Developing Crash-Modification Factors for High-Friction Surface Treatments: Friction Change Report

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FOREWORD

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

This study complements the FHWA study *Developing Crash-Modification Factors for High-Friction Surface Treatments* (FHWA-HRT-20-061) and documents results from friction testing of high-friction surface treatments (HFSTs).[1] This study used a highway friction tester, a continuous fixed-slip measurement device that provides a continuous friction plot, to measure and collect pavement friction values of the HFST and the existing pavement surface before HFST installation. In some cases, the study used the friction of the pavement leading up to and away from existing HFST sites to estimate the friction of the underlying pavement for comparison to HFST friction. This report presents the evaluation results of friction change before and after HFST installation, friction change of the HFST and existing pavement over time, and friction change within a curve. This report may benefit safety engineers, pavement engineers, and safety planners by providing greater insight into applications of HFST for improving highway safety.

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16. Abstract
This report documents results and observations from friction testing of high-friction surface treatments (HFSTs) as part of an FHWA research study, *Developing Crash-Modification Factors for High-Friction Surface Treatments*.[1] This larger study provides high-quality crash-modification factors and benefit–cost ratios for HFST with calcined bauxite aggregate and recommends materials and specifications for applying HFST to effectively reduce roadway-departure crashes. Friction testing was performed to document the friction of the HFST and underlying pavement. For a number of sites, friction testing was performed on the existing pavement surface before HFST installation and on the HFST after installation. In some cases, testing of the pavement leading up to and away from existing HFST sites was used to estimate the friction of the underlying pavement for comparison to HFST friction. To evaluate friction change of HFST over time, friction testing was also performed on several older HFST installations where previous friction data had been collected. All friction testing was performed with a highway friction tester, a continuous fixed-slip measurement device that provides a continuous plot of friction reported in 0.30-meter (1-foot) increments through the section of pavement tested. The advantage of continuous friction measurement is that variations in friction (e.g., through a curve) can be documented. The friction data collected during this research and documented in this report were evaluated for friction change before and after HFST installation, friction change of the HFST and existing pavement over time, and friction change within a curve.

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ACRONYMS

AADT	average annual daily traffic
CMF	crash-modification factor
EB	eastbound
ELCSI-PFS	Evaluation of Low-Cost Safety Improvements Pooled Fund Study
FHWA	Federal Highway Administration
HFST	high-friction surface treatment
HFT	highway friction tester
LWST	locked-wheel skid trailer
TTI	Texas Transportation Institute
WB	westbound

EXECUTIVE SUMMARY

This report summarizes several evaluations of the friction data collected as part of a safety performance evaluation of high-friction surface treatments (HFSTs). *Developing Crash-Modification Factors for High-Friction Surface Treatments* provides high-quality crash-modification factors and benefit–cost ratios for HFST with calcined bauxite aggregate and recommends materials and specifications for applying HFST to effectively reduce roadway-departure crashes.[1] For this safety performance evaluation, friction data were collected at several hundred HFST sites in six States and at several locations where previous (historical) friction data were available.

Three separate evaluations of friction change were performed:

1. Evaluation of friction before and after HFST application for sites in the six States included in the safety performance evaluation study.
2. Evaluation of friction change over time for HFST sites with historical friction data, as well as current friction of HFST based on age and traffic exposure.
3. Evaluation of friction change within curves to determine whether traffic-induced wear on pavement and HFST surfaces results in reduced friction within a curve.

The results of these evaluations verified the effectiveness of HFST. HFST was shown to dramatically increase the friction of virtually any pavement surface on both curves and ramps. HFST was also shown to maintain high levels of friction over time and under high traffic exposure. Although the evaluation of friction change within curves was not conclusive, the increased friction provided by HFST should minimize any potential reduction in friction within a curve over time.

CHAPTER 1. INTRODUCTION

This report supplements the technical report of the Federal Highway Administration (FHWA) study *Developing Crash-Modification Factors for High-Friction Surface Treatments*, which evaluated the safety performance of high-friction surface treatments (HFSTs).(1) For the safety performance study, crash, roadway, and friction data were collected from more than 500 existing and planned HFST sites for use in developing crash-modification factors (CMFs) and benefit–cost ratios for HFST. The friction data were used to develop CMFs based on friction change before and after HFST installation.

