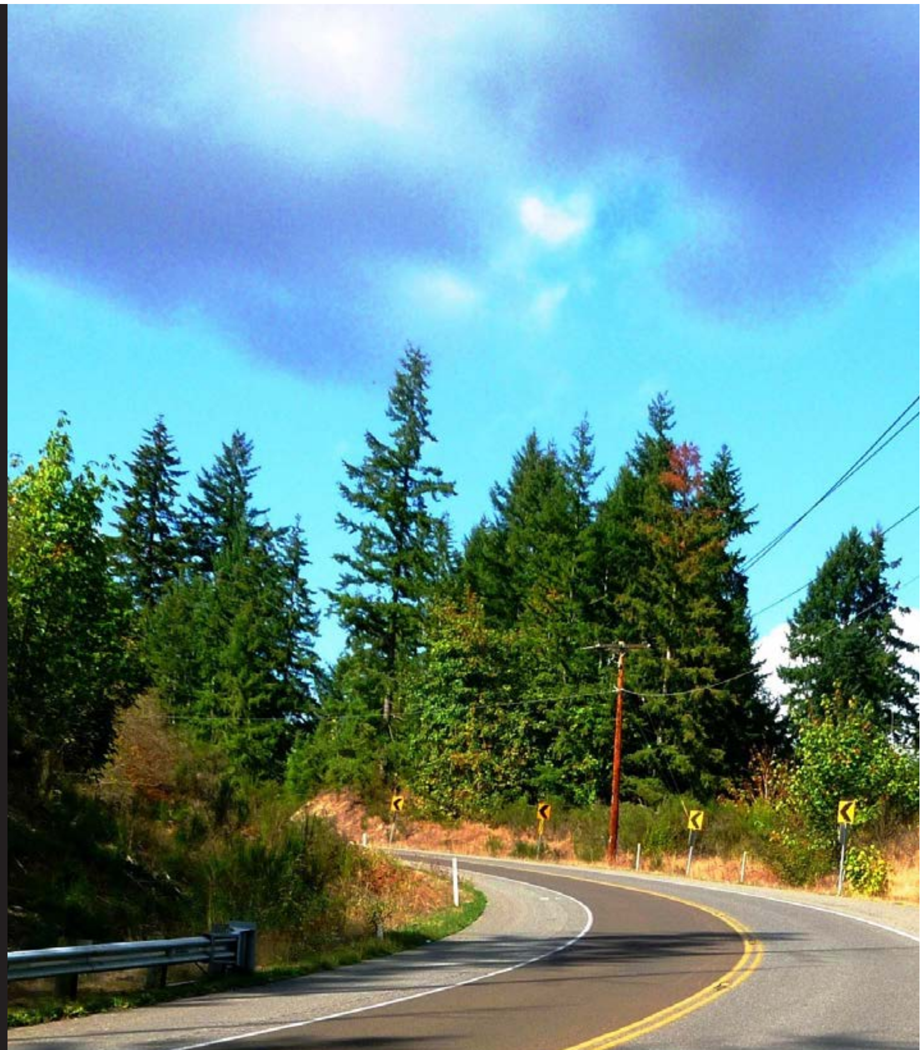
FHWA Research and Technology Evaluation



High Friction Surface Treatments

Final Report
August 2021

Publication No. FHWA-HRT-21-014

U.S. Department of Transportation
Federal Highway Administration

Foreword

The Federal Highway Administration's (FHWA) Research and Technology (R&T) Evaluation Program seeks to assess and communicate the benefits of FHWA's R&T efforts; ensure that the organization is expending public resources efficiently and effectively; and build evidence to shape and improve policymaking. FHWA partners with State transportation departments, local agencies, industries, and academia to conduct research on issues of national significance and accelerate adoption and deployment of promising research products.

This report examines how FHWA research on high friction surface treatments influenced the practices of State departments of transportation and contributed to improvements in safety. This report should be of interest to practitioners, researchers, and decisionmakers involved in the planning and execution of safety and infrastructure projects.

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Director, Office of Corporate Research, Technology and Innovation Management

Notice

Quality Assurance Statement

Cover photo source: FHWA.

Recommended citation: Federal Highway Administration, *FHWA Research and Technology Evaluation: High Friction Surface Treatments* (Washington, DC: 2021) https://doi.org/10.21949/1521640.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-HRT-21-014	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle FHWA Research and Technology Evaluation: High Friction Surface Treatments		5. Report Date August 2021 6. Performing Organization Code OST-R V-321
7. Author(s) Kaitlin Coppinger, Matthew Keen (ORCID: 0000-0002-3032-9435), Jennifer Gissel, and Lydia Rainville (ORCID: 0000-0003-3641-0012)		8. Performing Organization Report No. DOT-VNTSC-FHWA-19-20
9. Performing Organization Name and Address Volpe National Transportation Systems Center 55 Broadway Cambridge, MA 02142		10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Office of Corporate Research, Technology, and Innovation Management Federal Highway Administration 6300 Georgetown Pike McLean, VA 22101		13. Type of Report and Period Covered Final Report; 2009–2017 14. Sponsoring Agency Code HRTM-10
15. Supplementary Notes For this contract and program summary, John Moulden (HRTM-10) is the Research and Technology Program Manager and the Contracting Officer's Representative.		
16. Abstract This evaluation assesses how the Federal Highway Administration's (FHWA's) investment in research on high friction surface treatments (HFSTs) and related activities impact the availability and quality of such research; awareness, knowledge, and attitudes toward HFSTs in the United States; adoption of HFSTs as a safety measure; and safety performance of HFSTs on the U.S. transportation system. Although measuring the effect of specific FHWA activities is difficult, this evaluation found evidence that FHWA improved awareness, knowledge, and attitudes toward HFSTs and expanded the breadth of HFST research and performance data available to States considering technology deployment. The findings suggest FHWA played a key role in accelerating the consideration of HFSTs as a topic of interest, facilitated the exchange of knowledge between States at differing levels of adoption, and helped influence States' deployment of HFSTs. Many States saw a decrease in roadway-departure crashes. While FHWA cannot claim direct responsibility for this reduction, their continued research and promotion of HFSTs have enhanced roadway safety in the United States.		
17. Key Words High friction surface treatments, HFST, roadway departure, safety	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161. http://www.ntis.gov	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 76 / 22. Price N/A

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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List of Abbreviations and Acronyms

Abbreviation/Acronym	Definition
AASHTO	American Association of State Highway and Transportation Officials
AID	Accelerated Innovation Demonstration
ATSSA	American Traffic Safety Services Association
BCR	benefit–cost ratio
CMF	crash-modification factor
DCMF	Development of Crash Modification Factors
DOT	Department of Transportation
EDC-2	Every Day Counts Round 2
ELCSI-PFS	Evaluation of Low Cost Safety Improvements Pooled-Fund Study
EPSP	*Evaluation of Pavement Safety Performance*
FAQ	frequently asked questions
FHWA	Federal Highway Administration
HFST	High friction surface treatment
HSA	Office of Safety
HSIP	Highway Safety Improvement Program
IDOT	Iowa Department of Transportation
R&T	Research and Technology
SEaHC	Surface Enhancements at Horizontal Curves
SHSP	Strategic Highway Safety Plan
TAC	Technical Advisory Committee
TDOT	Tennessee Department of Transportation

Executive Summary

Purpose of the Evaluation

The purpose of this evaluation was to assess the effects of FHWA's investment in high friction surface treatment (HFST) research on the availability and quality of such research, deployment of the technology, and safety impacts of HFSTs in the United States. The goal of FHWA's research on high friction surface treatments (HFSTs) and related activities is to reduce the number and severity of roadway-departure crashes in the United States, particularly on horizontal curves. This research aligns with FHWA's strategic objective to "enhance the safety and performance of the Nation's transportation system through research and by accelerating the development and deployment of promising innovative technologies and practices."(1)

Program Description

HFSTs enhance skid resistance by bonding calcined bauxite, a polish-resistant aggregate, to a pavement surface using a polymer-resin binder. HFSTs are applied along portions of roadways that are susceptible to vehicle slippage (e.g., curves under precipitation, lacking a cross slope, or with nonoptimal superelevation).

Several lead-adopter States and product vendors initiated HFST deployment in the early 2000s, when HFST suppliers began marketing the treatment as a safety measure to transportation agencies in the United States. Documented domestic use of HFSTs as a safety measure on curves began in 2004. Both the Tennessee Department of Transportation (DOT) and Washington (City of Bellevue) installed epoxy-resin overlays on curves, ramps, and intersections, and reported significant improvements in friction for all sites.

In 2008, FHWA began partnering with States to install and study HFSTs through a national demonstration program. In 2010, the Evaluation of Low Cost Safety Improvements Pooled-Fund Study (ELCSI-PFS) initiated research to evaluate the safety performance of a range of surface improvements, including HFSTs. Because of the safety benefits demonstrated in research from the United Kingdom and New Zealand as well as early State experiences with HFSTs, HFSTs were included as a promising roadway departure–prevention technology in Every Day Counts Round 2 (EDC-2) (2013–2014). Through EDC-2, FHWA Resource Center technical assistance, and the Roadway Safety Professional Capacity Building Program, FHWA conducted outreach and technology-transfer efforts to raise awareness of HFSTs and promote further use of and research on HFSTs among the transportation-safety community.

The ELCSI-PFS has continued to support safety research, including the Development of Crash Modifications Factors (DCMF) Program, on HFSTs.[1] This research included a review of existing HFST evaluations as well as a rigorous, advanced statistical analysis of crash, road-friction, and pavement data from four States (West Virginia, Pennsylvania, Kentucky, and Arkansas), from which the authors developed crash-modification factors (CMFs) and conducted a benefit–cost analysis. The DCMF for

[1]All information on the DCMF study is from an upcoming report: Merritt, D.K., Lyon, C.A., Persaud, B.N. (in progress). *High Friction Surface Treatments*, FHWA, Washington, DC.

HFSTs study showed a 57-percent reduction in expected crashes at curves for all crash types and an 83-percent reduction for wet-weather crashes.

Methodology

This evaluation focused on the following four evaluation areas, establishing key evaluation hypotheses and performance measures for each area:

- Evaluation Area 1: Availability of HFST safety and performance data.
- Evaluation Area 2: Change in awareness, knowledge, and attitudes.
- Evaluation Area 3: Adoption of a safety measure.
- Evaluation Area 4: Safety impacts of HFSTs.

To assess these evaluation areas, the evaluation team collected documents, analyzed data, and interviewed stakeholders. Data sources reviewed included FHWA-program documents (internal and published), relevant research on HFSTs, technology-transfer materials, and benefit–cost studies. To assess the influence of FHWA research and outreach on State DOTs, the evaluation team reviewed State-level materials, including Strategic Highway Safety Plans (SHSPs), State-level specifications and special provisions, and State DOT websites. Where available, the evaluation team used quantitative data to understand the funding, installation data, and safety impacts of HFSTs. Additionally, the evaluation team conducted interviews with FHWA and State DOT staff to complement other data sources and provide further context.

Findings

When HFSTs were introduced in the United States, international experience indicated they had high safety-benefit potential, but little applicable domestic information was available. The findings in this evaluation show FHWA successfully played a role in accelerating adoption of HFSTs. FHWA contributed to an increase in the availability and quality of information on HFSTs in the United States through early CMF funding; Office of Safety (HSA) EDC-2 funding for demonstrations and development of outreach materials; collaboration with States for demonstration and data collection; and Resource Center leadership and technical assistance. Although attributing direct causation can be difficult, findings suggest that acceptance, consideration, and adoption of HFSTs are higher than would have occurred in the absence of FHWA research and technology-transfer investment—resulting in a real reduction in roadway-departure crashes. While FHWA cannot claim direct responsibility for this reduction, their continued research and promotion of HFSTs has enhanced roadway safety in the United States.

The path to deployment, however, has had challenges. HFST's complex technology posed a steep learning curve in States' early deployment experiences. These challenges include: coordination across safety and materials communities to deploy HFST; the perception of HFST as having higher installation costs than alternatives; and longevity and performance being dependent on multiple factors, including high-quality underlying pavement, correct installation processes, and specific materials. The findings and recommendations from this evaluation on the HFST research–lifecycle process provide insights for both future HFST deployments and for other innovative technologies FHWA selects for research. The findings are organized by evaluation area as follows:

Evaluation Area 1—availability of HFST safety and performance data.

- Finding 1a: FHWA contributed to an increase in the availability and quality of information on HFSTs in the United States through early performance research funding, collaboration with States for demonstrations and data collection, provision of HFST informational materials on roadway departures and HFSTs by HSA, and Resource Center leadership and technical assistance.
- Finding 1b: Research gaps related to HFST durability, HFST performance, and alternative aggregates may be barriers to HFST deployment.

Evaluation Area 2—change in awareness, knowledge, and attitudes.

- Finding 2a: Collaborative forums convened by FHWA in partnership with States, including EDC-2, peer exchanges, and the ELCSI-PFS Technical Advisory Committee, were effective in raising awareness of HFSTs among potential users and providing forums for learning and exchange.
- Finding 2b: State inclusion of HFSTs in informational materials, SHSPs, and HFST specifications demonstrates growing acceptance of HFSTs as a safety measure. References to FHWA resources indicate that FHWA's investment in HFST research played a role in this acceptance.

Evaluation Area 3—adoption as a safety measure.

- Finding 3a: The total number of HFST locations and their geographic distribution increased between 2004 and 2018, with the highest number of locations installed between 2013 and 2016. Direct funding from FHWA as well as technology transfer contributed to this growth.
- Finding 3b: Some of the most successful HFST programs have been characterized by two notable traits: State-level HFST champions and improvement of HFST specifications.
- Finding 3c: Barriers to HFST deployment are often a combination of multiple challenges at once, including concerns over performance, construction and installation issues, perception of cost, and issues with specifications.

Evaluation Area 4—safety impacts of HFSTs.

- Finding 4a: HFSTs can significantly reduce fatalities and other injuries from roadway departures; however, a wide range of estimated crash-reduction results can lead to uncertainty for potential deployers.
- Finding 4b: Especially in areas that experience a large number of wet-weather crashes, to date, studies show HFSTs are a cost-beneficial safety investment (i.e., present-value benefit from reduced crashes exceeds present-value installation costs). Pennsylvania estimated an annual economic savings of $357,427 per intersection. Florida monetized the benefit from avoided crashes, estimating for tight curves a 5-yr benefit of approximately $2.5 million per curve. The DCMF study monetized cost savings as $19,300,113 for 146 curve installations.

Recommendations

Based on these findings as well as input from interviewees and other research conducted, the evaluation team developed a set of specific, actionable recommendations to facilitate development, adoption, and use of HFSTs and other technologies with similar opportunities and challenges. In some cases, FHWA and other stakeholders are already enacting these recommendations. The recommendations are intended primarily for two groups: those engaged in technology transfer and outreach at FHWA and potential adopters of HFSTs.

Recommendations to facilitate technology transfer include the following:

- Recommendation 1: Maintain active engagement with States that are early in their respective HFST-adoption curves. FHWA can identify and support interested States that are earlier in their adoption curves who would benefit from technical assistance and engagement with more experienced States.
- Recommendation 2: Update the HFST website to enhance usability and ensure it is a comprehensive resource. FHWA's HFST website traffic is among the highest in its category. The site has a wealth of information but should be reorganized for more effective curation and improved information dissemination.
- Recommendation 3: Disseminate these results through another round of targeted HFST promotion with updated materials, including updating and adding additional detail to the existing high-level High Friction Surface Treatment Curve Selection and Installation Guide.(2)
- Recommendation 4: Continue to provide technical assistance and presentations on HFST through the FHWA Resource Center. With the retirement of a longstanding champion of HFSTs from the Resource Center, it will be important for the Resource Center to maintain its role as a resource and advocate for HFSTs.

Recommendations for potential adopters include the following:

- Recommendation 5: Designate a strong State champion. The champion can help new-adopter States move past challenging (or failed) first installations. Moreover, the champion can be an important resource for mediating between safety and materials professionals, educating on the need for calcined bauxite.
- Recommendation 6: Improve data-collection efforts before and during HFST installation. Improved data-collection efforts before and during HFST installations can help States better assess factors that contribute to both installation successes and failures. Ultimately, better data can help lessen the severity of the learning curve and reduce the likelihood of premature project failures or lack of durability.

Conclusion

The goal of FHWA HFST research–related activities was a reduction in the number and severity of roadway-departure crashes in the United States, particularly on horizontal curves. Overall, this evaluation found that FHWA's activity increased the availability of safety and performance data on HFSTs, contributed to a change in awareness and knowledge of HFSTs that facilitated and encouraged deployment of HFSTs, and plausibly led to safety impacts through reduced roadway departure accidents.

FHWA contributed to an increase in the availability and quality of information on HFSTs in the United States through early CMF funding, collaboration with States for demonstration and data collection, and Resource Center leadership and technical assistance. Although attributing direct causation is difficult, findings suggest that acceptance, consideration, and adoption of HFSTs were higher than would have occurred in the absence of FHWA research and investment in technology transfer. HFSTs were demonstrated to be an effective safety measure, indicating that FHWA efforts contributed to a reduction in roadway departures on curves, particularly in areas of high wet-weather crashes.

The path to deployment, however, faced challenges. HFSTs are a complex technology that presented a steep learning curve in States' early deployment experiences. Installation of HFSTs is perceived as high cost; and depends on multiple factors, including high-quality underlying pavement, correct installation processes, and specific materials for maximum longevity and performance. FHWA and peers provided resources which, along with trial and error, aided States in overcoming such challenges. These experiences resulted in a variety of project outcomes that future adopters could consult in their installations. The findings and recommendations from this evaluation on the HFST-research lifecycle offer insights for both future HFST deployments and other innovative technologies FHWA selects for research.

The findings from this evaluation demonstrate the importance of both foundational and ongoing research, dissemination of resources, and FHWA national leadership on a topic in collaboration with internal and external stakeholders, leaders, and other decisionmakers.

1. Introduction

1.1 Evaluation Overview

The Federal Highway Administration (FHWA) initiated the Research and Technology (R&T) Evaluation program to help FHWA leadership and program and project managers communicate the impacts of their research, ensure resources are being expended effectively, and build evidence to inform future projects and policymaking.

This evaluation examines FHWA's efforts related to conducting research on and analysis of high friction surface treatments (HFSTs) and supporting the adoption of the technology by State and local agencies. The goal of FHWA's HFST research–related activities is to reduce the number and severity of roadway-departure crashes in the United States, particularly on horizontal curves. This research aligns with FHWA's strategic objective to "enhance the safety and performance of the Nation's transportation system through research and by accelerating the development and deployment of promising innovative technologies and practices."[1]

Table 1 summarizes the four evaluation areas identified for the HFST evaluation.

Table 1. Evaluation areas.

Evaluation Area	Description
Availability of HFST safety and performance data	Improved availability of HFST safety and performance data for the research community and for use by State and local transportation agencies.
Change in awareness, knowledge, and attitudes	Changes in awareness of, knowledge of, attitude about, and confidence in HFSTs as a safety measure both within FHWA and among FHWA stakeholders.
Adoption as a safety measure	Growth in the number of HFST installations in the United States and perceptions of how FHWA research contributed to this growth.
Safety impacts of HFSTs	The extent to which the growth in the number of HFSTs in the United States contributed to improved safety.

This evaluation brings together observations on the deployment and impacts of HFSTs with information on FHWA research results, data, and other resources. The evaluation design emphasizes understanding FHWA's contribution to the availability and reliability of HFST research, the quality of that information, changing stakeholders' awareness and knowledge, and adoption of HFSTs as a safety measure.

[1]All information on the DCMF study is from an upcoming report: Merritt, D.K., Lyon, C.A., Persaud, B.N. (in progress). *High Friction Surface Treatments*, FHWA, Washington, DC.

