, Materials, and Construction. Florida Department of Transportation. Gainesville, FL, https://www.fdot.gov/docs/default-source/materials/pavement/performance/ndt/documents/hfstguidelines.pdf, last accessed June 10, 2021.

FHWA. (n.d.). "Focus on Reducing Rural Roadway Departures", https://safety.fhwa.dot.gov/FoRRRwD/index.cfm, last accessed May 1, 2021.

FHWA. (2015). A Life-Saving and Cost Effective Solution for an Environmentally Sensitive Location. Federal Highway Administration, FHWA-SA-15-055, Washington, D.C. https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/nocal/, last accessed June 10, 2021.

FHWA. (2016). "Pavement Friction", https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/, last accessed June 10, 2021.

FHWA. (2019). *2019 Noteworthy Practices Guide*. Federal Highway Administration. Washington, D.C.

FHWA (2020a). High Friction Surface Treatment at Intersections. Federal Highway Administration FHWA-SA-20-012. Washington, D.C.

FHWA. (2020b). "Roadway Departure Safety", https://safety.fhwa.dot.gov/roadway_dept/, last accessed October 4, 2021.

FHWA. (2020c). *The Safe System Approach*. Federal Highway Administration FHWA-SA-20-015. Washington, D.C.

FHWA. (2021a). "CMF Clearinghouse". http://www.cmfclearinghouse.org/, last accessed June 10, 2021.

FHWA. (2021b). "Continuous Pavement Friction Measurement (CPFM)", https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/cpfm/, last accessed July 14, 2021.

FHWA. (forthcoming). *HFST Installation and Inspection Guide*. Federal Highway Administration. Washington, D.C.

Glennon, J., and Weaver, G. (1971). *The Relationship of Vehicle Paths to Highway Curve Design*. Research Report 134-5. Texas Transportation Institute, College Station, Texas, 1971.

Gross, F. (2017, May). Highway Safety Improvement Program (HSIP) Evaluation Guide. FHWA FHWA-SA-17-039. Washington, D.C.

Gross, F., Harmon, T., Bahar, G., and Peach, K. (2016). *Reliability of Safety Management Methods: Systemic Safety Programs*. Federal Highway Administration Research Report No. FHWA-SA-16-041, Washington, D.C.

Gross, Frank, Persaud, B., and Lyon, C. (2010). A Guide to Developing Quality Crash Modification Factors. FHWA-SA-10-032. FHWA, Washington, DC.

Harkey, D., Srinivansan, R., Baek, J., Council, F., Eccles, K., Lefler, N., Gross, F., Persaud, B., Lyon, C., Hauer, E., and Bonneson, J. (2008). *Accident Modification Factors for Traffic Engineering and ITS Improvements*. NCHRP Report 617. National Academies of Sciences, Engineering, and Medicine. Washington, DC, http://www.trb.org/Publications/Blurbs/156844.aspx, last accessed June 10, 2021.

Harmon, T., G. Bahar, & F. Gross. (2018). *Crash Costs for Highway Safety Analysis*. Report No. FHWA-SA-17-071. Federal Highway Administration, Washington, D.C.

Heaton Manufacturing. (n.d.). “Steel Road Plates”. https://heatonmanufacturing.co.uk/steel-road-plates/, last accessed June 11, 2021.

Heitzman, M., Turner, P., and Greer, M. (2015). *High Friction Surface Treatment Alternative Aggregates Study*, NCAT Report 15-04. National Center for Asphalt Technology at Auburn University. Auburn, AL.

Heitzman, M. and Moore, J. (2017). *Evaluation of Laboratory Friction Performance of Aggregates for High Friction Surface Treatments*. NCAT Report 15-04. National Center for Asphalt Technology at Auburn University. Auburn, AL.

Hershock, J. (2020). *High Friction Surface Treatments in Pennsylvania – Keeping You on the Road*. FHWA Webinar: FoRRRwD Countermeasures: High Friction Surface Treatment (HFST) and Continuous Pavement Friction Measurement (CPFM).

Highways England (2019). *Manual of Contract Documents for Highway Works*, Volume 1 Specification for Highway Works. Series 900, Clause 924. Highways England. United Kingdom.

Highways England. (2020). *Surface Course Materials for Construction*. CD 236, Revision 4. Highways England. United Kingdom.