Table 1 summarizes the HFST sites that were tested for inclusion in the safety performance evaluation for this study, although not all sites were used for the final analysis. Two categories of sites were tested in the study: (1) existing HFST sites, which were tested in place; and (2) planned sites, which were tested before and after HFST installation.

Table 1. Number of HFST data collection sites by location and type.

State	Number of Curves		Number of Ramps		Number of Intersections	
	In Place	**Planned**	**In Place**	**Planned**	**In Place**	**Planned**
AR	5	0	17	0	6	0
GA	43	93	—	—	—	—
KY	58	0	27	0	1	0
LA	27	90	—	—	—	—
PA	85	22	—	—	—	—
WV	25	14	—	—	—	—
Total	**243**	**219**	**44**	**0**	**7**	**0**

—No data.

This report focuses on the evaluation of the friction data collected from these and additional HFST sites with friction history to assess friction change. Specifically, the following evaluations are summarized in this report:

1. *Friction change before and after HFST installation.* For sites tested as part of the safety performance evaluation, the friction of the pavement surfaces before and after HFST installation was evaluated. For existing HFST sites, the pavement friction leading up to (i.e., lead-in) and away from (i.e., lead-out) the HFST was used to estimate pavement friction before HFST installation.
2. *Friction change over time.* For HFST sites for which historical friction data were available, the friction was evaluated to assess change in HFST friction over time. In addition, HFST friction change based on age and estimated traffic exposure was evaluated.
3. *Friction change within curves.* Changes in pavement friction within curves before HFST installation and changes in HFST friction within curves after HFST installation were evaluated.

HIGH-FRICTION SURFACE TREATMENT

HFST is a specialty pavement treatment specifically used to restore or enhance friction. It is commonly used for spot treatments on curves, ramps, intersections, and steep grades, where friction demand is higher than conventional paving materials can provide. HFST is installed by spreading a thin layer of polymeric resin binder (typically epoxy or polyester) over the pavement surface and then broadcasting or dropping an abrasion- and polish-resistant aggregate 1–3 mm (0.04–0.12 inches) in size onto the resin layer (figure 1 through figure 4). Calcined bauxite, which exhibits exceptional polish resistance and skid resistance not achieved with conventional pavement aggregates, is used to maintain high skid resistance over time. All HFST sites tested as part of this friction change evaluation used HFST consisting of calcined bauxite aggregate.

Source: FHWA.

Figure 1. Photograph. HFST installation.

Source: FHWA.

Figure 2. Photograph. Machine laying aggregate for HFST.

Source: FHWA.

Figure 3. Photograph. Close-up view of HFST after installation.

Source: FHWA.

Figure 4. Photograph. HFST finished surface.

COLLECTION OF FRICTION DATA

The project team collected friction data used for the friction change evaluation to ensure consistency of the pavement and HFST friction data used in the analysis.

Method

In the United States, friction data have traditionally been collected using an ASTM E274 locked-wheel skid tester (LWST).[(2)] An LWST is a trailer-based testing system that measures friction by completely locking up the test wheel and recording the average sliding force for 3 s and reporting a 1-second average after reaching the fully locked state (100-percent slip). Thus, at a 40-mph[1] test speed, a 1-second test time is equivalent to testing the pavement surface for approximately 17.98 m (59 ft). The full-lock requirement means that measurements can be recorded only periodically over short intervals of time. Reporting one test per mile results in approximately 1.1 percent of the pavement surface being tested. In addition, testing with a trailer

[1]This document reports speed in mph. To calculate speed in km/h, multiply the speed in mph by 1.61. For example, 40 mph multiplied by 1.61 equals 64.4 km/h.

unit locking wheel on tight horizontal curves or at intersections can be challenging or prohibitive. Thus, an LWST may not adequately characterize pavement friction at these locations.