1.2 Program Background

HFSTs enhance skid resistance by bonding calcined bauxite, a polish-resistant aggregate, to a pavement surface using a polymer-resin binder. An HFST is applied along portions of roadways that are susceptible to vehicle slippage (e.g., curves under precipitation, lacking a cross slope, or with nonoptimal superelevation). The resulting higher pavement friction enables better control in both wet and dry driving conditions.(3) Common locations for HFSTs include two-lane urban or rural horizontal curves; sections at or near steep grades, such as highway ramps; segments at or near lane changes and merges; and rural and urban intersections.

The United Kingdom experimented with applying skid-resistant surface treatments in the late 1960s.(4) In the 1960s and 1970s, HFST use expanded to France, Germany, Italy, and Scandinavia. By the early 1980s, HFSTs were common. New Zealand began installations in the early 1990s, and HFST use now spans worldwide.(4,5) Domestically, early HFST deployment was initiated by several lead-adopter States and product vendors starting in the early 2000s, when HFST suppliers began marketing the treatment as a safety measure to transportation agencies in the United States.[2](6) However, documented domestic use of HFSTs as a safety measure on curves did not begin until 2004.(5) Both the Tennessee Department of Transportation (TDOT) and Washington (City of Bellevue) installed epoxy-resin overlays,[3] and reported significant improvements in friction for all sites.(5)

Initially, domestic HFST adoption was initiated by State leadership and vendors. While FHWA published early research on the subject (subsection 4.1), many of the first HFST projects were launched at the State level by vendors who, "came to the district in selling mode."[4] Vendor demonstration projects helped introduce HFSTs to the United States (HFSTs were already a "fledgling industry" abroad[5]) and generated interest in undertaking a larger program.[6]

Beginning in 2008, FHWA partnered with States to install and research HFSTs through a national demonstration program—Surface Enhancements at Horizontal Curves (SEaHC). This program assisted in HFST site selection, installation, and ongoing measurement of friction and texture. Pilot States included Alabama, Colorado, Kansas, Michigan, Montana, North Carolina, and Wisconsin.(7)

FHWA administers the Transportation Pooled-Fund Study Program, which enables State departments of transportation (DOTs), commercial entities, and FHWA program offices to combine resources and achieve common research goals. One of these shared efforts, the Evaluation of Low Cost Safety Improvements Pooled-Fund Study (ELCSI-PFS) Technical Advisory Committee (TAC), became an early forum for exchange on HFSTs. The ELCSI-PFS is conducted under the Development of Crash Modification Factors (DCMF) program. Work conducted under the ELCSI-PFS is intended to provide crash-modification factors (CMFs) and benefit–cost analyses for targeted safety strategies identified as priorities by the 40 ELCSI-PFS member States.(8)

CMFs are a tool used to find the expected change in crash incidence after implementing a safety improvement. CMFs are multiplicative determinants ranging from 0 to any positive number, with

[2]As early as the 1950s, the United States was using HFSTs as a thin polymer-bonded bridge-deck treatment.

[3]Tennessee used the calcined aggregate that now characterizes most domestic HFST installations.

[4]State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Kaitlin Coppinger, Lydia Rainville, and Matthew Keen in November 2017.

[5]FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

[6]FHWA Technical Contractor; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in November 2017.

values less than 1 representing an expected reduction in crashes. For example, the CMF for installing an HFST on a two- to six-lane road with a speed limit of 15–55 mph is 0.207. In terms of expected change in crashes, the CMF indicates a 79.3 percent (i.e., 100 × (1 − 0.207)) expected reduction in all crashes after the installation of the HFST. Transportation practitioners use CMFs to identify and compare safety impact or cost effectiveness of safety measures, identify where to deploy safety measures, and conduct benefit–cost analyses when selecting safety measures.(9)

In 2010, the ELCSI-PFS initiated research to evaluate a range of surface improvements designed to improve road safety. The goal of the study was to assess the effects of various low-cost pavement treatments, including HFSTs, on roadway safety and identify any potential differences in safety performance for various types of pavement treatments. The study made use of some of the HFST sites that were part of FHWA SEaHC demonstration program as well as additional sites in Kentucky, South Carolina, and Tennessee.(10) In December 2014, this research culminated in the publication of the report, *Evaluation of Pavement Safety Performance* (EPSP).(10) The EPSP report highlighted the relative effectiveness of HFSTs as a low-cost (and potentially high-return) safety investment, although the study was limited by insufficient treatment- and reference-group data. Reported CMFs from this study for horizontal curves were 0.48 for wet-road crashes and 0.76 for all crash types.(10)

HFSTs were included as a promising roadway departure–prevention technology in FHWA's Every Day Counts Program Round 2 (EDC-2) (2013–2014) largely based on research conducted in the United Kingdom and New Zealand.[7] Through the EDC model, FHWA, including its Office of Safety (HSA), worked with State and local transportation agencies and industry stakeholders to identify and champion proven but underutilized innovations to accelerate deployment. Through EDC-2, FHWA conducted outreach efforts to raise awareness of HFSTs and promote further use of and research on HFSTs among the transportation community.

HFSTs were a topic of interest in TAC meetings from 2010 to the present, and in 2015, the ELCSI-PFS Phase IX for Evaluation of High Friction Safety Improvements study started. The purpose of this follow-on research to the EPSP study was to develop CMFs and benefit–cost ratios (BCRs) for HFST application types, provide material and specification recommendations, and provide information on effective site selection for HFST installations. The study made use of the FHWA Highway Friction Tester vehicle to collect friction data at curve sites in Kentucky, Pennsylvania, and West Virginia and ramp sites in Arkansas and Kentucky. Results indicated strong crash reductions for both ramps and curves, particularly for wet-weather crashes.

Most recently, ELSCI-PFS has supported the DCMF program, a continuation of ELCSI-PFS Phase IX, for HFSTs. This study included a rigorous review of existing HFST studies as well as an analysis of crash, road friction, and pavement data from Arkansas, Kentucky, Pennsylvania, and West Virginia.[8] From the available data, using an empirical Bayes before–after analysis of installation sites, the evaluation team estimated the crash reduction relative to an unobserved but estimated postinstallation period. From this estimated reduction, they estimated CMFs for all crashes, injury crashes, run-off-road, wet-road, and head-on plus opposite-direction side-swipe crashes for each State with available curve data, and all crashes, injury crashes, run-off-road, and wet-road crashes for all States with ramp data. The analysis also included development of a crash-modification function for curves, though the analysis noted issues, possibly due to the limited sample size, that included counterintuitive coefficients (i.e., coefficients with the opposite sign from what would be expected) and statistically insignificant coefficients. The analysis also included a benefit–cost analysis. In this report, the benefit of reduced fatalities, injuries, and vehicle damage due to

[7]FHWA HSA, communication with evaluation team, January 6, 2020.
[8]Data were collected for Georgia and Louisiana but were inadequate given the study methodology.

installation of HFSTs is compared to the cost of installing HFSTs, both discounted to the present value.

Timeline

Table 2 contains a timeline of significant events and activities related to HFSTs.

Table 2. Timeline of events.

Year	HFST Research, Technology Transfer, and Deployment Milestones
2004	• Earliest documented U.S. installations in Tennessee and Washington State.[9]
2005	• ELCSI-PFS begins with 24 volunteer States.(7)
2006	• FHWA *Low-Cost Treatments for Horizontal Curve Safety*.(11) • Earliest domestic publication mentioning HFST.(12)
2008	• FHWA national demonstration program, SEaHC, created.(7)
2009	• Continuation of SEaHC demonstrations.(7)
2010	• EPSP study initiated.(10) • Continuation of SEaHC demonstrations.(7)
2011	• Continuation of SEaHC demonstrations.(7)
2012	• HSA recommends HFSTs as a curve safety measure in roadway departure safety implementation plans.[10]
2013	• EDC-2 includes HFSTs.[11] • Horizontal-curve and roadway-departure peer exchanges.[12] • Accelerated Innovation Demonstration grants for HFSTs.[13]
2014	• EDC Exchange: HFST.[14] • *Public Roads* "Gaining Traction on Roadway Safety."(5) • Systemic safety-implementation and horizontal-curve peer exchanges.[15]
2015	• EPSP published.(10) • DCMF Task B9: High Friction Surface Treatments project start.[16] • Systemic safety-implementation peer exchanges.[17]
2016	• Regional peer exchanges.[18]
2017	• Focus State Roadway Departure Safety Plan and HFST peer exchanges.[19]
2019	• DCMF Factors Task B9: High Friction Surface Treatments project completed.

[9]Interviewees suggested other early adopters may have begun in 2004 (i.e., Kentucky), but this suggestion appeared inconsistent with State self-reporting.

[10]FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

[11]FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

[12]FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

[13]FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

[14]FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

[15]FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

[16]FHWA HSA Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

[17]FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

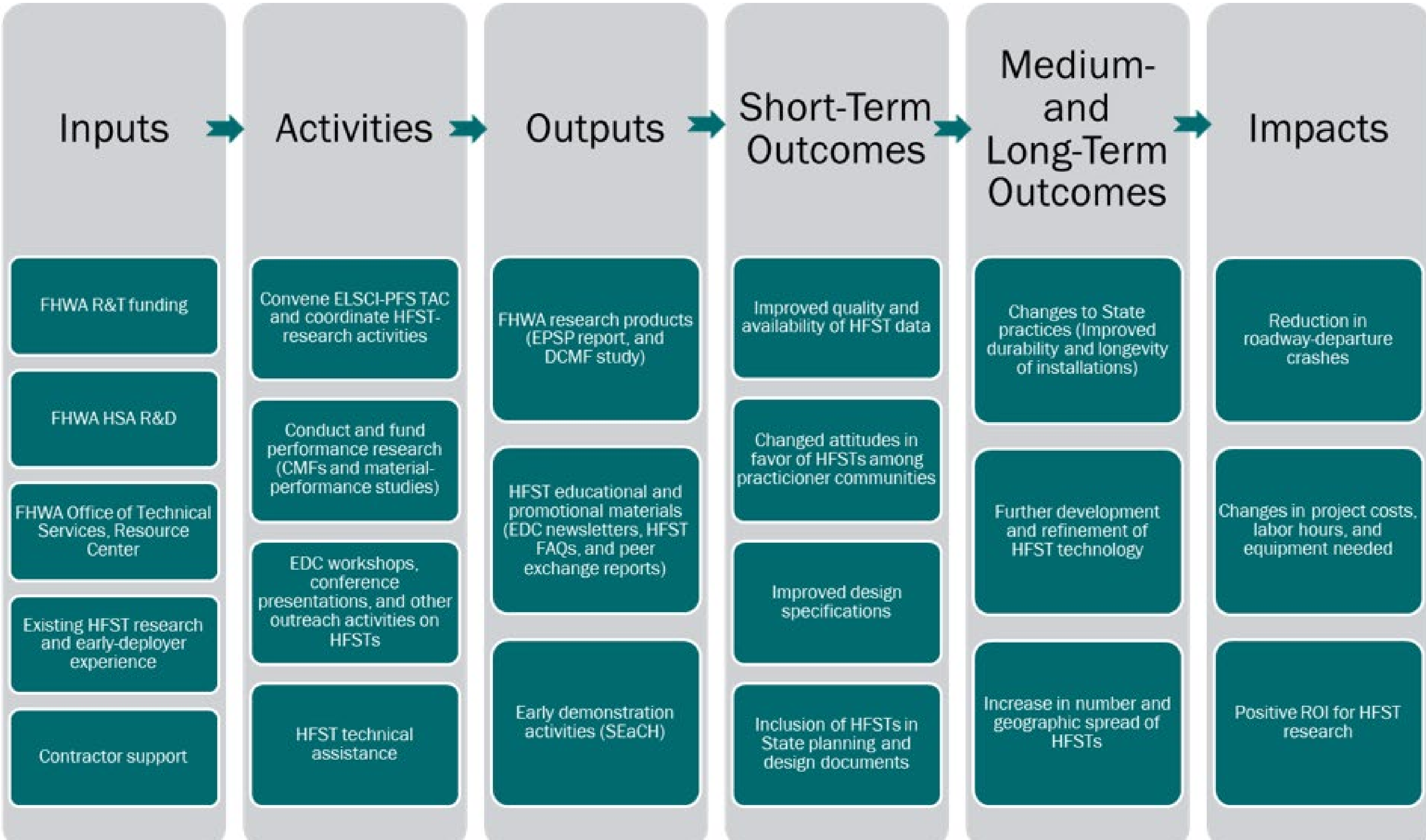
[18]FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

[19]FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

2. Evaluation Design

The evaluation team identified key outcome and impact areas on which to focus in the HFST evaluation through initial discussions with members of the R&T evaluation team and Safety Research and Development staff. Further discussions led to the development of an HFST research logic model that identifies potential relationships between four evaluation areas to more effectively investigate the outcomes and impacts of FHWA's HFST research. The logic model (figure 1) identifies the inputs, activities, and outputs from FHWA's HFST activities and the resulting short-term outcomes and long-term impacts, which represent a mix of short-term and long-term results. Table 3 summarizes the key hypotheses and associated performance metrics developed for each of the four evaluation areas.

An important component of the evaluation is the role played by FHWA. The evaluation team sought not only to determine the usage and outcomes of HFSTs, but also to identify what role FHWA played in influencing the state of the practice and usage of the technology. FHWA's primary inputs and activities consist of conducting HFST research in coordination with States through ELCSI-PFS and related outreach and implementation through the Resource Center and EDC-2 program. These activities have led to HFST projects, research reports, case studies, and other information for transportation agencies seeking to install HFSTs. Using these outputs as a reference, the evaluation team analyzed the outcomes and impacts of HFSTs, most notably in terms of adoption, effective practices, and safety benefits. A particular emphasis, evident through the progression of the logic model, is on the role FHWA played in generating outputs that have diffused the technology.



Source: FHWA.

ROI = return on investment.

Figure 1. Flow chart. Logic model.

Table 3. Summary of evaluation framework.

Evaluation Area	Key Hypotheses	Key Performance Measures
Availability of HFST-safety and -performance data	• FHWA improved the availability of HFST-related safety and performance data. • FHWA HFST-related research led to additional research products and outreach by early adopter States.	• Scope and breadth of FHWA research and activities. • Number of HFST research studies published and funded by FHWA over time. • Number of citations and references to key FHWA outputs and activities work in non-federally funded research. • Use/contribution of research in CMF Clearinghouse.
Change in awareness, knowledge, and attitudes	• FHWA HFST-related research influenced the level of awareness of HFST as a safety measure in the transportation community in the United States. • FHWA HFST-related research influenced the attitude of transportation decisionmakers, practitioners, and the public toward HFSTs as a safety measure.	• State DOT website references to HFSTs and related FHWA references. • Number of States with HFSTs included in their SHSPs. • Number of States with HFST specifications. • FHWA Web statistics for primary FHWA HFST pages. • Use of FHWA program activities and outputs. • Qualitative assessment of the effect of FHWA program activities and outputs.
Adoption as a safety measure	• FHWA R&T research contributed to an increase in number of HFST projects implemented and planned in the United States. • FHWA R&T research improved the understanding of the circumstances under which HFST projects are best implemented.	• Trend data of FHWA activities (e.g., analysis of HFST installations and State participation in ELCSI-PFS, FHWA outputs and activities vs. adoption timeline). • Growth in the total number of HFST installations in the United States. • Growth in the number of States installing HFSTs. • Perception of the impact of FHWA research on investment in HFSTs.
Safety impacts of HFSTs	• Implemented and planned HFST projects led to reductions in severe crashes relative to alternative measures.	• Existing research demonstrates a reduction in number of crashes as a result of HFST installation.

3. Evaluation Methodology

The evaluation team primarily relied on two methods of obtaining information—review of literature and documents and interviews with project stakeholders—to evaluate FHWA's HFST research and assess the hypotheses presented in table 3. The evaluation team also attended ELCSI-PFS TAC meetings in 2017 and 2018 to observe discussions related to HFSTs. The following subsections expand on the approach used to collect and analyze data.

3.1 Literature and Document Review

The literature and document review served as the foundation for assessing all four evaluation areas. The evaluation team collected publicly available literature, documents, and other primary-source materials from the late 2000s to the present that are related to HFSTs in the United States. For the purpose of this evaluation, "literature" refers to academic and scholarly publications, and "document" refers to primary-source records, such as FHWA and State DOT research products, Strategic Highway Safety Plans (SHSPs), State specifications, State DOT websites, and other similar sources. The evaluation team's collection of HFST documentation published prior to the start of this evaluation appears comprehensive, but the collection of materials available during the initial years of FHWA outreach and HFST implementation may not be exhaustive.

To understand FHWA's contribution to data availability and the role FHWA played in HFST research and technology transfer, the evaluation team collected and reviewed a wide variety of HFST-related FHWA outputs, including FHWA-funded research, outreach documentation and materials, and program documents. To better understand program activities and goals, the evaluation team reviewed FHWA program documents.

The evaluation team collected and coded the documents, literature, and relevant primary-source materials using qualitative analysis software. The team applied an inductive coding framework; codes were generated while reading the documents, literature, and relevant primary-source materials. Because inductive coding generates variables based on the source materials, it is more robust and captures a much finer level of detail than a deductive-coding framework, providing more rich and robust qualitative data from which to draw connections and develop findings. In all, the evaluation team coded 30 CMFs, 319 documents, literature, and relevant primary-source materials for a total of 16,095 coded segments across all reviewed publications.

For the purpose of assessing the safety impacts of HFSTs and, by extension, the impact of FHWA efforts in support of HFSTs, the evaluation team primarily relied on the DCMF study conducted by Merritt et al. Their study provided the most recent and rigorous estimates of CMFs as well as supporting material on benefit–cost analyses, which helped establish a touchstone against which other collected HFST materials were compared.

3.2 Citation Analysis

The evaluation team conducted a citation analysis to assess the extent to which FHWA research products were referenced by other users. Using qualitative analysis software, the evaluation team created a citation tag to capture any text segments citing a reference. Reference types included but were not limited to the following:

- Text: journal articles, news articles, books, websites, etc.
- People: designated contact person, conversations, interviews, personal email correspondence, etc.
- Digital media: videos, photographs, etc.

The evaluation team queried citations in Google® Scholar™ by author and/or title.(13) Each search result indicated the number of articles that cite the queried citation.

Using the same process, the evaluation team identified additional HFST materials that were not found during the course of literature and document collection. The team uncovered fewer than 10 additional documents by the citation analysis. Because this number is small relative to the total number of documents, literature, and primary-source material already uncovered by the evaluation team, the level of confidence that a large share of publicly available information pertaining to HFSTs was included is high.

3.3 State Safety and Planning Documents and Materials

To assess the influence of FHWA research and outreach on State DOTs, the evaluation team reviewed State DOT websites, SHSPs, and online standards and specifications for all 50 States and Washington, DC, when available.

State DOT Websites

As an input to assessment of awareness and attitudes toward HFSTs as well as FHWA's influence on these factors, the evaluation team reviewed State DOT website searches to document and collect State-level information on the uses of HFSTs. The evaluation team reviewed all State DOT or equivalent websites for mentions of "high friction surface" or "HFST." Specifically, they reviewed each State website for the presence of any HFST materials, the availability of a Web page dedicated to HFST outreach or information, and reference to FHWA. In addition to summarizing the current state of State DOT HFST outreach and activity, this website review collected HFST documentation for the literature and document review.

The evaluation team subjectively assessed the level of FHWA influence on each State's public HFST Web materials. State DOT websites were separated into one of four categories based on FHWA's level of influence: none, low, medium, and high. The evaluation team assigned a high level of influence when a Web page or similar document discussed specific FHWA materials and/or staff or when the State provided FHWA materials directly to the reader. They assigned a low level of influence to websites that included incidental mentions of Federal funding of HFSTs or materials (e.g., a brief mention of Highway Safety Improvement Program (HSIP) project funding). They assigned a medium level of influence to websites when FHWA influence appeared more prominently than "low" but was not as significant as high-influence examples. They assigned none when no clear reference to or materials from FHWA were presented publicly. Notably, they made this assessment only on public-facing documents; this categorization is only a proxy for actual FHWA influence on

State DOTs' HFST work. It is possible for States that received significant and continuous HFST support from FHWA to not indicate this circumstance on their website.