Li, S., Cong, P., Yu, D., Xiong, R., and Jiang, Y. (2019). Laboratory and Field Evaluation of Single Layer and Double Layer High Friction Surface Treatments. *Proceedings of the TRB 2019 Annual Meeting*. Transportation Research Board. National Academy of Sciences. Washington, D.C.

Li, S., Xiong, R., Yu, D., Zhao, G., Cong, P., and Jiang, Y. (2017). *Friction Surface Treatment Selection: Aggregate Properties, Surface Characteristics, Alternative Treatments, and Safety Effects*, JTRP Technical Report FHWA/IN/JTRP-201/09. Indiana Department of Transportation. Indianapolis, IN.

Lyon, C., Persaud, B., Merritt, D., and Cheung, J. (2020). Empirical Bayes Before-After Study to Develop Crash Modification Factors and Functions for High Friction Surface Treatments on Curves and Ramps. *Transportation Research Record*. Transportation Research Board. National Academy of Sciences.

McGee, H.W. (2018). *Practices for Preventing Roadway Departures*. NCHRP Synthesis 515. National Academies of Sciences, Engineering, and Medicine. Washington, DC.

McRae, A. (2020, December). *Louisiana Roadway Departure Implementation Plan*. FHWA Webinar: Moving FoRRRwD with Safety Action Plans: Statewide, Regional, and Local.

Merritt, D. K., Tallon, R., and Watson, R. P. (2020a). *Developing Crash-Modification Factors for High-Friction Surface Treatments: Friction Change Report*. Federal Highway Administration FHWA Research Report FHWA-HRT-20-062. McLean, VA.

Merritt, D. K., Lyon, C. A., Persaud, B. N., and Torres, H. N. (2020b). *Developing Crash-Modification Factors for High-Friction Surface Treatments*, Federal Highway Administration FHWA Research Report FHWA-HRT-20-061. McLean, VA.

MoDOT (2021). *Engineering Policy Guide, Section 616.6 Temporary Traffic Control Zone Devices (MUTCD 6F)*. Missouri Department of Transportation. Jefferson City, MO.

National Center for Statistics and Analysis. (2020, December). *Summary of Motor Vehicle Crashes in 2019*. National Highway Traffic Safety Administration, Report No. DOT HS 813 060, Washington, D.C.

Nevada DOT. (n.d.). Nevada Department of Transportation Research Problem Statements, https://www.nevadadot.com/Home/ShowDocument?id=16121, last accessed October 29, 2020.

NYCDOT. (2019) *Highway Rules, Section 2-11, "Street Openings and Excavations."* New York City Department of Transportation. Title 34, Chapter 2, Rules of the City of New York.

NHTSA. (2021, March). "Fatality and Injury Report System Tool", https://cdan.dot.gov/query, last accessed June 10, 2021.

NZTA. (2011). *Pilot Specification for Calcined Bauxite*. Specification SP/SPP25.

PennDOT. (2012). *Pennsylvania Roadway Departure*.

PennDOT. (2018). *High Friction Surface Treatment – Benefit/Cost 2018*. Highway Safety Section, Department of Transportation, Bureau of Maintenance and Operations.

PennDOT. (2019). *High Friction Surface Treatment Usage Guide*. Pavement Policy Manual, May 2015 Edition, Change No. 5. Publication 242, Appendix I.

Pratt, M. P., Geedipally, S. R., Pike, A.M., Carlson, P.J., Celoza, A.M., Lord, D. (2014). *Evaluating the Need for Surface Treatments to Reduce Crash Frequency on Horizontal Curves*. Texas A&M Transportation Institute Research Report No. FHWA/TX-14/0-6714-1. College Station, TX.

Pratt, M. P., Geedipally, S. R., Wilson, B., and Lord, D. (2018a). *Guidelines and Evaluation Framework for Horizontal Curve Wet-Surface Safety Analysis: A User Guide*. Texas A&M Transportation Institute Research Report No. FHWA/TX-18/0-6932-P1. College Station, TX.

Pratt, M. P., Geedipally, S. R., Wilson, B., Das, S., Brewer, M., and Lord, D. (2018b). *Pavement Safety-Based Guidelines for Horizontal Curve Safety*. Texas A&M Transportation Institute Research Report No. FHWA/TX-18/0-6932-R1. College Station, TX.