Alternatively, continuous friction measurement systems measure friction continuously and report it at 0.30-meter (1-foot) increments over the section of pavement evaluated, allowing any variations in friction to be measured and quantified. Because of the advantage of continuous friction measurement and the location of most HFST installations, the project team collected friction data for this study using a highway friction tester (HFT) (figure 5). The HFT is an ASTM E2340 continuous fixed-slip measurement equipment device that provides a continuous measurement of friction at prevailing highway speed.(3) Friction data are reported by the HFT every 0.30 m (1 ft) over the length of the pavement surface being tested. The HFT uses an ASTM E1551 smooth-tread test tire located in the left wheel path of the lane and a slip ratio of 14 percent.(4) The HFT applies a 0.5-millimeter (0.02-inch) water film to the pavement surface in front of the test tire during testing. The HFT is also equipped with a texture laser to estimate pavement texture as mean profile depth.

Source: FHWA.

Figure 5. Photograph. The HFT.

Because it operates at a low slip ratio, the HFT measures friction values closer to the peak friction value for a pavement surface, in contrast to the LWST, which uses the fully locked (100-percent) slip ratio. The HFT friction values are more representative of the friction available from a pavement surface for vehicles with antilock brakes, whereas the LWST friction values are more representative of the friction available from a pavement surface under a skidding (locked-wheel) condition. At the low slip ratio of the HFT, the measurements are very sensitive to pavement microtexture and the properties of the test tire. As such, the friction values reported by the HFT are generally higher than those commonly measured by highway agencies using an ASTM E274 LWST.

Because friction measurement is highly dependent on the method used by the device (e.g., fixed slip versus fully locked), the tire used by the device, and the characteristics of the pavement surface itself (microtexture and macrotexture in particular), friction values from the HFT are not directly comparable to those from the LWST for all pavement surfaces. A 2013 Texas Transportation Institute (TTI) evaluation comparing the HFT to two different ASTM E274 LWSTs found that the locked-wheel smooth-tread tire (ASTM E524) skid numbers were approximately two-thirds of the corresponding HFT friction number for the pavement surfaces tested.[5,6] However, because no HFST sections were included in the TTI evaluation, this correlation is not necessarily applicable to all surfaces, but it may provide a general understanding of the relative difference in readings. Pavement and HFST friction measurements presented herein are all based on data from the HFT.

Testing Procedure

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

A test speed of 40 mph was selected as the target test speed for most sites, regardless of higher posted speeds. For some sites, the test speed was limited to between 25 and 35 mph because of curve radius or prevailing traffic conditions. During trial runs of friction testing, the project team noted that speeds below 25 mph resulted in unreliable friction data; therefore, 25 mph was established as the absolute minimum test speed.

For this study, it was important to collect friction data before and after HFST installation to better understand the change in friction as a result of HFST installation. This was possible for planned sites, but for existing HFST sites, friction data were collected on the lead-in and lead-out pavement as a surrogate measure of underlying pavement friction. The ability to collect lead-in and lead-out friction data on abutting pavement varied widely from site to site depending on the location of the HFST site in relation to other curves, intersections, and so forth. The project team attempted to collect approximately 91.44–152.40 m (300–500 ft) of lead-in and lead-out friction data whenever possible. However, for some sites, only 60.96 m (200 ft) (or less) of data could be collected.

Data Reporting

Friction data were manually processed for each HFST site, and the average friction values for the HFST and the underlying or abutting (lead-in and lead-out) pavement were reported. For sites with two or more lanes, the average friction value for all lanes was reported. The project team noted any significant differences in friction between lanes in case further evaluation was needed to determine the cause. Any significant difference in lead-in and lead-out friction was also noted, and if the lead-in or lead-out pavement was different from the known surface under the HFST, only the data from the same type of surface were used.

The HFT reports friction as a "Mu" value. For the purpose of reporting data herein, the Mu value measured by the HFT at speed *S* (mph) is represented as HFT(*S*). In general, data collected at 40 mph were used for comparison purposes. Although a number of sites were tested at speeds other than 40 mph, a speed adjustment factor has not yet been determined for the HFT on surfaces with HFST, so only data collected at the same speed were compared.

Additionally, although the HFT reports Mu values greater than 1.0 (for HFST in particular), for the purpose of this report, anything above 1.0 is simply reported as 1.0. The exception is for the evaluation of friction change within curves.