State Standard and Specification Review

As a metric for acceptance of HFSTs, the evaluation team sought to identify States with State-specific standards, specifications, or special provisions. The team gathered information from several sources, including the American Traffic Safety Services Association (ATSSA) website, document review, and Web searches. They conducted a scan of common specifications and a comprehensive online search in September and October 2018.

The team used the ATSSA website, which maintains a list of State specifications for high-friction surfacing, as their starting point for identifying State specifications. While currently undated aside from a 2018 copyright, the site lists 10 States with unique standards.

For each State not included in the ATSSA list, the evaluation team searched the State DOT's website for HFST specifications that were related to individual projects and/or part of the State's general specifications. Some States without specifications outlined provisions in bid packages corresponding to the installment of HFSTs at specific locations.[1] The team searched each document for the following keywords: "friction," "surfacing," "high friction surface treatment," "high-friction," "HFST," "HFS" (high-friction surface), and "calcined bauxite." States whose specifications contained mentions of no such keywords relating to HFSTs were marked as without specifications. Analysis of documents in qualitative analysis software subsequently identified 10 additional States as having either existing or planned specifications. Finally, using Google's Advanced Search function, the team confirmed specifications for two additional States (Louisiana and Mississippi).

3.4 Other Data Analysis

When available, the evaluation team used data from FHWA to better understand funding, HFST-installation counts, and reach of HFST-related programs. Sources included FHWA program-funding data and FHWA's Web analytics.

FHWA Federal Funding Materials

The evaluation team analyzed two FHWA funding programs under which HFSTs are eligible—the HSIP and the Accelerated Innovation Demonstration (AID) grants—to understand FHWA's contribution to State investment in HFSTs. HSIP funding reports and the 2009–2017 HSIP-funding database were collected, providing information on the location, cost, and other information related to HSIP-funded HFST projects.[2] AID funding was collected using the AID demonstration project's website.(12)

FHWA HFST Web Visitor Analytics

Data on stakeholder use of FHWA's HFST material provide a proxy measure of interest and use of FHWA materials. The evaluation team reviewed the FHWA StaffNet Web Site Statistics, which includes data on the number of monthly visitors to selected HFST-related Web pages on the FHWA site.(14) Safety and EDC-related materials, including visitor counts for the HFST website entry page,

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[1] Such State websites only contained one set of project-specific provisions per State, except West Virginia's website, which listed multiple bid packages outlining special provisions for HFSTs.

[2] HSIP-funding data provided to evaluation team by FHWA HSA.

and HFST document–download counts, have been collected. Monthly counts were collected from July 2012 through July 2018. Earlier monthly count data exist, but July 2012 was chosen as it preceded by 1 month the first observed HFST-labeled Web page or document download.

During the data-collection process, issues with data quality were noted. Data were missing for a few periods, including for March 2015 and July–August 2017. Additionally, monthly totals varied dramatically in some months, suggesting incorrect temporal assignment and a short period of missing data.

During the review of materials and based on feedback from FHWA staff, concerns over the feasibility of using these data as a proxy for stakeholder interest were noted. These concerns include that these Web-access statistics likely represent initial interest in HFSTs. Also, as noted by FHWA staff, interest in HFSTs is highly seasonal, and dips over autumn and winter should be expected. Lastly, interviews with FHWA Resource Center staff and States suggest a good deal of HFST material may be sent directly from FHWA to State DOTs, and from State DOTs to local stakeholders. Despite these concerns, Web-traffic data provide an approximation of general interest in FHWA materials related to HFSTs and show how that interest changes over time. To help control for some of these confounding factors (i.e., missing periods of data and seasonality) the evaluation team's analysis is based on the ranking of HFST materials relative to all other Safety/EDC Web-page entries and document downloads.

3.5 Interviews

The evaluation team conducted semistructured interviews with FHWA Resource Center and HSA Research and Development staff as well as a contractor that began working on HFST implementation in 2008. Additionally, the evaluation team conducted nine interviews with State DOT staff. States interviewed include several early adopter States, States with large numbers of HFST installations (exceeding 50), and 2 States with a limited number of HFST installations at present, though both noted their plan to continue using the technology. No interviews with nonadopter States were conducted. Table 4 contains a full list of interviewees.

Table 4. HFST-evaluation interviewees.

Interviewee	Role	Interviewee Category
Alaska DOT	Engineer	State
Florida DOT	Engineer	State
Georgia DOT	Engineer	State
Illinois DOT	Engineer(s)	State
Indiana DOT	Engineer	State
Missouri DOT	Engineer	State
Pennsylvania DOT	Engineer	State
South Dakota DOT	Engineer	State
Texas DOT	Engineer	State
FHWA contractor	Technical contractor	Contractor
FHWA Turner-Fairbank Research Center	Research Highway Safety Specialist	Federal
FHWA Resource Center	Engineer	Federal

Interviewee	Role	Interviewee Category
FHWA HSA	Engineer	Federal

The evaluation team assured all interviewees that their identities would remain confidential to achieve unbiased answers to interview questions. Throughout this document, when interviewees are quoted, the evaluation team noted the month and year of the interview as well as the interviewer(s), but the interviewee name has been redacted. To maintain continuity and comparability between interviewee responses, a generic title was attributed to each interviewee.

4. Evaluation Findings

This section is divided into four subsections based on the evaluation areas the evaluation team examined. Each subsection assesses the evaluation area at a high level and then follows with an indepth discussion of findings. Findings are supported by evidence collected through the evaluation methods described in section 3.

The evaluation findings cover a large number of areas, but, broadly, the evaluation found an increase in published material on HFSTs attributable to FHWA R&T's research activities beginning in the late 2000s, bolstering interest in HFST. This interest in turn facilitated FHWA partnerships with State DOTs through the ELCSI-PFS and the SEaHC demonstration program, providing a foundation for FHWA technology-transfer activities that increased visibility and awareness of HFSTs as a safety measure. The deployment timeline of HFSTs indicates several mechanisms by which FHWA increased adoption of HFSTs as a safety measure, including funding for early demonstration projects and other deployments, outreach activities, and published research. The evaluation found that HFSTs are a technology with implementation challenges, including complexity and cost, though several characteristics of successful implementation are identified in the evaluation findings. HFSTs were demonstrated to be an effective safety measure, significantly reducing roadway departures on curves and particularly in areas susceptible to wet-weather crashes.

4.1 Evaluation Area One: HFST Safety and Performance Data Availability

This subsection describes the evaluation team's findings regarding the availability of HFST-safety and -performance data.

Overview of Findings

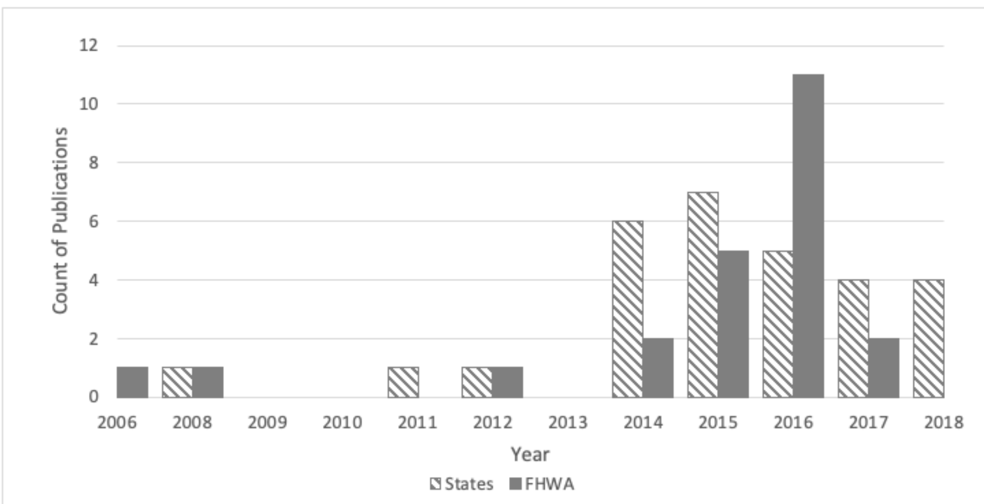
FHWA R&T's research activities from the late 2000s led to an increase in published material on HFSTs in the United States, including the EPSP.(10) Interviews and literature and document reviews yielded information about the timing and effect of research and related activities on the research community and showed that FHWA played a key role in accelerating consideration of HFSTs as a topic of interest.

> Finding 1a: FHWA contributed to an increase in the availability and quality of information on HFSTs in the United States through early performance research funding, collaboration with States for demonstration and data collection, and Resource Center leadership and technical assistance.

The logic model developed for this evaluation proposes that FHWA research advanced the availability and quality of safety and performance data by serving as a resource and repository of HFST performance–related data as well as actively supporting HFST performance–related data collection. Evidence demonstrates early FHWA R&T leadership on HFST, in partnership with lead-adopter States, led to an increase in the availability of HFST-safety research in the United States through a commitment to conducting domestic research and widely sharing the results of that research.

Early FHWA involvement and resource investment started, in part, when lead-adopter States began asking FHWA questions about HFST. When FHWA began researching and making inquiries, one contractor stated, “industry swooped down on me like you have never seen in your life.”[1] Vendors that had brought HFSTs from abroad often came with product familiarity and installation experience; however, some installers were still “tweaking” their installations.[2] Without clearly defined best practices of installation (i.e., automated versus manual, calcined bauxite versus bauxite or other alternative aggregates, etc.) and with a growing market for HFST installations, some players in the industry saw a new market for generating revenue. Unqualified vendors began applying for (and sometimes winning) projects, resulting in suboptimal installations and experiences with HFSTs in some early installations.[3] One State representative indicated their team “had to learn for ourselves the pros and cons”; when the State applied an HFST on an open-grade friction source, the State experienced problems. Meanwhile, other States had no issue with this type of application.[4]

The earliest domestic publication located by the evaluation team, *Low-Cost Treatments for Horizontal Curve Safety*, was published by FHWA in 2006.[(11)] Pre-EDC-2, only six research-focused HFST publications were authored by FHWA or State representatives. Research-focused publications include case studies, fact sheets, guides, magazines, and reports. Since EDC-2, FHWA has been publishing more HFST-related research documents and has been coordinating with other agencies, such as the American Association of State Highway and Transportation Officials (AASHTO) and ATSSA, as well as individual States, increasing the breadth and volume of HFST research publications available. Figure 2 shows counts of research documents published by FHWA and States.



Source: FHWA.

Figure 2. Bar chart. Count of research-focused publications separated into FHWA and State authorship.

[1]FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

[2]FHWA Technical Contractor; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in November 2017.

[3]State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Kaitlin Coppinger, Lydia Rainville, and Matthew Keen in November 2017.

[4]State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Kaitlin Coppinger, Lydia Rainville, and Matthew Keen in November 2017.

Using qualitative analysis software, the evaluation team found FHWA publications have some of the highest numbers of citations within HFST literature, although overall numbers remain low.[5] Across all the literature compiled by the evaluation team, *Low-Cost Treatments for Horizontal Curve Safety* was the most frequently referenced resource, being cited in over 10 other reports or studies.(11) Though this study was published over a decade ago, HFST-related publications continue to cite it, underscoring both the limited amount of early domestic HFST literature and FHWA's role in contributing to the availability and quality of early information on HFSTs.(11) The study discussed HFSTs in its chapter on minor roadway improvements, describing Florida's use of a proprietary HFST technology and providing friction values pretreatment and post treatment.

The FHWA EDC website, HFST frequently asked questions (FAQ), and *Low-Cost Treatments for Horizontal Curve Safety* and its 2016 update were cited most frequently.(15,11,16) Other FHWA HFST documents cited include *Field Performance of High Friction Surfaces*, the *HFST Curve Selection and Installation Guide*, and *Case Study: Kentucky Transportation Cabinet's High Friction Surface Treatment and Field Installation Program*, each of which was cited in two other reports.(2,17–18) The evaluation team also found, in addition to references to papers and websites, references to FHWA individuals, like one retired staff member, formerly of the FHWA Resource Center, which are not otherwise captured in the citation analysis.

While overall research-publication levels were initially low, FHWA and State-led research publications did trend upward over the observation period, demonstrating increased interest in HFSTs. During EDC-2, research-focused publication levels were low, but as will be discussed in greater detail in Evaluation Area 2, this circumstance is likely due to a shift toward activities extending beyond research and data, such as technology transfer to States. Post-EDC-2, State demand for quantitative data has driven a significant increase in the volume of research-focused publications by both FHWA and States. One interviewee noted:

> *"People who make policy and decisions need the highlights. They see crash reductions and it's the most impactful thing for them."*[6]

Figure 3 shows the count of HFST-related publications. Throughout 2012, absolute publication numbers are low; however, between 2006 and 2011, FHWA and State authors accounted for 80 to 100 percent of all domestic HFST-related materials. The number of FHWA publications increases as EDC-2 approached, averaging 1 or 2 documents per yr to sustained levels of around 15 per yr post-EDC 2.[7] It is important to note that this graph captures publication of all HFST-related documents, not just research publications. As such, "State-led" counts are inflated due to the prevalence of HFST mentions in nonresearch State documents, such as HSIP, Transportation Safety Improvement Program, and SHSP documents.

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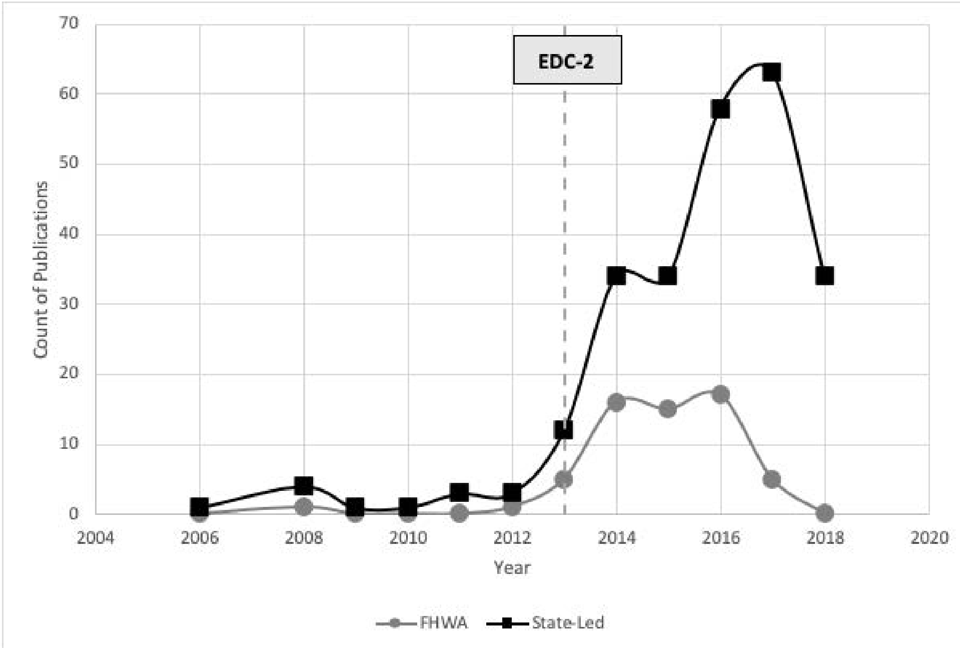
[5]Because of the practitioner-focused nature of FHWA's HFST publications, most end users of these materials are unlikely to be researchers that would cite the source of the publication. In other words, these materials are expected to aid States and others in preparation for and installation of HFSTs, rather than to serve as a knowledge source for academic and other agency publications on the technology.

[6]FHWA Technical Contractor; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in November 2017.

[7]This analysis began in 2016, and the main document collection ended in 2017. As such, while an effort was made to capture all new HFST publications after the end of the document-collection period, the list may not be comprehensive, possibly understating the number of 2018 publications.



Source: FHWA.

Figure 3. Line chart. Count of publications (all types) by author type.

After the first FHWA publication, authorship and sponsorship of domestic materials related to or mentioning HFSTs were largely split between FHWA and State-led research efforts, as depicted in figure 3.[8] The increase in FHWA publications was accompanied by an increase in State and local transportation agency–authored materials, both of which preceded an increase of academic research–community documents related to HFSTs. Although such trends do not necessarily prove FHWA improved availability of HFST-related safety and performance data in the United States, the timeline of the publications is consistent with this hypothesis: no domestic documents were found that were produced prior to FHWA's documents.

As domestic research on HFSTs expanded, Resource Center and other FHWA employees worked to disseminate that research and provided technical assistance. In speaking with State representatives, six interviewees mentioned speaking or working directly with a specific Resource Center representative.[9] Several interviewees also mentioned attending Resource Center or other FHWA-hosted events and presentations, helping raise awareness of HFSTs and improve understanding of existing research.

As FHWA engaged in HFST technology transfer through a strong HFST champion in the Resource Center and through the ELCSI-PFS and EDC-2, participating States gained a greater ability to share experiences and access information and resources from other States, improving overall awareness of the technology and laying the foundation for changing attitudes toward HFSTs.

[8]Appendix A provides a full list of documents with which FHWA was involved.

[9]State DOT Engineers; phone interviews conducted by evaluation team members Jennifer Gissel, Kaitlin Coppinger, Lydia Rainville, and Matthew Keen in August 2017–April 2018.

In addition to FHWA citations and mentions, the evaluation team found FHWA was actively involved in sponsoring State HFST research. The four examples in table 5 show where the evaluation team found direct evidence of FHWA involvement in sponsoring State and academic HFST research.

Table 5. Selected examples of FHWA-sponsored HFST research.

Study	Description
High Friction Surface Treatment Alternative Aggregates Study, National Center for Asphalt Technology(6)	• This study tested the pavement surface–friction performance of seven alternative aggregates to assess if they would perform similarly to calcined bauxite as an HFST. • No alternative aggregates were able to match the friction values achieved by HFSTs using calcined bauxite.
Field Performance of High Friction Surfaces, Virginia Tech Transportation Institute(17)	• This report, an evaluation of an HFST, was developed as guidance for agencies when considering whether HFSTs were an appropriate solution for addressing instances of low skid resistance and/or especially high-friction demand. • It also included a sample benefit–cost analysis from an installation in Wisconsin, which found that the crash-reduction benefits from increased skid resistance outweighed the costs of installation; project-specific BCRs ranged from 0.47 to 8.45.
Evaluating the Need for Surface Treatments to Reduce Crash Frequency on Horizontal Curves, Texas A&M University(19)	• This report developed an analysis framework to assess the need for surface treatments on curves based on safety-margin analysis. • The models and analysis presented can be applied by transportation agencies to evaluate the safety performance of a curve and estimate the potential safety benefit of installing an HFST at the curve.
High Friction Surface Treatments, Merritt and Persaud	• This study provided a rigorous review of prior HFST studies. • It collected data and estimated CMFs for four States both individually and combined, looking at both curves (three States) and ramps (two States). • The researchers conducted a benefit–cost analysis using combined installation-cost data.

Finding 1b: Research gaps related to HFST durability, performance, and alternative aggregates may be barriers to HFST deployment.

The earliest domestic research was led by FHWA; however, this research is limited in its ability to advocate for adoption of HFSTs as a safety measure. Early information was largely anecdotal,[10] but States want data before taking a risk on an unproven technology. The primary research gap remains the lack of high-quality CMFs. However, in addition to ongoing research to develop improved CMFs, several other topics emerged for which continued or new research and a more equal dissemination of existing knowledge could remove potential barriers to adoption.

[10]FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

Durability and Long-Term Performance

International experiences have provided baseline expectations for durability and service life of HFSTs, and when applied properly, HFSTs seem to be consistent in terms of durability and longevity.(18) However, interviews and document reviews indicate that States have overcome a diverse set of challenges and experienced a variety of project outcomes.

As some States and local governments still have limited experience with the technology, additional targeting of resources and research for these recent adopters could be beneficial. HFSTs are a complex technology with a learning curve (discussed in subsection 4.3), so an understanding of the many potential factors that impact installation durability and longevity is not always straightforward.