Pratt, M. P., Geedipally, S. R., Avelar, R.E., and Le, M. (2020). *Horizontal Curve Evaluation Handbook*. Texas A&M Transportation Institute Research Report No. FHWA/TX-18/0-6960-P1. College Station, TX.

Preston, H., Storm, R., Bennett, J., and Wemple, B. (2013). *Systemic Safety Project Selection Tool*. Federal Highway Administration Report No. FHWA-SA-13-019. Washington, D.C.

RSTA ADEPT. (2017). *Code of Practice for High Friction Surfacing*, 2nd Edition. Road Surface Treatment Association. United Kingdom.

Srinivasan, R., Carter, D., and Bauer, K. (2013). *Safety Performance Function Decision Guide: SPF Calibration vs SPF Development*. Federal Highway Administration Report No. FHWA-SA-14-004. Washington, D.C. 2013.

Tennessee DOT. (2021a). *Special Provision Regarding High Friction Surface Treatments (HFST)*. Special Provision 406HFST. Tennessee Department of Transportation. Nashville, TN.2021.

Tennessee DOT. (2021b). *QPL 31 High Friction Surface Treatments for Roadways – Polymer Modified Epoxy Systems*. Tennessee Department of Transportation. Nashville, TN.

Torbic, DJ., Harwood, D.W., Gilmore, D.K., Pfefer, R., Neuman, T.R., Slack, K.L., and Hardy, K.K. (2004). *Guidance for Implementation of the AASHTO Strategic Highway Safety Plan, Volume 7: A Guide for Reducing Collisions on Horizontal Curves*. NCHRP Research Report 500. National Academies of Sciences, Engineering, and Medicine. Washington, DC.

Torbic, DJ., Hutton. J.M., Harwood, D.W. (2020). *Guide for Quantitative Approaches to Systemic Safety Analysis*. NCHRP Research Report 955. National Academies of Sciences, Engineering, and Medicine. Washington, DC.

Traffic Calming USA website. https://www.trafficcalmingusa.com/colored-surfacing, last accessed May 1, 2021.

Tsai, Y., Wu, Y., Ai, C., and Pranav, C. (2018). *Developing Georgia's High Friction Surface Treatment (HFST) Program - HFST Site Characteristics (HFST-SC) Data Collection and Analysis*. Georgia Department of Transportation Research Report No. FHWA-GA-18-1504. Forest Park, GA.

United States Road Assessment Program (usRAP). (n.d.). "usRAP", http://www.usrap.org/, last accessed September 1, 2019.

Von Quintus, H. and Mergenmeier, A. (2015). *Case Study: Kentucky Transportation Cabinet's High Friction Surface Treatment and Field Installation Program*, Federal Highway Administration FHWA Research Report FHWA-SA-15-038. Washington, D.C.

Waters, J. (2011). High friction surfacing failure mechanisms Shear Stress at Calcined Bauxite – Binder Interface. *3rd International Surface Friction Conference, Safer Road Surfaces - Saving Lives*, 1–10.

Weiser, A. (2016, July). The Delaware Experience. One state's engagement with high-friction surface treatment-and what came of it. *Roads and Bridges*.

Wilson, B. and Mukhopadhyay, A. (2016). *Alternative Aggregates and Materials for High Friction Surface Treatments*. Texas A&M Transportation Institute Project Report No. BDR74-977-05. College Station, TX.

Wilson, B. T., Wang, K. C. P., Li, J. Q., and Yang, G. (2020). *Recommendations Report for High Friction Surface Treatments: Candidate Sites, Materials, and Construction*. Federal Highway Administration FHWA Research Report FHWA-SA-20-036. Washington, D.C.

Wilson, B. and Saca, M. (2021, June). *High Friction Surface Treatment (HFST) Synthesis for Florida Pavements*. FHWA/FL-21/BE923 Final Report, Texas A&M Transportation Institute, College Station, TX.

Winkler, P. (2014). Introduction to ICRI Technical Guideline No. 310.2R-2013, Selecting and Specifying Concrete Surface Preparation for Sealers, Coatings, Polymer Overlays, and Concrete Repair. *ICRI concrete Repair Bulletin*, pp. 17-19.

Woodward, D. and Friel, S. (2017). Predicting the Wear of High Friction Surfacing Aggregate. *Coatings*, 7(71).

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