Because of how friction data are collected by the HFT, friction values build up over the first 60.96 m (200 ft) of an HFST site before stabilizing at the apparent friction value for the HFST.

Challenges

The project team encountered many challenges with collecting friction data, which limited the number of sites that could be tested and included in the study. Some of these challenges included the following:

- *Inability to collect friction data on stop-controlled and most signal-controlled intersections.* The HFT must be operating at a relatively constant speed because braking and acceleration can affect the friction data. As such, the project team was not able to test HFST sites at stop-controlled intersections. Likewise, signal-controlled intersections were difficult to test because testing needed to coincide with a green signal. Although the project team was able to successfully test several signal-controlled intersections, the total number of these intersections was very small.

- *Inability to collect friction data on tight-radius ramps and curves.* To obtain reliable friction data, the HFT must be operating at a minimum of 25 mph, so tight-radius ramps and curves with advisory speeds less than 25 mph had to be excluded from testing because of safety concerns for the friction testing operation.

- *Inability to collect friction data on most ramps terminating at intersections.* Many of the ramp sites planned for inclusion in the study terminated at intersections, requiring the HFT to stop collecting data well before the end of the ramp. Although it was still possible to test many ramps with this configuration, several had to be eliminated for this reason.

CHAPTER 2. FRICTION CHANGE BEFORE AND AFTER HFST INSTALLATION

EVALUATION OVERVIEW

This chapter presents the results from an evaluation of friction data before and after HFST installation at HFST sites. Two sets of data were analyzed for this purpose:

- *Planned HFST sites where pre-HFST pavement friction data and postinstallation HFST friction data were measured over the same area.* These sites were located in Georgia and Pennsylvania. In Louisiana, some planned sites were tested before HFST installation, but delays in HFST installation prevented postinstallation friction testing within the project timeframe.

- *Existing HFST sites where lead-in and lead-out pavement friction was used to estimate the friction of the underlying pavement.* These sites were analyzed separately from the planned HFST sites because the lead-in and lead-out pavement friction was only an estimate of the pavement friction before HFST installation and likely changed with time since the HFST was installed.

DATA SUMMARY

Table 2 summarizes friction change for sites in Georgia and Pennsylvania where pre- and post-HFST friction data were collected. All sites in Georgia were tested at 40 mph, and all sites in Pennsylvania were tested at either 30 mph or 35 mph because of site characteristics. All sites were asphalt pavement surfaces, and all were curve sites (no ramps). The project team measured the friction of the pavement surface before HFST installation over the approximate area where the HFST was to be installed, although the planned HFST installation area was not always well marked. The reported friction does not include lead-in and lead-out pavement for a true before-and-after comparison of friction data.

Table 2. Summary of friction change for sites with pre- and post-HFST friction data.

State	Total Number of Sites	Nominal Test Speed (mph)	Number of Sites at Nominal Speed	Pre-HFST Friction at Nominal Speed (HFT Mu)	Post-HFST Friction at Nominal Speed (HFT Mu)	Friction Change (HFT Mu)	Friction Change (%)
GA	85	40	85	0.58–0.87 Avg. = 0.73	0.74–1.0 Avg. = 0.96	+0.01–0.4 Avg. = 0.23	+1–65 Avg. = 33
PA	14	30	7	0.42–0.68 Avg. = 0.54	0.75–1.0 Avg. = 0.86	+0.11–0.55 Avg. = 0.32	+17–131 Avg. = 64
		35	5	0.53–0.63 Avg. = 0.57	0.84–0.99 Avg. = 0.94	+0.27–0.46 Avg. = 0.37	+47–87 Avg. = 67

1 mph = 1.61 km/h.
Avg. = average.