The following are questions the evaluation team included in their interviews: Why is California getting more life out of the applications on open-graded mixes than Florida?(20) What are States' experiences with special circumstances, such as harsh winter weather, snow plows, or studded snow tires?[11] As an agency that interacts with all State DOTs, FHWA can continue to act as a repository of knowledge—collecting and collating the experiences of States and sharing them with other States looking for more information on unique HFST-installation circumstances. This sharing can be achieved through publicly available resources, through technical assistance from the Resource Center, and by making connections between practitioners when a question arises.

A few interviewees expressed uncertainty or hesitation regarding adoption and harsh winter conditions. One interviewee noted snow and ice crashes would be excluded from their CMF analysis, but stated it was "not really intended for snow/ice" and was not sure whether any States use HFSTs specifically to mitigate roadway-departure crashes due to snow or ice.[12] Additionally, one State DOT noted that one of their districts was slow to adopt after expressing concern that the treatment may cause additional wear and shorten the useful life of snowplow blades.[13]

Because discussing benefits can aid in encouraging new States to adopt a technology, much of the early research focused on successful projects. And as such, FHWA has played an important role in in its early focus on HFSTs benefits that were demonstrated internationally. However, by limiting detailed discussion of the early challenges, such as the trial and error States went through before achieving maximum HFST durability or reasons why applications may have failed, some of the avoidable problems may have been repeated. One interviewee noted the following:

> *We need to learn about the materials themselves and how to apply them so we make sure we're getting a long-lasting product. When a State tries it and we get a failure, then States don't want anything to do with it. We need a better handle on how thick the resin is going down, need to make sure we're putting it down on a pavement that is compatible.*[14]

More recently, FHWA has begun to address variations in durability by mentioning projects that overcame challenges or failed installations; updated HFST FAQ as well as other published reports

[11] The desire for additional research on HFST durability with regard to harsh winter conditions, snow plows, and/or studded snow tires was expressed in three separate evaluation team interviews with State DOT employees (Illinois, Alaska, and South Dakota).

[12] FHWA Technical Contractor; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in November 2017.

[13] State Engineers; phone interview conducted by evaluation team members Jennifer Gissel, Kaitlin Coppinger, Lydia Rainville, and Matthew Keen in November 2017.

[14] FHWA Technical Contractor; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in November 2017.

have helped raise awareness of challenges. This type of knowledge transfer is also conducted outside formal publications, such as at peer exchanges.

The benefit of FHWA addressing this research gap would be twofold: FHWA and States would be more able to anticipate potential challenges and develop advanced strategies to overcome obstacles to HFST-related performance concerns. By collecting data and researching the causes of and contributing factors to durability and long-term performance challenges or failures, States could be better positioned to write more effective specifications and better evaluate project bids, mitigating challenges before they impact the durability of the installation and resulting in safety improvements from longer-lasting, higher-quality installations and cost savings to agencies funding and deploying HFSTs.

Materials—Why Calcined Bauxite?

HFSTs are, first and foremost, a safety measure, but some material engineers from State DOTs have shown interest in chip seals and other pavement treatments due to their superficial similarity to HFSTs as a resurfacing material. As such, State DOTs have expressed interest in conducting additional research on domestic and other alternative aggregates to help bring down its cost. The high cost of calcined bauxite is driven by multiple factors, including the fact that it is a processed form of bauxite, which is the raw material source of aluminum, resulting in competition between industries for the material. Additionally, unlike most aggregates used in pavements, limited deposits of bauxite exist in the United States, and the material has to be shipped long distances, raising prices further.

Initially, with little domestic research available on HFSTs, States lacked a clear understanding of why the friction properties of calcined bauxite are preferable to other aggregates. Questions arose as to how high a friction number is actually needed: “don’t need 80, but maybe 50,” which could be achieved at a significantly lower cost ($6/yd^2 as opposed to $38).[15] As such, early adopter States often partnered with industry to test sections using alternative aggregates. In 2005, one State installed test sections using limestone aggregates, but friction numbers were low, and operators felt unsafe. After 2005, the State switched to a proprietary product that uses calcined bauxite, and achieved the desired friction values.[16] In another State, calcined bauxite was not identified in their specification initially, and for cost-control reasons, the contractor opted for a different bauxite aggregate that was not calcined. The result was increased time and cost from the need to manage and monitor it more closely to ensure it did not have different properties or wear differently as time went on.[17]

Largely led by States and industry, existing research on domestic and alternative aggregates is limited with a high demand remaining for additional research, to “continue to test and continue to look for more reasonably priced materials.”[18] However, should these more reasonably priced aggregates fail to provide the friction values necessary for HFSTs, it is likely that additional research

[15]State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Kaitlin Coppinger, Lydia Rainville, and Matthew Keen in November 2017.

[16]State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Kaitlin Coppinger, Lydia Rainville, and Matthew Keen in November 2017.

[17]State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in October 2017.

[18]State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Kaitlin Coppinger, Lydia Rainville, and Matthew Keen in November 2017.

or communication is required to help potential deployers understand what makes calcined bauxite so effective and why the friction values it provides are essential to a successful HFST.

With respect to domestic sources of calcined bauxite, through the FHWA Center for Accelerating Innovation, FHWA communicated to its stakeholders that Arkansas installed the first domestic HFST using calcined bauxite mined and calcined in the United States.[19]

4.2 Evaluation Area Two: Change in Awareness, Knowledge, and Attitudes

This subsection describes the evaluation team's findings on changes in stakeholder awareness of HFSTs as a safety measure, knowledge about the effective implementation of HFSTs, and attitude toward use of HFSTs.

Overview of Findings

As described in subsection 4.1, FHWA's R&T research activities from the late 2000s to the present increased published material on HFSTs in the United States, with early partnerships between FHWA and State DOTs through the ELCSI-PFS and the SEaHC demonstration program. This research provided the foundation for FHWA engagement in technology-transfer activities that increased visibility and awareness of HFSTs and their promising safety impacts and, over time, informed attitudes toward them as a safety measure.

Finding 2a: Collaborative forums convened by FHWA in partnership with States, including EDC-2, peer exchanges, and the ELCSI-PFS TAC, were effective in raising awareness of HFSTs among potential users and providing forums for learning and exchange.

EDC-2

Beyond research and data-collection efforts, FHWA actively worked to encourage technology transfer of HFSTs to States from abroad. Technology-transfer activities included facilitating peer exchanges, including HFST activities in newsletters, and producing publicly available videos. The FHWA Resource Center, with assistance from HSA staff, also provided presentations and other technical assistance to States and other stakeholders. These activities contributed to an increase in State awareness and improved attitudes toward HFSTs.

EDC-2 generated awareness of the technology and brought together early adopters with those considering HFSTs. During interviews, four States directly credited EDC-2 for encouraging use of HFSTs and raising awareness of the technology's safety-benefit potential.[20]

EDC-2 promoted HFSTs through the EDC website.(15) The EDC-2 HFST website provides background information along with other informative resources for States considering HFST implementation. Such resources include a fact sheet, a brochure, FAQ, various case studies, an article in *Public Roads*, and the chat pod from the virtual EDC Exchange.

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[19]FHWA Center for Accelerating Innovation newsletter, August 9, 2018.

[20]State Engineers; phone interviews conducted by evaluation team members Jennifer Gissel, Kaitlin Coppinger, Lydia Rainville, and Matthew Keen in August 2017–April 2018.

The evaluation team was able to locate information on the virtual EDC Exchange mentioned on the EDC-2 website. Conducted on June 26, 2014, the webinar targeted local and tribal agencies.(21) Based on agendas, the exchange appears to be a sort of hybrid webinar–in-person meeting; a portion of the exchange was hosted via webinar and included presentations from various States and FHWA representatives, while a secondary portion allowed for individual, more localized discussion facilitated by Local Technical Assistance Programs (LTAPs) or other local transportation practitioners.

Additionally, FHWA maintains *EDC News*, which provides updates on new HFST projects and success stories.(22) HFST projects have been included in the newsletter at least 22 times, beginning in September 2013. In addition, the EDC-2 HFST team released two versions of a video on the benefits of HFSTs. While the videos received some views (2,718 for the short version and 704 for the longer version), these were not a notable resource mentioned during interviews with States.

In one interview conducted for this report, the interviewee explained that they were not familiar with this news resource until EDC-2 had been released as follows:

> *"Knowledge, getting the word out—this came out in 2014, EDC. Used a lot overseas, [but] U.S. is still new to this. We didn't know anything about it until EDC-2."*[21]

Also, for States that had already been introduced to HFSTs but did not necessarily have widespread installations, EDC-2 re-introduced the technology as a low-cost and proven safety measure.[22]

Peer Exchanges

Peer exchanges provided another opportunity for States, experts, and others to convene in person or via Web conference around a specific set of topics and share knowledge, ideas, and experiences. The evaluation team identified 14 peer exchanges that included HFSTs as a topic of discussion between 2013 and 2017, with 43 States attending at least 1 of these.[23] The average number of peer exchanges attended by States was just under 2, and 5 States each attended 4 peer exchanges.[24] The majority of these peer exchanges were facilitated by FHWA under the Roadway Safety Professional Capacity Building Program, which provides resources to help safety experts and specialists develop critical knowledge and skills within the roadway-safety workforce.(23) Table 6 lists these peer exchanges.

Table 6. HFST-related peer exchanges (2013–present).

Peer Exchange (Location)	Year	Participants
Horizontal Curves Virtual Peer Exchange (virtual)(24)	2013	Delaware, Illinois, Iowa, Maryland, Michigan, Minnesota, New Jersey, Ohio, and Wisconsin
Horizontal Curves Virtual Peer Exchange (virtual)(25)	2013	Alabama, Florida, Indiana, Louisiana, Missouri, Oklahoma, South Carolina, Tennessee, Texas, and West Virginia

[21]State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in October 2017.

[22]Kansas LTAP.

[23]Alaska, Hawaii, Massachusetts, Nebraska, New York, Rhode Island, and Vermont were not listed as participants in any of the peer exchanges located by the evaluation team, though FHWA division offices from Massachusetts, Rhode Island, and New York are listed as attendees.

[24]Iowa, Louisiana, Michigan, and Ohio each attended four peer exchanges.

Peer Exchange (Location)	Year	Participants
Roadway Departure Six-State Peer Exchange (Virginia)(26)	2013	Kentucky, North Carolina, South Carolina, Tennessee, Virginia, and West Virginia
Horizontal Curves Peer Exchange Alabama (Alabama)(21)	2014	Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, and Missouri
Systemic Safety Implementation Peer Exchange (Ohio)(27)	2014	Connecticut, Delaware, Iowa, Louisiana, Michigan, Ohio, and Pennsylvania
Systemic Safety Implementation Peer Exchange (Utah)(27)	2014	Arizona, Kansas, Nevada, North Dakota, Oklahoma, Utah, and Washington
Horizontal Curves Peer Exchange (virtual)(28)	2014	Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, South Dakota, Utah, Wyoming, tribal and county agencies, and Western and Central Federal Lands Highway Divisions
Thurston County-hosted peer review (Washington) (29)	2014	35 individuals, 21 from local governments in Washington State
Systemic Safety Implementation Peer Exchange (Arizona)(30)	2015	Arizona, Arkansas, California, Colorado, Idaho, Illinois, Nevada, Texas, and Wisconsin
Systemic Safety Implementation Peer Exchange (Tennessee)(30)	2015	Alabama, Florida, Kentucky, Maine, Maryland, Mississippi, New Jersey, Pennsylvania, Puerto Rico, and Tennessee
Northeast Roadway Departure Safety Peer Exchange (Pennsylvania)(31)	2016	Connecticut, Maryland, New Jersey, Ohio, Pennsylvania, and West Virginia
Contributions of SHSP and HSIP in Driving Down Fatalities (Virginia)(32)	2016	Florida, Louisiana, and Minnesota
Peer Exchange in Phoenix, AZ (HSA)[25]	2016	Arizona, California, Texas, Kansas, New Mexico, Utah, Nebraska, and Nevada.
Focus State Roadway Departure Safety Plan and HFST Peer Exchange (Colorado)(33)	2017	California, Colorado, Idaho, North Dakota, South Dakota, Montana, Utah, and Wyoming
Roadway Departure and HFST Peer Exchange in Vancouver, WA (HSA)[26]	2018	Arizona, Alaska, California, Hawaii, Idaho, Nevada, New Mexico, Oregon, and Washington
HFST and CMF Peer exchange in Harrisburg, Pennsylvania (HSA)[27]	2019	California, Florida, Indiana, Iowa, Kentucky, New Jersey, Oklahoma, and Pennsylvania

During interviews with State DOTs, interactions with Resource Center staff during these exchanges were consistently cited as a resource for safety information on HFSTs. Support from other States

[25]FHWA HSA, email communication with evaluation team, January 6, 2020.
[26]FHWA HSA, email communication with evaluation team, January 6, 2020.
[27]FHWA HSA, email communication with evaluation team, January 6, 2020.

(through peer exchanges) was also mentioned as beneficial both in terms of deciding whether to undertake an HFST project and in troubleshooting potential installation challenges.

In addition to raising awareness, peer exchanges and other EDC-2 events also provide opportunities for States to ask questions of their peers and learn about the challenges they faced. TDOT hosted a peer exchange that included a discussion of strategies to evaluate safety and material performance as well as site-selection guidelines. The information gleaned during the peer exchange and accompanying site visits enabled Puerto Rico Highways and Transportation staff to prepare for Puerto Rico's first HFST installation.[(34)] These opportunities are one way of reducing the learning curve and facilitating knowledge transfer between early adopter, highly experienced States and those still learning about the benefits of HFSTs.

Peer exchanges also provided an opportunity for cost discussions in the context of safety measures (as opposed to a pavement treatment), which reframed benefit–cost discussions. State DOT safety staff provided additional insight into how to select sites and measure success. For example, Georgia began using a systemic approach to identifying horizontal curves for HFSTs, choosing to treat curves that did not necessarily have sufficiently low friction to contribute to high crash rates (yet) but showed similar characteristics to existing high-crash, low-friction curves.[28] FHWA research and materials provided information to support the systemic approach.

ELCSI-PFS TAC

The pooled fund–study approach has been well suited to a complex technology like HFSTs. Pooled-fund studies, including ELCSI-PFS, enable FHWA and States to leverage research funds to conduct projects of interest to multiple States that may be difficult for an individual State to undertake. The ELCSI-PFS TAC also provided a forum for early and ongoing information sharing among the member States, as well as opportunities for States to ask questions of FHWA employees and industry experts invited by FHWA.[29]

FHWA shared information on HFSTs and States identified HFSTs as an area of interest at TAC meetings as early as 2010. Some States wanted clarification in these early meetings on the connection between safety measures and pavement design. In particular, States discussed the lack of communication between pavement and safety groups, namely that decisions for each are largely made independently from the other. FHWA stressed the need for safety groups to work with maintenance, pavement, and other groups to make more informed safety decisions. During the early years, the overall attitude toward HFSTs was positive, but the lack of detailed information and specifications made some States hesitant to take safety funds away from other improvement efforts to invest in HFSTs. Other implementation barriers States mentioned were liability concerns and staffing limitations that made maintenance groups resistant to new technologies.

Starting in 2014, HFSTs feature more prominently at TAC meetings than they did previously. One State indicated in their presentation on their roadway-departure safety-improvement plan that HFSTs were being applied on curves and ramps, with 30 currently installed, 150 planned for 2014, and a goal of 250 sites by 2015. Another presentation was on the results of the EPSP study, and another was on a State's pavement-friction research, again highlighting the combined effort from materials and safety groups. This State described their experience using a friction tester at certain points in the curve, noting that this tool could prove a useful in establishing where to start application. While

[28] State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in October 2017.

[29] At the 2010 meeting, a lead-adopter State presented on their involvement with the SEaHC demonstration program.

this research allowed for communications across different research groups, it also brought forth a new issue in determining the best approach to site selection: preventive versus reactionary treatments. At the 2014 meeting, high-friction surfaces received 31 percent of the vote in the balloting process used to determine priority safety improvements for evaluation, which was the second highest area of interest by a substantial margin (the third highest received 13 percent).

At the 2015 meeting, HFSTs were an established area of interest for States, and presentations and discussions highlighted the member States' experience with HFSTs. These discussions explored nuances discovered through direct experience and trial and error, such as location identifying strategies, application methods, and the effect of climate on the treatments. At this point in the ELSCI-PFS, States generally considered HFSTs an effective safety measure, and the focus of discussions was on the specifics of the measure rather than the justification for it. By 2017, HFSTs were again listed as one of the highest priority measures with several presentations given on the technology, including an overview of State approaches to road-network screening for HFST site selection, manual- versus automated-application method, friction testing, effectiveness over time, and materials for aggregates and course treatments. States also were able to share data and lessons learned, as lead-adopter States had been using HFSTs for several years. One lead adopter presented their States' follow-up testing strategy to ensure performance thresholds were met throughout the expected lifespan of the treatment.

Finding 2b: State inclusion of HFSTs in informational materials, SHSPs, and HFST specifications demonstrates growing acceptance of HFSTs as a safety measure. References to FHWA resources indicate that its investment in HFST research played a role in this acceptance.

To understand the change in acceptance of HFSTs, the evaluation team reviewed State materials, including State DOT websites, SHSPs, and specifications, to assess the extent to which HFSTs were included. Within these materials, the evaluation team identified explicit references to FHWA research and technology-transfer activities. Evidence of the inclusion of HFSTs demonstrates growing State acceptance of HFSTs, though some States have progressed farther along the acceptance and adoption curve than others. References to FHWA within these State materials are evidence of the role FHWA played in awareness and influencing attitudes toward HFSTs among their stakeholders.

Review of State SHSPs, HSIP Annual Reports, Websites, and Specifications

To assess the level of awareness of HFSTs as a safety measure in the United States, the evaluation team reviewed each State's latest SHSP, HSIP Annual Report, and online standards and specifications, for references to HFSTs. References to HFSTs in key safety and planning documents are an indicator of both awareness and acceptance of HFSTs as a safety measure. To understand any potential influence of FHWA in State attitudes toward HFSTs, the evaluation team sought references to FHWA within these materials.

As of July 2017, 42 percent of States (21 out of 50) mention HFSTs in their SHSPs. SHSPs mentioning HFSTs were coded in qualitative analysis software for benefit information and evidence of FHWA involvement. Twelve of the 21 SHSPs mentioned a safety benefit, and some States mentioned other benefits, such as durability and lifecycle costs relative to other measures, and four referenced FHWA.

The review of State DOT websites showed that, as of July 2017, 45 States listed or mentioned HFSTs on at least one Web page or other publicly posted document.[30] The level of detail and focus on HFSTs on State DOT sites vary by State. For example, Montana and Wisconsin have dedicated Web pages providing information and updates on State HFST projects. Several States, including Texas and Ohio, provide information oriented toward contractors and bidders with no general information about HFST planning or efficacy.

Of those 45 States mentioning HFSTs on a Web page or in their documentation, 31 directly reference FHWA. The level of use or reference to FHWA products ranges across websites. Eighteen State DOT websites further reference FHWA. For example, Florida includes an HFST study conducted in conjunction with FHWA.(35)

Finally, information on State-specific standards, specifications, or special provisions was gathered from several sources, including the ATSSA website; the document, literature, and relevant source-material review; and Web searches.(36) In total, the scan identified 22 States with either specifications or special provisions. An additional 11 States potentially have specifications, but the evaluation team was unable to locate them online. Table 7 summarizes the findings of the secondary scan and comprehensive Web search.

Table 7. State HFST specifications.

Presence of Specification	Number of States	States
Specification present	18	Alabama, Alaska, California, Connecticut, Florida, Georgia, Illinois, Iowa, Kentucky, Louisiana, Maryland, Michigan, Ohio, Pennsylvania, South Carolina, Tennessee, Texas, and Virginia
No specification found online	17	Arizona, Arkansas, Colorado, Connecticut, Idaho, Maine, Minnesota, Missouri, Montana, Nevada, New Hampshire, New Mexico, New York, North Dakota, Oregon, Vermont, Washington, and Wyoming
Possible specification—unable to locate online	10	Delaware; Washington, DC; Hawaii; Indiana; Kansas; Mississippi; Nebraska; New Jersey; Utah; Virginia; and West Virginia
Special provision	6	Massachusetts, North Carolina, Oklahoma, Rhode Island, South Dakota, and Wisconsin

Specifications are critical to not just the performance of an individual site with HFST, but ultimately the success of HFST as oftentimes, if the first application of a technology is a failure, the adoption of that technology is delayed or, at worst, abandoned by the State.

HFSTs require highly detailed specifications with three especially important areas to the success of an HFST: the polymer binder, calcined bauxite, and construction methods used. Contractors may try to substitute lesser-grade aggregates in an effort to be more competitive in bidding. Unfortunately, by doing so, the substituted aggregate tends to shear and polish in the high-friction environments, where HFSTs are installed. With epoxy, the most expensive material used in an HFST, it is important that details in the specification outline underlying pavement cleanliness, temperature thresholds, and moisture thresholds as these factors can weaken the bond between the epoxy and roadway, resulting in premature failure. Furthermore, the performance of an HFST relies heavily on the construction methods used. HFSTs require specialized equipment that applies a uniform layer of

[30]The review was conducted between February 6 and February 17, 2017. The website search was conducted using Google, with manual review of selected documents of interest.

calcined bauxite moments after applying the epoxy binder. Applying the calcined bauxite prior to the epoxy-binder curing is vital, or the calcined bauxite will not be embedded in the epoxy and can easily be removed from the road surface on heavy-traffic roadways. Implementation of HFSTs in a State can be hindered if specifications do not account for these details.

References to Use of FHWA Resources

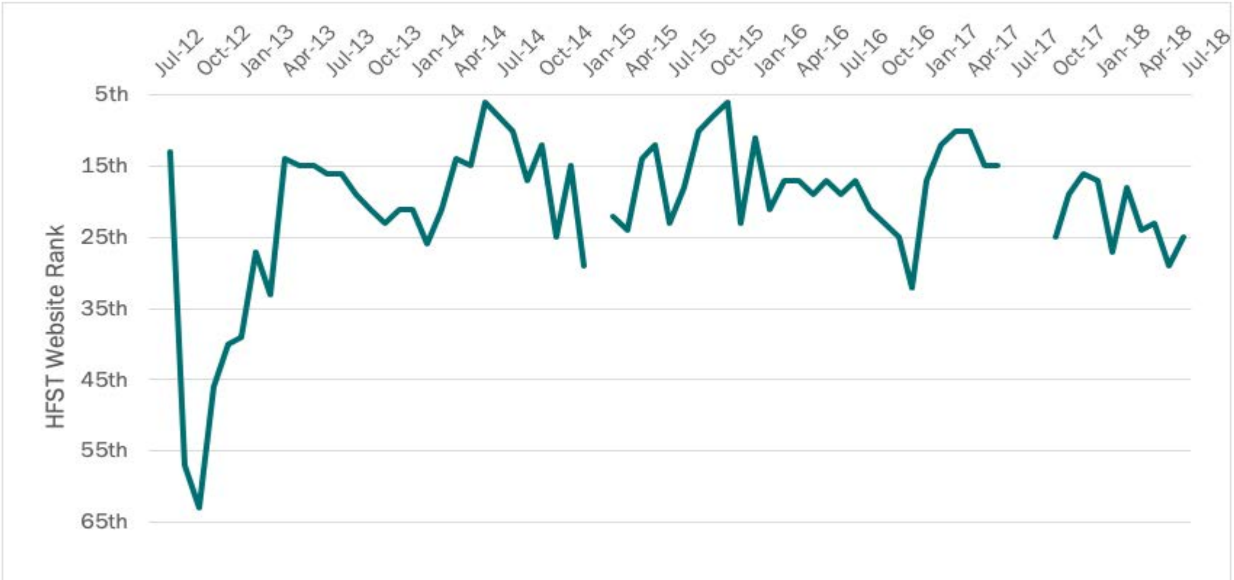
The evaluation team reviewed visitor access to FHWA Web pages pertaining to HFSTs as a proxy for public and State agency interest in and access to HFST information. The HSA HFST information page has been the most common HFST entry Web page available from FHWA since at least July 2012.[31] As of June 2018, this Web page provided a concise explanation of the technology, its history, current status map (as of December 2017), and employee contact and other information.

Figure 4 shows the rank of this HFST Web page relative to all other FHWA safety Web pages, as measured by unique visitors entering the website via that page each month. A ranking of 1 means that the Web page received the greatest share of visitors that month out of the approximately 500 entry FHWA safety Web pages.[32] For example, in June 2017, the most popular HFST-related Web page received 21 unique visitors, placing it 15th in the ranking, in the context of 260 unique FHWA safety Web pages visited by 1,872 unique visitors.[33]

[31]The current Web page contains materials and dates that suggest occasional updates, and as such, the evaluation team does not have information on the exact materials presented when the Web page was launched.

[32]The actual number of entry FHWA safety Web pages varies over time. Earlier months in the observation period only reported the top-ranking entry page values.

[33]As these are entry counts, they do not include visitors who clicked through from other FHWA Web pages.



Source: FHWA.

Figure 4. Line chart. Ranking of most accessed HFST entry Web page (out of all safety entry Web pages).[34,35]

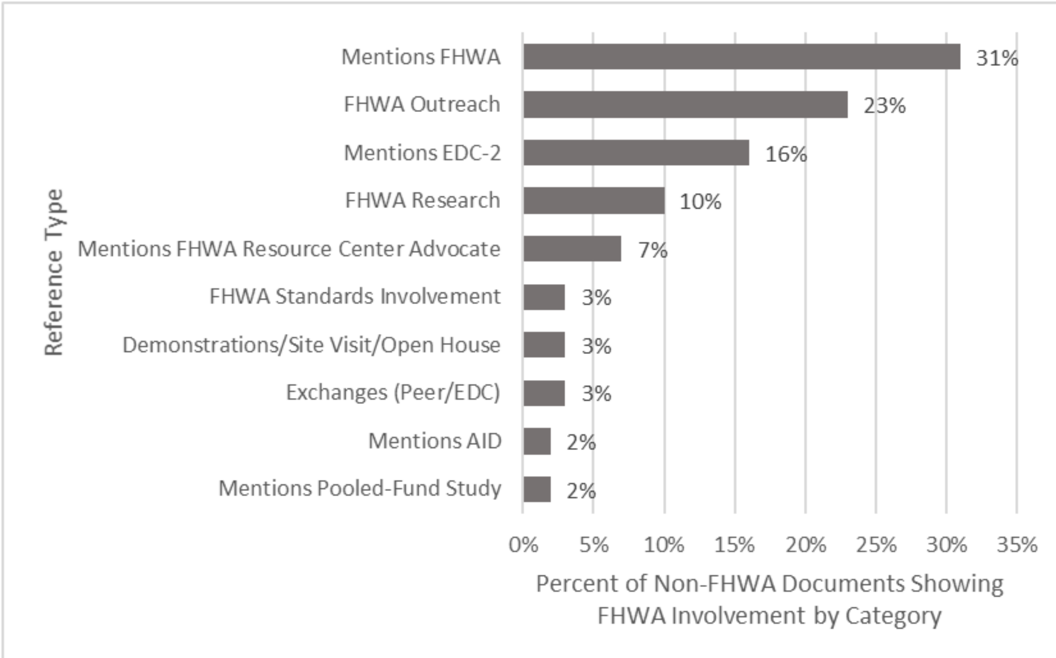
The HFST Web page rankings, as shown in figure 5, are a proxy for interest in HFSTs. They show a relatively consistent interest in HFSTs beginning in spring 2013. A correlation between initial interest in HFST resources and the start of EDC-2 appears to exist. Of the HFST documents available for download (e.g., PDF files rather than Web pages shown in figure 4),[36] the HFST FAQ sheet remained the first or second most popular safety document downloaded from FHWA from spring 2014 through fall 2017.(15) For example, in June 2017, 141 unique safety documents were downloaded a total of 2,221 times, of which 5.3 percent were HFST-related FAQ sheets or EDC-2 HFST materials.

References to use of FHWA research and materials noted above indicate these resources played a role in awareness and acceptance of HFSTs. The evaluation team analyzed non-FHWA-authored HFST documentation (as detailed in subsection 2.3) for citations or mentions of FHWA research and related activities. Figure 5 shows how these documents reference FHWA influence.

[34]The vertical axis is in descending order so that high rankings (lower numbers) appear toward the top of the graph.

[35]Gaps are due to missing records. Variations in the total number of website visitors (not shown) suggest some missing months may have been included in adjacent monthly data. Relative page rankings are shown rather than absolute visitor counts to control for these possible data issues.

[36]The FAQ sheet has been updated since its initial release.



Source: FHWA.

Figure 5. Bar chart. Percent of 281 non-FHWA documents showing evidence of FHWA involvement.

While not a definitive representation of the level of FHWA engagement in each area, it is notable that FHWA research and outreach make up large shares (22 and 23 percent, respectively) of all citations and mentions. In total, these activities show that FHWA is effectively reaching out to State and local transportation agencies to improve technology awareness and influence levels of adoption.

4.3 Evaluation Area Three: Deployment of HFSTs as a Safety Measure

This subsection describes evaluation team findings on the successful deployment of HFSTs as a safety measure.

Overview of Findings

Both the total number and the geographic distribution of HFST installations increased between the first domestic installations in 2004 and the present, although data limitations prevent an exact estimate of this growth. FHWA directly contributed to this growth and supported States deploying HFSTs through the SEaHC demonstration projects; further, HFST installations were funded, in part, through HSIP and AID. Based on a review of the deployment timeline of HFST installations in relation to FHWA outreach activities, like EDC-2 and peer exchanges, and other published research, it is likely that these activities influenced States' deployment of HFSTs.

The path to deployment for States has not been without challenges and barriers. Based on interviews, case studies, and other research publications, it is clear that HFSTs are a complex technology and multiple factors, such as pavement type and quality, construction process, and inspector and contractor knowledge and experience, need to align for HFST installations to match or exceed HFST's projected performance and lifespan. States that overcame these challenges were often characterized by a strong HFST champion, numerous demonstration projects, and standards that evolved and improved as States gained experience installing HFST.

Detailed Findings

Finding 3a: The total number of HFSTs and their geographic distribution increased between 2004 and 2018, with the greatest number of installations occurring between 2013 and 2016. Direct funding from FHWA as well as technology transfer contributed to this growth.

Funding from FHWA programs supported States deploying HFSTs. FHWA funding supported SEaHC demonstration projects, and further, HFST installations were funded, in part, through HSIP and AID.[37](12) Other smaller funding sources included the Accelerated Safety Activities Program grant and State Transportation Innovation Councils grant.[38] SEaHC pilot demonstrations occurred in 7 States beginning in 2008, with additional installations following the initial round, for a total of 23 installations across 10 States.(37) The SEaHC pilot projects, in particular, were frequent sources of data for CMF studies as well as of early deploying States' experiences shared at ELCSI-PFS TAC meetings and peer exchanges.

A few States indicated that their programs would not be as large, or would not have installed any sites without Federal funding.[39] Large-scale FHWA HFST project funding began around 2013, as shown in table 8. AID funding supported projects in three States in 2014.(12) HSIP funding supported projects in 36 States and Washington, DC, with peak HFST activity (as measured in funds allocated) occurring in 2016.[40] A significant level of growth in funds occurred between 2013 and 2014, which notably, is concurrent with EDC-2 and related HFST activities. In addition to direct funding, FHWA provided substantial time and expertise in support of HFST installations.

Table 8. FHWA HSIP and AID project funding.

Year	HSIP (1,000$)	AID (1,000$)	Total (1,000$)
2013	9,164	0	9,164
2014	43,545	2,142	45,687
2015	73,541	0	73,541
2016	86,902	0	86,902
2017	55,997	0	55,997

Because of the imprecise nature of the available data on HFST installations nationwide, the evaluation team elected to use a range of values to convey the number of installations (completed and planned) for each State. The information provided, shown in table 9, was up to date as of June 2019.

[37]HSIP-funding data provided to evaluation team by FHWA HSA.
[38]FHWA HSA, email communication with evaluation team, January 6, 2020.
[39]State Engineers; phone interviews conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in October and August 2017.
[40]HSIP-funding data provided to evaluation team by FHWA HSA.

Table 9. Number of HFST installations (June 2019).[41]

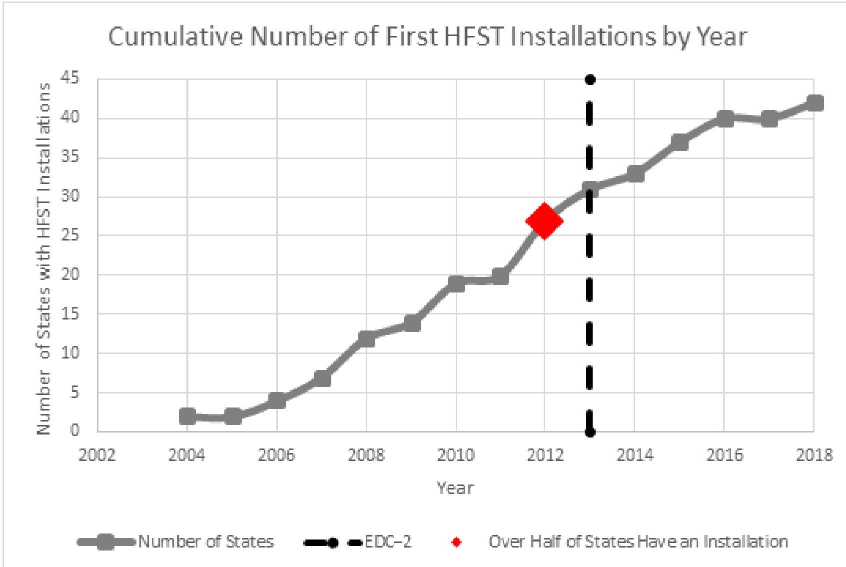
State	Number of HFST Installations
Alabama	10–49
Alaska	50–99
Arizona	1
Arkansas	100+
California	100+
Colorado	2–9
Connecticut	10–49
Delaware	10–49
Florida	50–99
Georgia	100+
Hawaii	1
Idaho	0
Illinois	10–49
Indiana	10–49
Iowa	10–49
Kansas	2–9
Kentucky	100+
Louisiana	100+
Maine	0
Maryland	10–49
Massachusetts	10–49
Michigan	10–49
Minnesota	1
Missouri	10–49
Missouri	10–49
Montana	2–9
Nebraska	10–49
Nevada	1
New Hampshire	0
New Jersey	1
New Mexico	2–9
New York	10–49
North Carolina	10–49
North Dakota	Several planned
Ohio	10–49

[41]Data provided by FHWA Resource Center Staff and DCMF preliminary data collection.

State	Number of HFST Installations
Oklahoma	10–49
Oregon	1
Pennsylvania	100+
Rhode Island	50–99
South Carolina	10–49
South Dakota	10–49
Tennessee	100+
Texas	100+
Utah	50–99
Vermont	Several planned
Virginia	50–99
Washington	10–49
West Virginia	10–49
Wisconsin	2–9
Wyoming	0

Based on a review of the available documents and data, the evaluation team found 44 States have at least 1 HFST installation, 4 States (Idaho, Maine, New Hampshire, and Wyoming) have no existing or planned installations, and 2 States (North Dakota and Vermont) have indicated some planning but had no installations at the time of data collection.

Table 9 shows the widespread nature of deployment but does not provide insight into the rate at which States adopted or tested HFST technology, while figure 6 approximates the number of States with HFST installations, showing deployment numbers in relation to the point where over half of States adopted HFSTs and EDC-2, showing an approximation of the rate at which States installed their first HFST.



Source: FHWA.

Figure 6. Line chart. Cumulative number of first HFST installations by year. [42]

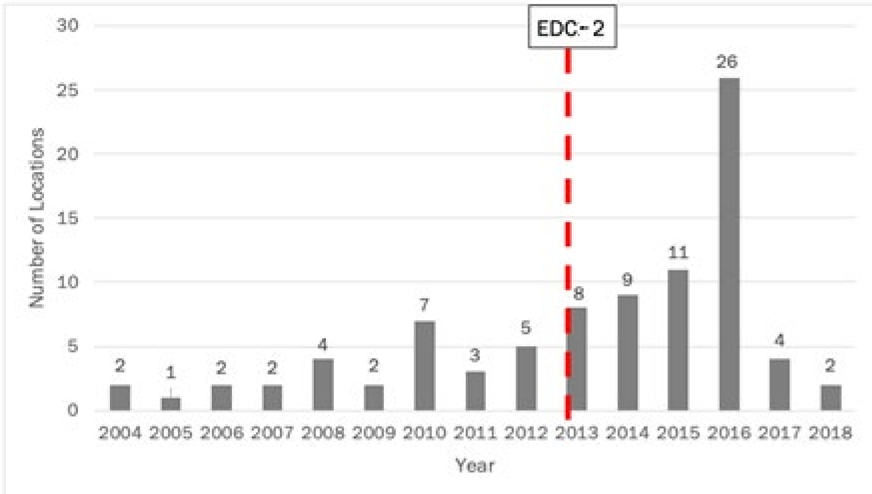
Because not all States had a clearly identified first installation, the evaluation team used the first mention of an existing HFST installation in a State as a proxy for a specific mention of a State's first installation. Due to a lack of early research, this method has the potential to bias the curve to show middle adopters as deploying later than they actually did; however, it is unlikely that this bias would significantly impact the shape of the trend line.[43]

Figure 6 shows that HFST installations trended upward before HFST became an EDC-2 initiative, with over half of the States having at least one HFST installation by 2012, 1 yr before the start of EDC-2. However, one limitation of this deployment curve is that it does not indicate volume. Documents reviewed by the evaluation team sometimes indicated a failed first installation, after which the State decided not to pursue further HFST installations until years later, when more information and assistance became available. Figure 7 provides some insight into deployment rates, though a lack of uniform reporting means any measure of installations, locations, or projects imprecise.[44] Pre-EDC-2, yearly installation numbers were relatively low.

[42]The figure was generated from coded segments in qualitative analysis software, including first installation, evidence of existing installations, and evidence of planned installations. These document codes were extracted and sorted into the following categories: confirmed first installation, specific planned, specific existing, general planned, and general existing. Then the data were sorted by State and year.

[43]One FHWA count lists 39 States as having at least one completed HFST project in 2012, which is significantly more than the 27 States depicted in this graph. Figure 6, however, is a representation of the publicly available information collected by the evaluation team, and as the document does not provide a list of these States or their dates of adoption, these installations could not be added to the graph.

[44]Figure 7 has been limited to a single installation metric, locations. Because not all States report installations in terms of locations, this graph understates the number of HFSTs installed each year; however, based on available research, the use of the location metric provided the largest sample of installations and were deemed an appropriate proxy for the number of HFSTs installed each year.



Source: FHWA.

Figure 7. Bar chart. Number of locations where HFSTs were installed by year.

Post-EDC-2, there have been a significant number of new HFST locations, moving from 8 locations in 1 yr to over 25 locations in 1 yr nationwide between 2013 and 2016. While figure 6 suggests EDC did little to change the rate at which States undertook their first HFST projects, it also suggests EDC may have impacted the rate at which States undertook additional projects. This possibility is consistent with the previous finding that, in addition to helping raise awareness of HFSTs as a safety measure through EDC-2 and other published research and outreach activities, FHWA played a role in helping States overcome some of the challenges and barriers to deployment.

Finding 3b: Some of the most successful HFST programs have been characterized by two notable traits: State-level HFST champions and improvement of HFST specifications.

Several early adopters overcame challenges and project failures to implement successful HFST programs at the State level. These programs were often characterized by a strong HFST champion, numerous demonstration projects, and standards that evolved and improved as States gained experience installing HFSTs.