Table 3 summarizes friction change for existing HFST sites using lead-in and lead-out friction data to estimate the underlying pavement friction. A total of 276 sites were tested, but for the purpose of comparing friction values, only the 191 sites tested at 40 mph are summarized in the table. These sites were predominantly curve locations, with a few ramps in Arkansas and

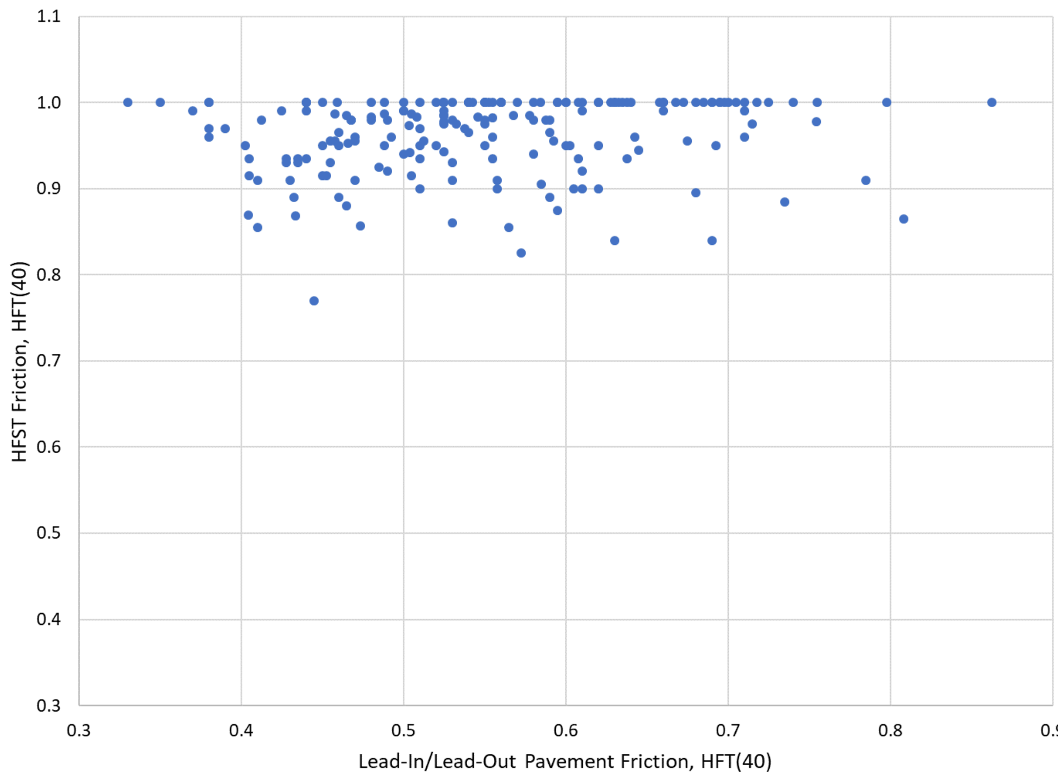
Kentucky that could be tested at 40 mph. All but 11 sites were asphalt pavement. Because of the wide range of pavement friction values, there was no distinguishable difference between concrete pavement and asphalt pavement sites.

Table 3. Summary of friction change for sites using lead-in and lead-out pavement friction data.

State	Total Number of Sites	Number of HFT(40) Sites	Pavement Friction (HFT(40))	HFST Friction (HFT(40))	Friction Change (HFT(40))	Friction Change (%)	Pavement Type
AR	19	15	0.33–0.71 Avg. = 0.51	0.89–1.0 Avg. = 0.95	+0.25–0.67 Avg. = 0.44	+35–203 Avg. = 97	2 concrete
GA	42	40	0.48–0.76 Avg. = 0.60	0.84–1.0 Avg. = 0.98	+0.21–0.5 Avg. = 0.38	+32–105 Avg. = 65	All asphalt
KY	61	40	0.35–0.74 Avg. = 0.53	0.86–1.0 Avg. = 0.98	+0.26–0.65 Avg. = 0.45	+35–186 Avg. = 90	6 concrete
LA	27	27	0.41–0.49 Avg. = 0.51	0.89–1.0 Avg. = 0.97	+0.42–0.57 Avg. = 0.48	+74–138 Avg. = 100	All asphalt
PA	98	58	0.40–0.86 Avg. = 0.56	0.84–1.0 Avg. = 0.95	+0.13–0.55 Avg. = 0.39	+16–136 Avg. = 76	1 concrete, 4 concrete/asphalt
WV	29	11	0.45–0.81 Avg. = 0.59	0.77–1.0 Avg. = 0.90	+0.06–0.44 Avg. = 0.32	+7–87 Avg. = 57	2 concrete

Avg. = average.