State-Level HFST Champion

Often, local champions led demonstration projects to help show the capabilities of HFSTs. Iowa DOT (IDOT), unaware of a documented history of successfully applying HFSTs to bridge decks in States with cold climates, installed an HFST on their office campus grounds. This installation gave staff the opportunity to observe the installation process and test the results, which helped convince IDOT staff of its merits.(38)

In the following quotation, an FHWA employee describes that the far-reaching value of local champions is recognized as positively contributing to overall education and success of new processes and technologies:

> *"The secret is to find somebody there that will be your champion through thick and thin; that's your person you keep educating."*[45]

The champion's role as State- and local-level educator is important as HFST information is decentralized and may lack consensus on issues like automated versus manual installation, site-selection criteria, and so forth.

Evolution and Improvement of HFST Specifications

In addition to a strong State-level HFST advocate, evolving and improving HFST specifications were crucial to implementing a successful statewide program. Through interviews with State DOTs, the evaluation team found that some States updated their specifications in response to obstacles or challenges experienced during early installations. These updates tended to include specifying an application type (i.e., manual, semiautomatic, or automatic) as well as mandating, as opposed to recommending, the use of calcined bauxite. One State described their specifications as "developmental specs" explaining that this classification, "developmental," meant they could respond quickly to changes in the new, dynamic market. When their specifications are locked in, everything must be approved for 1 yr before going live, limiting the ability to evolve and improve based on experience.[46]

Finding 3c: Barriers to HFST deployment are often a combination of multiple challenges at once, including a steep learning curve, concern over performance, installation issues, perception of cost, and issues with specifications.

Based on interviews, case studies, and other research publications, it is clear that HFSTs are a complex technology with a relatively steep learning curve. Users noted that, with experience, specifications were refined, inspectors were better qualified to evaluate installations, and projects were more likely to be durable—matching or possibly exceeding the HFST's projected lifespan.

The Learning Curve and Risk Aversion

Despite being in use internationally for many years, domestic unfamiliarity with HFSTs may give the impression that HFSTs are a new, still-developing technology that has associated high risks.[47] As such, some States were initially reluctant to deploy HFSTs without more authoritative research or information and safety and performance data, as expressed in the following quote from an FHWA employee:

> *"When State DOTs are concerned with liability and all that, they say they're going to wait. That was one of the drawbacks we have; we are trying to get some States to try it, and a lot of them are reluctant until a couple years later."*[48]

Early HFST deployment was led by a few lead-adopter States. Information for early adopters was decentralized and largely produced by other early adopters. The AASHTO standard specification was

[45] FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

[46] State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Kaitlin Coppinger, Lydia Rainville, and Matthew Keen in November 2017.

[47] FHWA HSA Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

[48] FHWA HSA Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

first published in 2014, and States may not be aware of specifications-related work being done in other States. In response to a need for guidance on monitoring contractors or inspecting installations, ATSSA, in cooperation with State DOTs, industry experts, and FHWA staff, put together a 1-d inspector training course; however, one interviewee noted the course is under promoted and costly.[49]

When discussing challenges, a few interviewees mentioned they had chosen inexperienced contractors or contractors that, despite having experience, were still tweaking their application process. Some States sought to resolve this issue by calling on States that already had specifications or seeking advice for installation or inspection practices.

Additionally, some early adopter States were willing to embrace HFSTs, but experienced early failures, ultimately increasing their risk aversion. This circumstance resulted in States waiting to perform additional installations until one of the following possibilities occurred:

- The technology was more mature.
- The technology was more reliable.
- Safety and performance data were available.
- Vendors and/or contractors have more experience.
- More resources (guidance and/or funding) are available for States.

In recent years, the benefit claims of the early publications have been bolstered by the availability of some CMFs and limited safety and performance data, but additional work is needed to help States overcome the risk and uncertainty of embracing a technology that, domestically, is still maturing.

Interviewees explained that a remaining obstacle still exists in the application and process of HFSTs as follows:

> *The science, the safety, is easy. The durability and getting people to do it right is hard. There is a narrow path to getting it in so that it will be durable and perform as it's supposed to.*[50]

The interviewees also revealed acceptance of HFSTs as a safety measure is not consistent across disciplines within State DOTs. This variation in awareness and understanding was identified by some States as a barrier to deployment. As mentioned in multiple interviews, a particular case of this variation was the distinction between the materials and safety disciplines and their different approaches to the same problem.

Interviewees, who primarily represented the safety discipline, described concerns from the pavement and materials communities as potentially stemming from a lack of understanding of the technology

[49]FHWA HSA Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

[50]FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

behind HFSTs. One interviewee expressed the opinion that safety communities more readily embrace the treatment as crash-reduction numbers justify the higher cost.[51]

Alternatively, materials groups question the need for such an expensive treatment and want to try more conventional, less-expensive treatments before investing in HFSTs. One interviewee mentioned that the materials group's approach HFSTs as just another type of pavement treatment and are, therefore, less willing to accept the higher (relative to other measures) expense of HFSTs. Several interviewees noted the importance of communication and understanding across disciplines and the need for materials and safety groups to relate and learn from each other. Such cooperation would offer opportunities to educate the materials discipline on the substantial benefit of increasing friction via calcined bauxite (as opposed to other aggregates) and educate safety practitioners on the importance of initial pavement quality and proper installation practices.

Interviews with FHWA and more advanced adopters indicate data on HFST benefits, overcoming installation challenges, and materials testing (both calcined bauxite and alternative materials) are limited, but later adopters' lack of awareness indicates that perhaps this information is not being distributed among States. One industry interviewee noted that, while there is significantly more information available on HFSTs now than when the technology was first introduced in the United States, it is not compiled into a central repository.[52]

Delayed Availability of a General Specification and Other Formal Recommendations

Successful HFST installations require coordination among safety and materials professionals, optimal ambient and environmental conditions, a certain level of underlying pavement type and quality, and enough knowledge and experience with HFSTs to oversee installation and inspect the final result. Many of these requirements for successful installations are documented in general or project-specific specifications. However, until 2014,[53] no national-level standard specifications were available, and little formal guidance on site selection or formal training was available for inspectors. Several interviewees mentioned not having definitive specifications and not knowing the ideal conditions for installation.[54] Moreover, without a central repository of HFST information, States looking for guidance needed to directly reach out to other States, who had a wide variety of experiences and specifications.

Other interviewees noted that the treatment was degrading in certain areas (usually in an early installation), but they could not definitively say why. This uncertainty creates a potential deployment barrier, as incorrect installation leads to early degradation—meaning the useful life of the HFST is much shorter than expected. Early degradation coupled with the high cost of HFSTs may result in States believing an installation will not last and, therefore, being less willing to install HFSTs. FHWA Resource Center staff reported issues with vendor substitution of materials, including using inferior aggregate material, which was brought to their attention by several States.

Several States noted issues with initial manual installations. As a consequence, several States interviewed have moved to a semi-automated or fully automated installation to reduce issues with

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[51]FHWA Technical Contractor; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in November 2017.

[52]FHWA Technical Contractor; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in November 2017.

[53]The AASHTO PP 79, *Provisional Standard Practice for High Friction Surface Treatment for Asphalt and Concrete Pavements* was first published in 2014.

[54]FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

epoxy or aggregate application. However, these early failures accompanying manual installations were not universal; one Resource Center employee noted that a relatively early adopter with a high number of manual HFST installations has not had these issues with installation.[55] States mentioned that additional guidance and information on installation types would be beneficial when writing their own State-specific specifications.

Finally, States have taken a variety of approaches to selecting installation sites for HFSTs. Some States, like Missouri, have undertaken a site-by-site approach, applying HFSTs to the most accident-prone curves.[56] Approaches to site selection driven by crash data tend to show higher BCRs since, when successfully installed, the crash reductions have the potential to be significant.[57] Meanwhile, other States, like Georgia, have taken a more systemic approach, opting instead to "head off crashes" by applying the treatment to areas that show risk factors, not necessarily high crash numbers.[58] One interviewee noted that for the systemic-type approach, BCRs may be lower as the treatment is applied to curves showing risk factors as opposed to only those with high crashes, making it difficult to quantify the number of crashes avoided by proactively installing the treatment.[59]

BCRs monetize a project's benefits relative to its costs in an attempt to summarize the overall value of a project. When a BCR exceeds 1, the potential benefits are likely to exceed costs and a positive return on investment is likely. When a BCR is less than 1, the potential costs of a project outweigh the potential benefits, and funds may be of greater benefit if spent elsewhere. Monetized benefits can include quality-of-life improvements, reductions in travel time, or savings due to avoided crashes and/or fatalities.

There remains little formal guidance on the best way(s) to select sites. To better inform their approach to site selection, States would benefit from both additional research on approaches to site selection and a better understanding of the costs and benefits associated with each approach.

Cost

Compared to other pavements and many other safety measures, HFSTs are more expensive, and costs depend on the quality of the material to be installed and the site location of the project.(3) In 2017, project costs ranged from $21/yd^2 to $26/yd^2.(3) However, this cost has been steadily decreasing for larger projects and smaller projects that have been bundled with other safety-related projects. Typically, the larger the scope of the project, the lower the cost per square yard.(3) Without high-quality data on safety, performance, and durability, many States have been cautious in undertaking such a costly risk. This hesitance has been mitigated for some States following recent FHWA publications.(10)

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[55] FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

[56] State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in August 2017.

[57] A BCR is the total monetized benefits of a project (appropriately discounted to the present value) divided by total project costs (again in present value). A BCR above 1 indicates the project benefits exceed costs, and a BCR below 1 indicates costs exceed benefits.

[58] State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in October 2017.

[59] FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

One driver of cost is over application. Pennsylvania indicated that they could pave the road for the cost of a single application.[60] However, with additional experience, States began working to optimize their HFST applications. One respondent noted the following:

> *"In the past, we put more in than we had to optimize usage—600 ft versus 1,000. We'll look to tweak this tighter, more conservative… We want to be more careful; rather go too long and [be] wasteful than too short [which is a safety issue]."*[61]

Moreover, it is also important for a realistic comparison of costs; not all measures can be used in all situations—the cost of an HFST should not be compared to rumble strips and/or chevrons when the only viable measure would be for the curve to undergo geometric realignment. To lessen these obstacles, FHWA, States, AASHTO, or other key partners could continue to work together in refining standard specifications, offering guidance on how to optimize HFST application size, and improving States' awareness of funding opportunities and understanding of cost drivers.

4.4 Evaluation Area Four: Safety Impacts

This subsection describes the evaluation team's findings on the safety impacts of HFSTs.

Overview of Findings

Interviewees identified HFSTs as the most effective safety measure for several specific safety issues—wet pavement, poor friction, curves with a small radius, and places where the other alternative is to realign or restructure the location. One interviewee called HFSTs "an astounding safety measure" because the before–after crash data showed a significant reduction in crashes at curve locations where other measures (e.g., signage) were not working. The strongest safety impact of HFSTs is in terms of lives saved and prevented roadway departures. In areas of high wet-weather crashes, no other safety measure can match the safety benefit and durability of HFSTs.

Detailed Findings

Finding 4a: HFSTs can significantly reduce fatalities and other injuries from roadway departures; however, the wide range of estimated crash-reduction results lead to uncertainty for potential deployers.

HFSTs have been consistently shown to reduce crashes. Several State-directed studies on HFSTs' safety impacts have led to estimates of the crash-reducing effects of HFSTs (table 10). Additionally, CMFs have been produced from three studies: the DCMF study, the original Pooled-Fund Study, and a State-led research effort from Pennsylvania.[10,39] Methodologies and the magnitude of impacts vary, but the greatest safety impacts from HFSTs are in reducing run-off-road crashes on tight curves. Wet-weather crashes, when measured separately, show the largest decrease from HFSTs. In addition

[60]State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in August 2017.

[61]State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Kaitlin Coppinger, Lydia Rainville, and Matthew Keen in November 2017.

to these studies, States with HFST experience have repeatedly expressed anecdotal support for large crash reductions from HFSTs.[62]

State-led studies have produced crash-reduction estimates ranging from 5.7 to 100 percent, with most individual studies producing ranges of a similar scale (table 10).

62FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

Table 10. Reported crash-reduction figures. [63]

Location	Crash-Reduction Figures
California	Statewide, California reports crash-reduction rates between 30 and 100 percent.
Delaware	Statewide, Delaware reports wet-weather-crash-reduction rates between 55 and 75 percent.
Florida	Statewide, Florida reports wet-weather-crash-reduction rates between 16.3 and 84.2 percent. Total crash reductions were found to have much more variation with one study finding a 50.6 percent increase in crashes for all approach sites, while an interviewee estimated an 84-percent decrease in total crashes.[64]
Kentucky	Studies of multiple installations/locations in Kentucky found wet-weather-crash-reduction rates averaging around 86 percent. Dry-weather-crash-reduction rates ranged from 47 to 79 percent, and total crash reduction ranged from 73 to 89 percent. Studies of individual sites showed much greater variability in crash reductions. Single site estimates for wet weather–crash reductions ranged from 23.1 to 91.1 percent; dry-weather crashes ranged 5.7 to 57.3 percent; and total crashes ranged from 21.1 to 96 percent.
Pennsylvania	Statewide, studies found total crash-reduction figures ranging from 78 to 93 percent. For single-location studies, total crash-reduction findings were sometimes higher with one installation eliminating an estimated 100 percent of crashes at that site.
South Carolina	South Carolina's signature trial project was reported to have reduced total crashes by 57 percent at the project location. However, later studies of multiple installations found even higher total crash reductions, averaging around 70.5 percent. Reported wet-weather-crash-reduction figures were between 77 and 81 percent.
Wisconsin	For Wisconsin, total crash reduction was calculated for individual sites, averaging around 95.5 percent.

The large variations in findings, while consistently demonstrating HFSTs' positive effect on safety, have the potential to create uncertainty for decision-makers and may lead to suboptimal use of crash-reduction findings. For example, a safety engineer considering an HFST installation may face a crash-reduction rate with a range of 20 to 90 percent (a range comparable to findings from some State reporting, as seen in table 10) and may reasonably choose to use the smallest value given a site's characteristics (e.g., a tight curve), representing a relatively minor reduction in crashes. However, using the conservative estimations of crashes avoided and lives saved may lead to the decision not to install an HFST that might have been considered feasible when using a value from the middle of the range presented.

The wide range of values, both within and across studies, has several plausible causes, such as the following:

[63] The research team used the following decision rules to determine which crash-reduction figures to include in the study: State must have at least two reported crash-reduction figures for a single metric (total crashes, wet crashes, etc.) and a single location (either all individual sites or all multiples, statewide, etc.), and the figures must be reported by no less than two separate publications.

[64] State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Kaitlin Coppinger, Lydia Rainville, and Matthew Keen in November 2017.

- Many studies test multiple sites, which have a variety of characteristics; values may or may not be estimated for these characteristics individually in other studies. For example, curve radius appears to affect the significance of crash reduction, with tighter curve radii (which would tend to see a greater number of run-off-road crashes, all else being equal) seeing larger reductions. Most studies group all curves together, possibly due to sample-size concerns (table 9). Identifying multiple site characteristics creates a larger number of point estimates but provides more targeted and functional crash-reduction rates when evaluating potential sites.

- Studies commonly test wet-weather crashes separately or in addition to all or dry-weather crashes. Most studies that do test separately find a larger reduction in wet-weather crashes, all else being equal. This approach produces a greater number of point estimates but may allow the study results to be adjusted to local weather patterns.

- Differences in methodology may increase the range of estimates across studies. Of particular concern is potential bias in crash-reduction estimates. Safety interventions like HFSTs present a challenge when estimating the safety improvement by using a before–after analysis of crashes. HFST sites are generally selected based on a recent history of frequent or severe crashes, which may have returned to a lower baseline number of crashes even in the absence of an HFST. As no study can observe the same curve with and without an HFST installed at the same time, a study must control for this regression-to-mean bias. Studies that do not, often due to limitations in resources or data, risk producing inflated crash-reduction figures (i.e., the crash-reduction value includes the "true" reduction from the HFST and reduction that would have occurred over time regardless).

While States noted reductions in crashes following an HFST installation,[65] the EPSP study initiated under phase four of the FHWA ELCSI-PFS provided the first HFST CMFs accepted by CMF Clearinghouse, the FHWA-sponsored online repository of CMFs.[66](10) This study included development of HFST CMFs, drawing on data from eight States.[67] It produced CMFs using a combination of before-and-after comparisons with and without control sites (i.e., similar sites, where no HFST was applied).[68] Four CMFs were produced (table 11), representing two crash conditions (all, including wet weather, or wet-weather only) and two installation areas (ramp or curve). Notably, each CMF received a four-star quality rating on CMF Clearinghouse, with study design and potential bias being the only categories with ratings outside the "excellent" category.

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[65]FHWA Resource Center Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Lydia Rainville, and Matthew Keen in July 2017.

[66]CMFs are a tool used to find the expected change in crashes after implementing a safety improvement. Transportation practitioners use CMFs to identify and compare safety impacts or cost effectiveness of safety measures, identify where to deploy measures, and to conduct benefit–cost analyses when selecting safety measures. CMFs are multiplicative factors ranging from 0 to any positive number, with values less than 1 representing an expected reduction in crashes (e.g., a CMF of 0.80 indicates a safety improvement would reduce expected crashes by 20 percent). CMFs are defined for specific interventions (e.g., installation of an HFST) and may include more specific conditions when they are applicable (e.g., a small-radius curve or wet weather) and specific categories of crashes (e.g., fatalities, or single-vehicle run-off-road crashes).

[67]The study observed 12 ramps in 6 States (Kansas, Kentucky, Michigan, Montana, South Carolina, and Wisconsin) and 35 curves in 7 States (Colorado, Kansas, Kentucky, Michigan, Montana, South Carolina, and Tennessee).

[68]While the EPSP study was published in February 2015, ELCSI participating States had access to insights and preliminary results, including CMFs, prior to this date due to the study's performing contractor participating in the annual TAC meetings.

Table 11. EPSP HFST CMFs.(10)

CMF	Crash Type	Area Type
0.653	All	Ramp
0.481	Wet weather	Ramp
0.759	All	Curve
0.139	Wet weather	Curve

The purpose of the most recent DCMF study was to produce more reliable CMFs for a variety of crash types. CMFs were produced through an empirical Bayes before–after analysis; actual crash outcomes at treatment sites were compared to expected crash outcomes for reference sites, as projected by a safety-performance function. Due to mechanical malfunctions and a lack of reference sites, the study was only able to evaluate HFST-installation sites in four States, though the overall number of sites analyzed was considerably higher than in the previous ELCSI-PFS study.[69] CMFs were produced for all curve installation areas for five crash conditions (all, wet weather, injury, run off road, and head on plus opposite-direction side swipe). These CMFs range from 0.168 to 0.691 and are reproduced in table 12 (lower CMFs indicate a greater reduction in crashes, and values near 1 indicate little-to-no reduction in crashes). These CMFs corroborate observations from the previous pooled-fund study that HFSTs are especially effective at reducing wet-weather crashes at curve sites.

Table 12. EPSP HFST CMFs for curves.

CMF	Crash Condition
0.430	All
0.168	Wet
0.515	Injury
0.279	Run off road
0.691	Head on plus opposite-direction side swipe

Due to a lack of data from reference sites, CMFs were only calculated for ramp sites in Kentucky. This study also attempted to quantify CMFs based on site-specific characteristics. A univariate categorical analysis and a multivariate regression analysis suggested a consistent relationship between CMFs, change in friction due to an HFST installation, average annual daily traffic (AADT) at a test site, and crash frequency before treatment.

More recently, a 2017 Pennsylvania study produced a large number of HFST CMFs.(39) However, this study received consistently low ratings from the CMF Clearinghouse (1 or 2 stars) due to poor design, sample size, standard error, and potential bias. (39) The study produced 26 CMFs, which ranged from 0 to 0.511, with most at or near 0.

The large number of State-led studies and ongoing efforts to collect safety-effectiveness data indicate a need for States to have high-quality CMFs and suggest a lack of consensus. The initial FHWA ELCSI-PFS CMF results provide a good starting point, though State-led efforts to identify crash-reduction results for particular site characteristics (e.g., curve radius) indicate demand for more specific CMFs. The DCMF study provides more reliable CMFs for various crash conditions. Further,

[69]The study observed 36 ramps in 2 States (Arkansas and Kentucky) and 146 curves in 3 States (West Virginia, Pennsylvania, and Kentucky).

information on and promotion of these new DCMF CMFs may reduce the incentive to produce the independent, though potentially biased, crash-reduction figures States require for decisionmaking.

Finding 4b: Especially in areas with a large number of wet-weather crashes, studies, to date, show HFSTs are a cost-beneficial safety investment.

State DOTs mentioned a variety of other measures used instead of or in conjunction with HFSTs. The costliest measure was rebuilding or changing the alignment of curves. State DOTs mentioned this option but stressed their preference for HFSTs. Many saw HFSTs as having the potential to deliver similar safety impacts (reduction in roadway departures and fatalities) at a lower cost. For some sites, an HFST was not the first measure applied, with chevrons and rumble strips frequently mentioned by State DOTs. Both are less expensive, and State DOTs expressed that they did provide some safety benefits and were occasionally used in conjunction with later HFST projects. However, especially in areas with large numbers of wet-weather crashes, neither could provide the same level of safety impact or performance as an HFST.

Some State DOTs indicated that they believed the safety impact of HFSTs was due to the use of calcined bauxite because of the high-friction numbers it provides during testing when installed properly. Some State DOTs clearly expressed the belief that, despite the expense of calcined bauxite and the availability of cheaper, albeit untested alternatives, the safety benefits in terms of lives saved and road-departures prevented greatly outweighed the additional cost of using calcined bauxite.[70] Additionally, several State DOTs explicitly stated that the benefits of HFST outweigh the costs. State DOTs mentioned design, training, materials, and construction aspects as drivers of cost. The benefits of HFSTs are the safety impacts of lives saved and prevented roadway departures because HFSTs improve driver control of vehicles, reduce stopping distance, and reduce skidding in wet weather.

The DCMF study quantified economic benefits due to crash savings as $19,300,113 for the 146 treated curve sites and as $9,063,309 for the 21 treated ramp sites; treated sites included a combination of planned and in-place sites.[71] The BCRs were 6.00 for curve sites and 18.74 for ramp sites. Pennsylvania monetized the economic savings due to reductions in fatality and injury crashes from installing HFSTs at 15 locations, finding an annual economic savings of $357,427 per intersection.[(40)] When this benefit is compared to Pennsylvania's HFST installation fee, $17,440.41 (average area of 985 yd^2 per location), the BCR is 20.49.[(40)] Similarly, Florida monetized the benefit from avoided crashes, estimating a 5-yr benefit of $2,522,000 for tight curves.[(35)] When this benefit is compared to Florida's average installation cost on tight curves, $171,000, the BCR is 24.5.[(35)]

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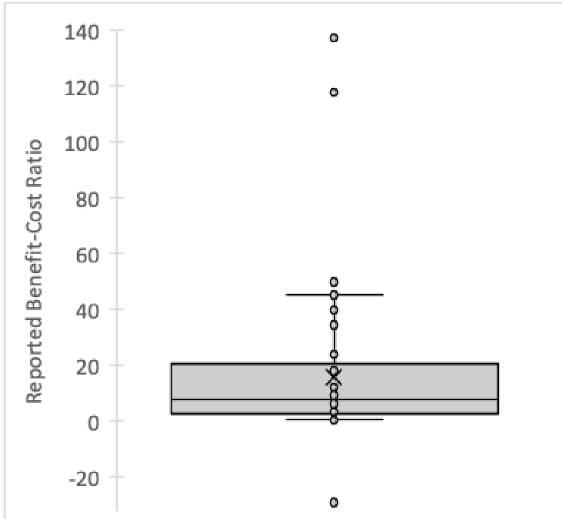
[70]Expressed in several interviews, including those with State DOT employees from Georgia and South Dakota as well as other FHWA employees.

[71]BCRs were calculated solely for ramp installation sites in Kentucky.

Generally, reported BCR values are high for HFSTs, but there is some variation. Figure 8 looks at reported nationwide BCRs, showing the mean (X) and median (central horizontal line) values, as well as the interquartile range (box) and outliers (dots).



Source: FHWA.

Figure 8. Chart. Range of reported BCRs.[72]

Overall, reported values are highly variable, with extremes ranging from negative 29.1 to positive 137.5.(39) Some studies have estimated the BCRs as tending to range from 0.47 to 8.45, while others cite even higher figures of 18 to 118 for individual sections of a larger project, depending on the calculation method.(20,35) Estimates for a single State, California, all showed potential benefits exceeding costs with BCRs ranging from 1.89 to 45.53.(41) Some variability may be due to calculation methodology, but as these BCRs were reported in a single presentation, the magnitude of variability is likely due to site characteristics. Based on reported values collected by the evaluation team, most BCRs for HFST installations are concentrated between 2.88 and 20.5.

State DOTs were unanimous in their assertion that the largest benefits are seen on tight and compound curves and expressed confidence in the safety value of HFSTs. Several stressed that HFSTs are an outstanding safety measure that does save lives: "when it comes to vehicles leaving [the] road, HFST is one of the options we are looking at not only for friction but for wet pavement, no other measures we're aware of that will maintain car on roadway other than adding shoulder."[73]

[72]This figure excludes BCRs from the most recent DCMF study due to possible double counting of test sites. The BCRs for that study were 6.00 for curve sites and 18.74 for ramp sites.

[73]State Engineers; phone interview conducted by evaluation team members Jennifer Gissel, Kaitlin Coppinger, Lydia Rainville, and Matthew Keen in November 2017.

5. Conclusions and Recommendations

The goal of FHWA HFST research–related activities is a reduction in the number and severity of roadway-departure crashes in the United States, particularly on horizontal curves. This evaluation addressed FHWA's efforts related to conducting HFST-related research and analysis and supporting the adoption of the technology by State and local agencies.

When HFSTs were introduced in the United States, international experience indicated they had high safety-benefit potential, but little applicable domestic information was available. The findings in this evaluation show that FHWA played a role in accelerating adoption of HFSTs. FHWA contributed to an increase in the availability and quality of information on HFSTs in the United States through early CMF funding, collaboration with States for demonstration and data collection, and Resource Center leadership and technical assistance. Although attributing direct causation is difficult, findings further suggest that acceptance, consideration, and adoption of HFSTs are higher than would have occurred in the absence of FHWA research and investment in technology transfer—resulting in a real reduction in roadway-departure crashes. While FHWA cannot claim direct responsibility for this reduction, their continued research and promotion of HFSTs have enhanced roadway safety in the United States. Completion of ongoing CMF research will better enable quantitative estimation of these safety impacts.

However, the path to deployment has presented challenges. HFSTs are a complex technology that presented a steep learning curve in States' early deployment experiences. Installation of HFSTs requires coordination across safety and materials communities; is perceived as high cost; and depends on multiple factors, including high-quality underlying pavement, correct installation processes, and specific materials for maximum longevity and performance. With assistance from peers, FHWA resources, and their own trial and error, States have learned from and overcome such challenges. These experiences resulted in a variety of project outcomes that future adopters could consult in their installations. The findings and recommendations from this evaluation on the HFST-research lifecycle offer insights for both future HFST deployments and other innovative technologies FHWA selects for research.

As with other FHWA R&T evaluations, the findings from this evaluation underscore the importance of both foundational and ongoing research, dissemination of resources, and FHWA national leadership on a topic in collaboration with internal and external stakeholders, leaders, and other decisionmakers.

5.1 Recommendations

Based on these findings as well as input from interviewees and other research conducted, the evaluation team developed a set of specific, actionable recommendations to facilitate adoption, usage, and development of HFSTs and other technologies with similar opportunities and challenges. In many ways, FHWA and other stakeholders are already enacting these recommendations. The recommendations are intended primarily for two groups: those engaged in technology transfer and outreach at FHWA and potential adopters of HFSTs.

Recommendations for FHWA

The following recommendations are intended primarily for FHWA.

Facilitate Technology Transfer

Early outreach worked to connect States via active engagement activities—peer exchanges, demonstration projects, and TAC meetings—that promoted dialog, asked questions, and shared institutional knowledge. As the research lifecycle progressed, more recent HFST outreach has been less resource intensive, primarily the provision of information through Web links to existing research, notes from previous TAC meetings, records of demonstration projects, and so on.

Recommendation 1: Maintain active engagement with States that are early in their respective HFST-adoption curves.

For technologies that are not new to FHWA, it remains important to maintain a space for active engagement with States at various stages in their respective technology-adoption curves. While HFSTs have been in use domestically for over a decade, it is still relatively early in the technology-deployment trend line in absolute numerical terms. Most States have an installation, but the opportunity remains for further growth. FHWA can identify and support interested States that are earlier in their adoption curves and would benefit from technical assistance and engagement with more experienced States.

Additionally, as FHWA revisits certain topic areas (e.g., roadway departure) in future EDC rounds or other technology-promotion initiatives, there is an opportunity to also revisit the research related to previously highlighted innovations (e.g., additional real-world experience, new data, or even improved results/higher-quality CMFs) and conduct updated outreach on those technologies. This opportunity would provide additional exposure for those States originally not willing to take the risk on an unproven or still-maturing technology.

Recommendation 2: Update the HFST website to enhance usability and ensure it is a comprehensive resource,

As discussed in subsection 4.2, Web traffic at the HFST website is among the highest in its category—States and other industry professionals are utilizing it as a resource. FHWA's HFST website has a wealth of information, but should be reorganized for more effective curation and improved information dissemination. FHWA's roundabouts website is one example of content and organization that was effective—simple to navigate, clearly labeled categories, and informative.(42) FHWA's *FAQs, Links, and Other Resources* page, which is accessible via FHWA's HFST primary Web page, starts to gather, sort, and organize information. However, it does not provide States with some of the resources they requested, such as State-level reports or links to State specifications.(3) This information might be accessible via the Web links provided on the page or the main FHWA HFST page, but further categorization would improve user experience.

Recommendation 3: Facilitate deployment decisions with updated information on site selection and installation.

HFSTs can be deployed systemically or targeted at specific locations in response to crashes. During interviews, some States expressed uncertainty about which approach is best and how to most effectively apply the treatment. Determining which approach to take needs to be a State-level decision based on a variety of factors, such as availability, accuracy, and completeness of crash data; funding availability; and State-level acceptance of the technology.

Following publication of the DCMF study, FHWA could work to disseminate these results through another round of targeted HFST promotion with updated materials. FHWA can update and build on its existing high-level *HFST Curve Selection and Installation Guide* and highlight new performance and safety data and lessons learned.(2) This updated resource could also address the coverage of the treatment and seek to minimize unnecessary application, resulting in improved cost effectiveness. Additional information could include identifying which States deployed HFSTs systematically versus targeting crashes, what factors contributed to the methodological choice, and the result.

Recommendation 4: Continue to provide technical assistance and presentations on HFSTs via the FHWA Resource Center.

Just as interviewees mentioned interactions with other States as improving technology adoption, several States indicated that support provided by FHWA staff and contractors was instrumental in decreasing the severity of the HFST-installation learning curve. When asked about their contact with FHWA, one State representative indicated they would sometimes reach out to FHWA, especially regarding design issues.[1] With the retirement of FHWA's HFST champion, it will be important to establish and maintain continuing technical assistance and actively provide outreach for HFSTs. A strong HFST effort at the Resource Center can be an important contributor to the success of HFSTs. The Resource Center's role is twofold: supporting and acting as a resource for States undertaking HFST projects and continuing outreach and education to States considering undertaking a project or demonstration.

Encourage Research Collaboration

As discussed in subsection 4.1, despite an increase in HFST-related publications and improving data availability, remaining research gaps act as a barrier to States adopting HFSTs.

Recommendation 5: Continue partnering with industry, States, and academia to address research gaps related to HFST durability, performance, and alternative aggregates.

Research Gap: Overcoming Failed Projects

Based on available literature, the evaluation team noticed existing research may not sufficiently address where States experienced challenges and how they overcame them or what caused specific projects to fail. As a complex technology, it is difficult to disentangle effectiveness, durability, and quality of installation without additional data on installation factors (e.g., photographic evidence of underlying pavement quality and documentation of installation methods). Research is still needed to identify where along the curve to place an HFST and in what condition the underlying pavement needs to be. This research could help new adopters overcome barriers and those with failed projects to troubleshoot installation challenges. Moreover, it may even provide the support these States need to undertake additional projects.

[1]State Engineer; phone interview conducted by evaluation team members Jennifer Gissel, Kaitlin Coppinger, Lydia Rainville, and Matthew Keen in November 2017.

Research Gap: Why Calcined Bauxite?

States are interested in alternative materials, but after early failures, many are relying on the experts to do the testing. States were interested in gaining more information on the durability of alternative aggregates and domestic aggregates as well as a greater understanding of HFST material costs. FHWA can partner with States to conduct additional research on alternative and domestic aggregates to either expand the range of aggregates appropriate for use in HFSTs or to better clarify why calcined bauxite is the superior choice. Coordination with international partners who have decades of experience with HFST would also be beneficial.

Recommendations for Potential Adopters

Recommendation 6: Designate a strong State-level HFST champion.

Similar to that of the Resource Center's HFST champion, discussed earlier, the role of the State-level HFST champion is twofold: to help educate those at the State and local levels about the benefits of HFSTs and installation best practices as well as act as the link between State and local teams and FHWA Resource Center staff. The champion can help new adopter States move past challenging (or failed) first installations. Moreover, the champion can be an important resource for mediating between safety and materials professionals, educating on the need for calcined bauxite. This person can also provide training to those who are new to HFSTs and enforce specifications. Ideally, the champion also knows whom to contact when their State encounters challenges or when additional training of inspectors or other employees is needed.

Recommendation 7: Improve data-collection efforts before and during HFST installation.

In interviews and across literature, a frequent barrier to installation was initial project failure. States would perform a first installation, or several HFST installations, but would experience early project failures—aggregate shedding, cracking, or friction loss, among other challenges. Because States did not have detailed before-and-after data on each site (e.g., photographs of underlying pavement quality, recorded measurements of aggregate thickness, or details on temperature and environmental conditions during the installation), determining the specific cause or causes of these premature failures was difficult. Improved data-collection efforts before and during HFST installations can help States better assess the factors that contribute to both installation successes and failures. Ultimately, better data can help lessen the severity of the learning curve and reduce the likelihood of premature project failures or lack of durability.

Appendix. FHWA-Involved HFST Publications

Table 13 lists publications on HFSTs in which FHWA was involved.

Table 13. FHWA-Involved HFST publications.

FHWA Involvement	Publication Title	Date	Citation
Sponsored	*Low-Cost Treatments for Horizontal Curve Safety*(11)	2006	McGee, H.W. and Hanscom, F.R. (2006). *Low-Cost Treatments for Horizontal Curve Safety*, Report No. FHWA-SA-07-002, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/horicurves/fhwasa07002/, last accessed May 3, 2019.
Published	*Gaining Traction in Roadway Safety*(5)	2008	Julian, F. and Moler, S. (2008). *Gaining Traction in Roadway Safety*, Report No. FHWA-HRT-08-005, FHWA, Washington, DC. Available online: https://www.fhwa.dot.gov/publications/publicroads/08july/05.cfm, last accessed May 3, 2019.
Sponsored	*Field Performance of High Friction Surfaces*(17)	2010	De Leon Izeppi, E., Flintsch, G.W., and McGhee, K. (2010). *Field Performance of High Friction Surfaces*, Report No. FHWA/VTRC 10-CR6. Virginia Transportation Research Council, Charlottesville, VA. Available online: https://vtechworks.lib.vt.edu/bitstream/handle/10919/46662/10-cr6.pdf?sequence=1&isAllowed=y, last accessed May 3, 2019.
Published	*Pavement Friction*(43)	2010	FHWA. (2010). *Pavement Friction*, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/pavement_friction.pdf, last accessed May 6, 2019.
Published	*Roadway Departure Safety Implementation Plans: Kentucky Implements Roadway Departure Safety Plan with Rumble Stripes and Friction Treatments*(44)	2011	FHWA. (2011). *Roadway Departure Safety Implementation Plans: Kentucky Implements Roadway Departure Safety Plan with Rumble Stripes and Friction Treatments*, Report No. FHWA-SA-11-20, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/strat_approach/fhwasa1120/kyhires.pdf, last accessed May 3, 2019.
Published	*High Friction Surface Treatments (HFST) Implementation Plan*(45)	2012	FHWA. (2012). *High Friction Surface Treatments (HFST) Implementation Plan*, FHWA, Washington, DC.

FHWA Involvement	Publication Title	Date	Citation
In cooperation with	*Evaluating the Need for Surface Treatments to Reduce Crash Frequency on Horizontal Curves*(19)	2014	Pratt, M.P., Geedipally, S.R., Pike, A.M., Carlson, P.J., Celoza, A.M., and Lord, D. (2014). *Evaluating the Need for Surface Treatments to Reduce Crash Frequency on Horizontal Curves*, Report No. FHWA/TX-14/0-6714-1, Texas A&M Transportation Institute, College Station, TX. Available online: https://static.tti.tamu.edu/tti.tamu.edu/documents/0-6714-1.pdf, last accessed May 3, 2019.
Published	*Frequently Asked Questions about High Friction Surface Treatments (HFST)*(46)	2014	FHWA. (2014). *Frequently Asked Questions about High Friction Surface Treatments (HFST)*, Report No. FHWA-CAI-14-019, FHWA, Washington, DC. Available online: https://www.fhwa.dot.gov/innovation/everydaycounts/edc-2/pdfs/fhwa-cai-14-019_faqs_hfst_mar2014_508.pdf, last accessed May 3, 2019.
Published	*Case Study: Kentucky Transportation Cabinet's High Friction Surface Treatment and Field Installation Program*(18)	2015	Von Quintus, H. and Mergenmeier, A. (2015). *Case Study: Kentucky Transportation Cabinet's High Friction Surface Treatment and Field Installation Program*, Report No. FHWA-SA-15-038, FHWA Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/kytc/ky_hfst_15_038.pdf, last accessed May 3, 2019.
Published	*EDC-2 Final Report March 2015*	2015	FHWA. (2015). *EDC-2 Final Report*, Report No. FHWA-15-CAI-003, FHWA, Washington, DC. Available online: https://www.fhwa.dot.gov/innovation/everydaycounts/reports/edc2_finalreport.pdf, last accessed May 3, 2019.
Published	*Missouri Demonstration Project: The Use of High-Friction Surface Treatments on Missouri Highways*(47)	2015	Bledsoe, J. (2015). *Missouri Demonstration Project: the Use of High-Friction Surface treatments on Missouri Highways*, FHWA, Washington, DC. Available online: https://www.fhwa.dot.gov/hfl/projects/mo_hfst_highways.pdf, last accessed May 3, 2019.
Published	*Proven Safety Countermeasures*(48)	2015	FHWA. (2017). *Proven Safety Countermeasures: Enhanced Delineation and Friction for Horizontal Curves*, Report No. FHWA-SA-17-058, FHWA Washington, DC. Available online: https://safety.fhwa.dot.gov/provencountermeasures/enhanced_delineation/, last accessed May 3, 2019.
Sponsored	EPSP(10)	2015	Merritt, D.K., Lyon, C.A., Persaud, B.N. (2015). *Evaluation of Pavement Safety Performance*, Report No. FHWA-HRT-14-065, FHWA, Washington, DC. Available online: https://www.fhwa.dot.gov/publications/research/safety/14065/14065.pdf, last accessed May 3, 2019.
Sponsored	*High Friction Surface Treatment Alternative Aggregates Study*(6)	2015	Heitzman, M., Turner, P., and Greer, M. (2015). *High Friction Surface Treatment Alternative Aggregates Study*, Report No. NCAT 15-04, FHWA, Washington, DC. Available online: https://eng.auburn.edu/research/centers/ncat/files/technical-reports/rep15-04.pdf, last accessed May 3, 2019.