Figure 6 shows pavement friction versus HFST friction for these 191 sites, providing an indication of the range of friction values for pavement versus HFST.



Source: FHWA.

Figure 6. Graph. Summary of friction change for sites using lead-in and lead-out friction data.

OBSERVATIONS

The following are some of the key observations from the evaluation of friction data collected before and after HFST installation.

- HFST provided dramatic increases in pavement friction regardless of the friction of the existing pavement. Friction increased by between 1 and 131 percent, with an average increase of 33 percent for Georgia sites (which already had relatively high friction) and 67 percent for Pennsylvania sites tested at 35 mph (which had lower existing pavement friction).

- Friction change for sites where lead-in and lead-out friction data were used to estimate the friction of the existing pavement was even more dramatic. Friction increased by between 7 and 203 percent, with an average increase of approximately 80 percent. However, the pavement friction values may not have accurately reflected actual pavement friction under the HFST before installation.

- Although pre-HFST pavement friction for Pennsylvania sites was similar to the friction estimated from lead-in and lead-out pavement, lead-in and lead-out pavement friction for Georgia sites was noticeably lower than pre-HFST pavement friction.

- Friction values for HFST were consistently high across all sites in all States, with an average of more than 0.95 HFT Mu regardless of HFST age, pavement type, or site type (e.g., curve, ramp).

CHAPTER 3. FRICTION CHANGE OVER TIME

EVALUATION OVERVIEW

This chapter discusses the evaluation of friction change over time for HFST and underlying pavement. Two sets of sites were evaluated for this purpose:

- *HFST sites where historical HFT friction data were available*. Some HFST installations in the United States had previously been tested with the HFT and were tested again for this study.
- *HFST sites tested as part of the safety performance evaluation*. The sites from the six States summarized in chapter 2 vary widely in age and provided valuable information on friction change over time even though initial friction values were not available.

For each site, friction change was analyzed for both the HFST and the underlying pavement. For sites where pre-HFST friction data were not available, the friction of the underlying pavement was estimated from lead-in and lead-out pavement friction at each site.

Friction change was analyzed in terms of age and traffic exposure. Friction change in terms of age was evaluated by the raw age of the treatment and the change in friction between measurements. Friction change in terms of traffic exposure was based on total estimated traffic exposure, which was calculated by multiplying the average annual daily traffic (AADT) by 30 d by the number of months (either raw age or time between friction tests). Although this is not the exact traffic exposure because of changes in traffic volume over time, it should be within 10 percent of actual and is primarily intended to demonstrate the relative order of magnitude of traffic exposure for each HFST site. Note that this calculation does not account for the mix of traffic (passenger vehicles versus trucks), which can have a significant impact on HFST wear, but still provides a better indication of the impact of traffic than age alone.

Table 4 lists the sites with historical HFT friction data that were evaluated. This table indicates HFST installation date and when pre-HFST and post-HFST friction data were collected. Traffic volumes (measured by AADT) for each site are also provided. Note that traffic data shown in table 4 are estimates for each lane at a particular site, which were calculated by dividing the total AADT for the roadway by the number of lanes. Although this averaging may result in slight underestimation or overestimation because of unequal directional or lane distribution factors, the intent is to show the relative order of magnitude of traffic exposure at the various sites. Ramp traffic data for sites H03 and H04 were not available and were estimated based on intersecting mainline traffic data and ramp traffic data for similar interchanges in the vicinity of these sites.

Table 4. Summary of HFST sites with historical friction data.