FHWA Involvement	Publication Title	Date	Citation
Published	*Case Study: Northern California, US 199-Del Norte County*(49)	2016	FHWA. (2015). *Case Study: Northern California US 199-Del Norte County High Friction Surface Treatment (HFST)*, Report No. FHWA-SA-15-055, FHWA, Washington, DC. Available online: https://rspcb.safety.fhwa.dot.gov/noteworthy/html/documents/roadwaydeparture_ca.pdf, last accessed May 3, 2019.
Published	"Center for Accelerating Innovation: High Friction Surface Treatments"(50)	2016	FHWA. (2016). "Center for Accelerating Innovation: High Friction Surface Treatments." (website) FHWA, Washington, DC. Available online: https://www.fhwa.dot.gov/innovation/everydaycounts/edc-2/hfst.cfm, last accessed May 6, 2019.
Published	*High Friction Surface Treatment Applications by Thurston County, Washington*(29)	2016	FHWA. (2016). *High Friction Surface Treatment Applications by Thurston County, Washington.* Report No. FHWA-SA-16-060, FHWA Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/docs/thurston.pdf, last accessed May 3, 2019.
Published	*High Friction Surface Treatment Curve Selection and Installation Guide*(2)	2016	Atkinson, J., Clark, J., and Ercisli, S. (2016). *High Friction Surface Treatment Curve Selection and Installation Guide*, Report No. FHWA-SA-16-034, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/faqs_links_other/hfst_guide/hfst_guide.pdf, last accessed May 3, 2019.
Published	*High Friction Surface Treatment, Case Study: Iowa I-380, Cedar Rapids, High Friction Surface Treatments: Not Just for Rural Curves*(51)	2016	FHWA. (2016). *High Friction Surface Treatment, Case Study: Iowa I-380, Cedar Rapids, High Friction Surface Treatments: Not Just for Rural Curves*, Report No. FHWA-SA-16-021, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/iowa/hfst_ia_cs.pdf, last accessed May 3, 2019.
Published	*High Friction Surface Treatment, Case Study: Pennsylvania SR 611-Northampton County, Successfully Disseminating the Practice*(52)	2016	FHWA. (2016) *High Friction Surface Treatment, Case Study: Pennsylvania SR 611-Northampton County, Successfully Disseminating the Practice*, Report No. FHWA-SA-16-056, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/docs/penn.pdf, last accessed May 3, 2019.
Published	*High Friction Surface Treatment, Case Study: South Carolina US 25-Greenville County, A Cost-Effective and Time-Sensitive Safety Solution*(53)	2016	FHWA. (2016). *High Friction Surface Treatment, Case Study: South Carolina US 25-Greenville County, A Cost-Effective and Time-Sensitive Safety Solution*, Report No. FHWA-SA-15-056, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/sc/sc.pdf, last accessed May 3, 2019.

FHWA Involvement	Publication Title	Date	Citation
Published	*High Friction Surface Treatments, Project Case Study: Intersection of Forest Drive and Cole Creek Parkway in Bellevue, Washington*(54)	2016	FHWA. (2016). *High Friction Surface Treatments, Project Case Study: Intersection of Forest Drive and Cole Creek Parkway in Bellevue, Washington*, Report No. FHWA-CAI-14-016, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/docs/bellevue.pdf, last accessed May 3, 2019.
Published	*Systemic Applications of High Friction Surface Treatment in Tennessee*(55)	2016	FHWA. (2016). *Systemic Applications of High Friction Surface Treatment in Tennessee*, Report No. FHWA-SA-16-058, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/docs/tdot.pdf, last accessed May 3, 2019.
Published	*Systemic Installations of High Friction Surface Treatments on Small Curves in Kentucky*(56)	2016	FHWA. (2016). *Systemic Installations of High Friction Surface Treatments on Small Curves in Kentucky*, Report No. FHWA-SA-16-057, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/docs/kentucky.pdf, last accessed May 6, 2019.
Published	*Texas Department of Transportation's Methodology for Selecting Curves to Receive High Friction Surface Treatments and Other Safety Improvements*(57)	2016	FHWA. (2016). *Texas Department of Transportation's Methodology for Selecting Curves to Receive High Friction Surface Treatments and Other Safety Improvements*, Report No. FHWA-SA-16-059, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/docs/txdot.pdf, last accessed May 3, 2019.
Published	*Accelerated Implementation and Deployment of Pavement Technologies Annual Report*(58)	2016	FHWA. (2016). *Accelerated Implementation and Deployment of Pavement Technologies Annual Report*, Report No. FHWA-HIF-16-031, FHWA, Washington, DC. Available online: https://www.fhwa.dot.gov/pavement/pubs/hif16031.pdf, last accessed May 3, 2019.
Published	"Frequently Asked Questions – High Friction Surface Treatments (HFST) – 2017"(3)	2017	FHWA. (2017). "Frequently Asked Questions – High Friction Surface Treatments (HFST) – 2017." (website) FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/faqs_links_other/hfst_faqs/, last accessed May 3, 2019.
Publication in progress	*High Friction Surface Treatments*	In progress	Merritt, D.K., Lyon, C.A., Persaud, B.N. (in progress). *High Friction Surface Treatments*, Report No. TBD, FHWA, Washington, DC.

Acknowledgments

The evaluation team would like to thank all those who contributed information to this report, including the interview participants and those who responded to email requests for information.

References

1. Strategic Management Team, Office of Transportation Policy Studies, FHWA. (2018). *Federal Highway Administration (FHWA) Strategic Plan Fiscal Years 2019–2022*, Report No. FHWA-PL-18-025, FHWA, Washington, DC.

2. Atkinson, J., Clark, J., and Ercisli, S. (n.d.) *High Friction Surface Treatment Curve Selection and Installation Guide*, Report No. FHWA-SA-16-034, FHWA, Washington, DC.

3. FHWA. (2017). "Frequently Asked Questions – High Friction Surface Treatments (HFST) – 2017." (website) FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/faqs_links_other/hfst_faqs/, last accessed May 3, 2019.

4. Waters, J. (2011). "High Friction Surfacing Failure Mechanisms." *3rd International Surface Friction Conference, Safer Road Surfaces—Saving Lives*, Gold Coast, Australia. Available online: https://saferroadsconference.com/wp-content/uploads/2016/05/Waters-High-Friction-Surfacing-Failure-Mechanisms.pdf, last accessed May 3, 2019.

5. Julian, F. and Moler, S. (2008). *Gaining Traction in Roadway Safety*, Report No. FHWA-HRT-08-005, FHWA, Washington, DC. Available online: https://www.fhwa.dot.gov/publications/publicroads/08july/05.cfm, last accessed May 3, 2019.

6. Heitzman, M., Turner, P., and Greer, M. (2015). *High Friction Surface Treatment Alternative Aggregates Study*, Report No. 15-04, National Center for Asphalt Technology at Auburn University, Ashburn, AL.

7. High Friction Roads. (2020). "Completed SEaHC Demonstrations." (website) High Friction Roads, Austin, TX. Available online: https://www.highfrictionroads.com/seahc-demonstration-projects/completed/, last accessed August 28, 2020.

8. Office of Safety Research and Development. (n.d.). *Evaluations of Low Cost Safety Improvements Pooled-Fund Study (ELCSI–PFS).* FHWA, Washington, DC. Available online: . https://highways.dot.gov/research/safety/evaluations-low-cost-safety-improvements-pooled-fund-study/evaluations-low-cost-safety-improvements-pooled-fund-study-elcsi%E2%80%93pfs, last accessed August 28, 2020.

9. Crash Modification Factors Clearinghouse. (n.d.). "Introduction to Crash Modification Factors." (website) FHWA, Washington, DC. Available online: http://www.cmfclearinghouse.org/userguide_CMF.cfm, last accessed January 29, 2019.

10. Merritt, D., Lyon, C., and Persaud, B. (2015). *Evaluation of Pavement Safety Performance*, Report No. FHWA-HRT-14-065, FHWA, Washington, DC.

11. McGee, H.W. and Hanscom, F.R. (2006). *Low-Cost Treatments for Horizontal Curve Safety*, Report No. FHWA-SA-07-002, FHWA, Washington, DC.

12. Center for Accelerating Innovation. (n.d.). "AID Demonstration Projects." (website) FHWA, Washington, DC. Available online: https://www.fhwa.dot.gov/innovation/grants/projects/, last accessed January 29, 2019.

13. Google. (n.d.). "Google Scholar." (website) Google, Mountain View, CA. Available online: https://scholar.google.com/, March 25, 2019.

14. FHWA. (n.d.). "FHWA StaffNet Web Site Statistics." (website) FHWA, Washington, DC. Available online: http://staffnet.fhwa.dot.gov/wpcz/statistics.htm, last accessed December 12, 2018.

15. FHWA. (2018). "EDC-2: High Friction Surface Treatments." (website) FHWA, Washington, DC. Available online: https://www.fhwa.dot.gov/innovation/everydaycounts/edc-2/hfst.cfm, last accessed May 3, 2019.

16. Albin, R., Brinkly, V., Cheung, J., Julian, F., Satterfield, C., Stein, W., Donnell, E., et al. (2016). *Low-Cost Treatments for Horizontal Curve Safety 2016*, Report No. FHWA-SA-15-084, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/countermeasures/horicurves/fhwasa15084/, last accessed May 3, 2019.

17. De Leon Izeppi, E., Flintsch, G.W., and McGhee, K. (2010). *Field Performance of High Friction Surfaces*, Report No. FHWA/VTRC 10-CR6, Virginia Transportation Research Council, Charlottesville, VA. Available online: https://vtechworks.lib.vt.edu/bitstream/handle/10919/46662/10-cr6.pdf?sequence=1&isAllowed=y, last accessed May 3, 2019.

18. Von Quintus, H. and Mergenmeier, A. (2015). *Case Study: Kentucky Transportation Cabinet's High Friction Surface Treatment and Field Installation Program.* Report No. FHWA-SA-15-038, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/kytc/ky_hfst_15_038.pdf, last accessed May 3, 2019.

19. Pratt, M.P., Geedipally, S.R., Pike, A.M., Carlson, P.J., Celoza, A.M., and Lord, D. (2014). *Evaluating the Need for Surface Treatments to Reduce Crash Frequency on Horizontal Curves*, Report No. FHWA/TX-14/0-6714-1, Texas A&M Transportation Institute, College Station, TX. Available online: https://static.tti.tamu.edu/tti.tamu.edu/documents/0-6714-1.pdf, last accessed May 3, 2019.

20. Wilson, B. and Mukhopadhyay, A. (2016). *Alternative Aggregates and Materials for High Friction Surface Treatments.* Texas A&M Transportation Institute, College Station, TX. Available online: https://www.odot.org/materials/tech-reports/BDR74-977-05.pdf, last accessed August 28, 2020.

21. FHWA. (2014). *Horizontal Curves Peer Exchange – June 2014.* Report No. FHWA-SA-15-041, FHWA, Washington, DC.

22. FHWA. (2018). "EDC News: Weekly Newsletter." (website) FHWA Center for Accelerating Innovation, Washington, DC. Available online: https://www.fhwa.dot.gov/innovation/everydaycounts/edcnews/20180809.cfm, February 4, 2019.

23. FHWA. (n.d.). "About the Roadway Safety Capacity Building Program." (website) FHWA, Washington, DC. Available online: https://rspcb.safety.fhwa.dot.gov/about.aspx, last accessed August 28, 2020.

24. FHWA (2013). "Horizontal Curves Virtual Peer Exchange – May 2013." (website) FHWA, Washington, DC. Available online: https://rspcb.safety.fhwa.dot.gov/p2p_reports/horizcurves_May2013.aspx, last accessed May 3, 2019.

25. FHWA. (2013). "Horizontal Curves Virtual Peer Exchange - January 2013." (website) FHWA, Washington, DC. Avialable online: https://rspcb.safety.fhwa.dot.gov/p2p_reports/horizcurves_Jan2013.aspx, last accessed May 3, 2019.

26. Roadway Safety Professional Capacity Building Program. (2013). *Roadway Departure Six-State Peer Exchange*, FHWA, Washington, DC. Available online: https://rspcb.safety.fhwa.dot.gov/p2p_reports/peer_report_VA_Sept2013.pdf, last accessed May 3, 2019.

27. FHWA. (2014). *Systemic Safety Implementation Peer Exchange.* FHWA, Washington, DC. Available online: https://rosap.ntl.bts.gov/view/dot/50461, last accessed May 3, 2019.

28. FHWA. (2014). *Horizontal Curves Peer Exchange – June 2014*, Report No. FHWA-SA-15-041, FHWA, Washington, DC. Available online: https://rspcb.safety.fhwa.dot.gov/p2p_reports/horizcurves_June2014.aspx, last accessed May 3, 2019.

29. FHWA. (2016). *High Friction Surface Treatment Applications by Thurston County, Washington.* Report No. FHWA-SA-16-060, FHWA Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/docs/thurston.pdf, last accessed May 3, 2019.

30. FHWA. (2015). *Systemic Safety Implementation Peer Exchange*, Report No. FHWA-SA-16-070, FHWA, Washington, DC.

31. FHWA. (2016). *Northeast Roadway Departure Safety Peer Exchange*, FHWA, Washington, DC.

32. FHWA. (2016). *Virginia Peer Exchange: Contributions of SHSP and HSIP in Driving Down Fatalities*, Report No. FHWA-SA-18-011, FHWA, Washington, DC.

33. Colorado Department of Transportation. (2017) "Colorado Department of Transportation and Federal Highways Administration Host 2017 Peer Exchange," Colorado Department of Transportation. Available online: https://www.codot.gov/business/process-improvement/change-management/colorado-department-of-transportation-and-federal-highways-administration-host-2017-peer-exchange, last accessed August 28, 2020.

34. FHWA. (2016). "Tennessee Hosts High-Friction Surface Treatment Peer Exchange." *EDC News: Weekly Newsletter*, FHWA, Washington, DC.

35. Wilson, B.T., Brimley, B.K., Mills, J., Zhang, J., Mukhopadhyay, A, and Holzschuher, C. (2016). "Benefit–Cost Analysis of Florida High-Friction Surface Treatments." *Transportation Research Record*, pp. 54–62, Transportation Research Board, Washington, DC.

36. ATSSA. (2020). “High Friction Surfacing.” (website) ATSSA, Washington, DC. Available online: http://www.atssa.com/Resources/HighFrictionSurfacing/StateSpecifications.aspx, last accessed October 1, 2018.

37. FHWA. (2019). “High Friction Surface Treatments (HFST).” (website) FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/high_friction/, last accessed January 15, 2019.

38. FHWA. (2016). *Iowa I-380, Cedar Rapids Case Study: High Friction Surface Treatments: Not Just for Rural Curves*, FHWA, Washington, DC.

39. Musey, K., Park, S., and Kares, M. (2017). *Safety Impact of High Friction Surface Treatment Installations in Pennsylvania*, Paper No. 17-02448, presented at the 96th Annual Meeting of the Transportation Research Board, Washington, DC.

40. Gray, G. (2016). *DRAFT High Friction Surface Treatment Benefit/Cost 2016*, Pennsylvania Department of Transportation, Harrisburg, PA.

41. Holloway, S., Castleberry, S., Davini, T., and Kochevar, K. (2013). *High Friction Surface Treatment (HFST) Applications for Cycle 6 Call-for-Projects*, California Department of Transportation, Sacramento, CA.

42. FHWA. (2018). “Roundabouts and Mini Roundabouts.” (website) FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/intersection/innovative/roundabouts/, last accessed March 29, 2019.

43. FHWA. (2010). *Pavement Friction*, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/pavement_friction.pdf, last accessed May 6, 2019.

44. FHWA. (2011). *Roadway Departure Safety Implementation Plans: Kentucky Implements Roadway Departure Safety Plan with Rumble Stripes and Friction Treatments*, Report No. FHWA-SA-11-20, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/strat_approach/fhwasa1120/kyhires.pdf, last accessed May 3, 2019.

45. FHWA. (2012). *High Friction Surface Treatments (HFST) Implementation Plan*, FHWA, Washington, DC.

46. FHWA. (2014). *Frequently Asked Questions about High Friction Surface Treatments (HFST)*, Report No. FHWA-CAI-14-019, FHWA, Washington, DC. Available online: https://www.fhwa.dot.gov/innovation/everydaycounts/edc-2/pdfs/fhwa-cai-14-019_faqs_hfst_mar2014_508.pdf, last accessed May 3, 2019.

47. Bledsoe, J. (2015). *Missouri Demonstration Project: the Use of High-Friction Surface treatments on Missouri Highways*, FHWA, Washington, DC. Available online: https://www.fhwa.dot.gov/hfl/projects/mo_hfst_highways.pdf, last accessed May 3, 2019.

48. FHWA. (2017). *Proven Safety Countermeasures: Enhanced Delineation and Friction for Horizontal Curves*, Report No. FHWA-SA-17-058, FHWA Washington, DC. Available online: https://safety.fhwa.dot.gov/provencountermeasures/enhanced_delineation/, last accessed May 3, 2019.

49. FHWA. (2015). *Case Study: Northern California US 199-Del Norte County High Friction Surface Treatment (HFST)*, Report No. FHWA-SA-15-055, FHWA, Washington, DC. Available online: https://rspcb.safety.fhwa.dot.gov/noteworthy/html/documents/roadwaydeparture_ca.pdf, last accessed May 3, 2019.

50. FHWA. (2016). "Center for Accelerating Innovation: High Friction Surface Treatments." (website) FHWA, Washington, DC. Available online: https://www.fhwa.dot.gov/innovation/everydaycounts/edc-2/hfst.cfm, last accessed May 6, 2019.

51. FHWA. (2016). *High Friction Surface Treatment, Case Study: Iowa I-380, Cedar Rapids, High Friction Surface Treatments: Not Just for Rural Curves*, Report No. FHWA-SA-16-021, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/iowa/hfst_ia_cs.pdf, last accessed May 3, 2019.

52. FHWA. (2016) *High Friction Surface Treatment, Case Study: Pennsylvania SR 611-Northampton County, Successfully Disseminating the Practice*, Report No. FHWA-SA-16-056, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/docs/penn.pdf, last accessed May 3, 2019.

53. FHWA. (2016). *High Friction Surface Treatment, Case Study: South Carolina US 25-Greenville County, A Cost-Effective and Time-Sensitive Safety Solution*, Report No. FHWA-SA-15-056, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/sc/sc.pdf, last accessed May 3, 2019.

54. FHWA. (2016). *High Friction Surface Treatments, Project Case Study: Intersection of Forest Drive and Cole Creek Parkway in Bellevue, Washington*, Report No. FHWA-CAI-14-016, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/docs/bellevue.pdf, last accessed May 3, 2019.

55. FHWA. (2016). *Systemic Applications of High Friction Surface Treatment in Tennessee*, Report No. FHWA-SA-16-058, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/docs/tdot.pdf, last accessed May 3, 2019.

56. FHWA. (2016). *Systemic Installations of High Friction Surface Treatments on Small Curves in Kentucky*, Report No. FHWA-SA-16-057, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/docs/kentucky.pdf, last accessed May 6, 2019.

57. FHWA. (2016). *Texas Department of Transportation's Methodology for Selecting Curves to Receive High Friction Surface Treatments and Other Safety Improvements*, Report No. FHWA-SA-16-059, FHWA, Washington, DC. Available online: https://safety.fhwa.dot.gov/roadway_dept/pavement_friction/case_studies_noteworthy_prac/docs/txdot.pdf, last accessed May 3, 2019.

58. FHWA. (2016). *Accelerated Implementation and Deployment of Pavement Technologies Annual Report*, Report No. FHWA-HIF-16-031, FHWA, Washington, DC. Available online: https://www.fhwa.dot.gov/pavement/pubs/hif16031.pdf, last accessed May 3, 2019.

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