State	Site ID	Site Type	AADT[1] (yr)	HFST Installation (mo/yr)	Pre-HFST Installation HFT Friction Data (mo/yr)	Post-HFST Installation HFT Friction Data (mo/yr)
OK	H01	Rural road curve, EB and WB lanes	650 (2012)	12/13	12/13	12/13, 12/14, 7/17
	H02	Rural road curve, EB and WB lanes	280 (2017)	3/14	12/13	12/14, 7/17
AL	H03	Urban single-lane connector ramp	10,800[2] (2017)	5/14	4/14	12/14, 7/17
	H04	Urban single-lane connector ramp	14,000[2] (2017)	5/14	4/14	12/14, 7/17
WI	H05	Urban two-lane connector ramp	19,050 (2019)	9/11	NA	6/12, 8/13, 12/14, 3/18
IA	H06	Urban freeway curve, EB and WB, 6 lanes	10,833 (2017)	6/12	6/12 (NB lanes only)	9/12, 8/13, 12/14, 3/18
	H07	Urban single-lane connector ramp	6,200 (2017)	6/12	6/12	9/12, 8/13, 3/18
	H08	Urban single-lane connector ramp	13,900 (2017)	6/12	6/12	9/12, 8/13, 3/18
	H09	Urban single-lane connector ramp	10,100 (2017)	6/12	6/12	9/12, 8/13, 3/18
GA	H10	Rural road curve, EB and WB lanes	1,050 (2017)	4/14	4/14 (WB lane only)	4/14, 12/14, 4/17
MI	H11	Urban two-lane exit ramp	4,563 (2009)	9/10	NA	6/12, 8/13, 12/14

[1]Estimated AADT by lane based on total AADT for the roadway divided by the number of lanes.
[2]Ramp AADT for H03 and H04 sites was estimated using mainline traffic data and similar interchanges.
EB = eastbound; NA = not available; NB = northbound; WB = westbound.

DATA SUMMARY

HFST Sites With Historical Friction Data

Table 5 summarizes the friction change for the HFST sites with historical friction data. Because friction data were not available for all sites immediately after installation, this table shows the change in friction from the earliest to the latest HFT measurements at the site, corresponding initial friction, and number of months between the initial and final tests. Table 5 also shows an estimate of total traffic exposure on the HFST between the two tests.

Test speeds were not always the same during the initial and final tests, as indicated in the last column of the table. This difference in speed may have affected the reported friction change because friction generally measures lower at higher speeds, particularly for conventional (i.e., non-HFST) pavements, and the data should be viewed with this in mind.

Table 5. Friction change for HFST sites with historical friction data.

State	Site ID	Time Between Tests (mo)	Estimated Traffic Exposure (Millions of Vehicles)	Initial HFST Friction (HFT Mu)	Friction Change (HFT Mu)	Friction Change (%)	Test Speed, Initial/Final (mph)
OK	H01, EB	43	0.84	0.90	0.10	11.1	30/40
	H01, WB	43	0.84	0.82	−0.04	−4.9	30/40
	H02, EB	31	0.26	1.00	0.00	0.0	30 /35
	H02, WB	31	0.26	0.62	0.06	9.7	30/35
AL	H03	31	10.04	1.00	0.00	0.0	30
	H04	31	13.02	1.00	−0.05	−5.0	30/40
WI	H05, L1	69	39.43	0.96	−0.11	−11.5	40
	H05, L2	69	39.43	0.96	−0.17	−17.7	40
IA	H06, NB L1	65	21.12	1.00	−0.05	−5.0	40
	H06, NB L2	65	21.12	1.00	−0.10	−10.0	40
	H06, NB L3	65	21.12	1.00	−0.06	−6.0	40
	H06, SB L1	66	21.45	0.99	−0.09	−9.1	40
	H06, SB L2	67	21.77	0.92	−0.08	−8.7	40
	H06, SB L3	67	21.77	0.94	−0.07	−7.4	40
	H07	66	12.28	1.00	−0.01	−1.0	40
	H08	66	27.52	1.00	−0.09	−9.0	40
	H09	66	20.00	1.00	−0.07	−7.0	40
GA	H10, EB	36	1.13	1.00	0.00	0.0	40
	H10, WB	28	0.88	1.00	0.00	0.0	40
MI	H11, L1	30	4.11	0.85	0.05	5.9	30
	H11, L2	30	4.11	0.84	−0.01	−1.2	30

1 mph = 1.61 km/h.
EB = eastbound; L1 = lane 1; L2 = lane 2; L3 = lane 3; NB = northbound; SB = southbound; WB = westbound.

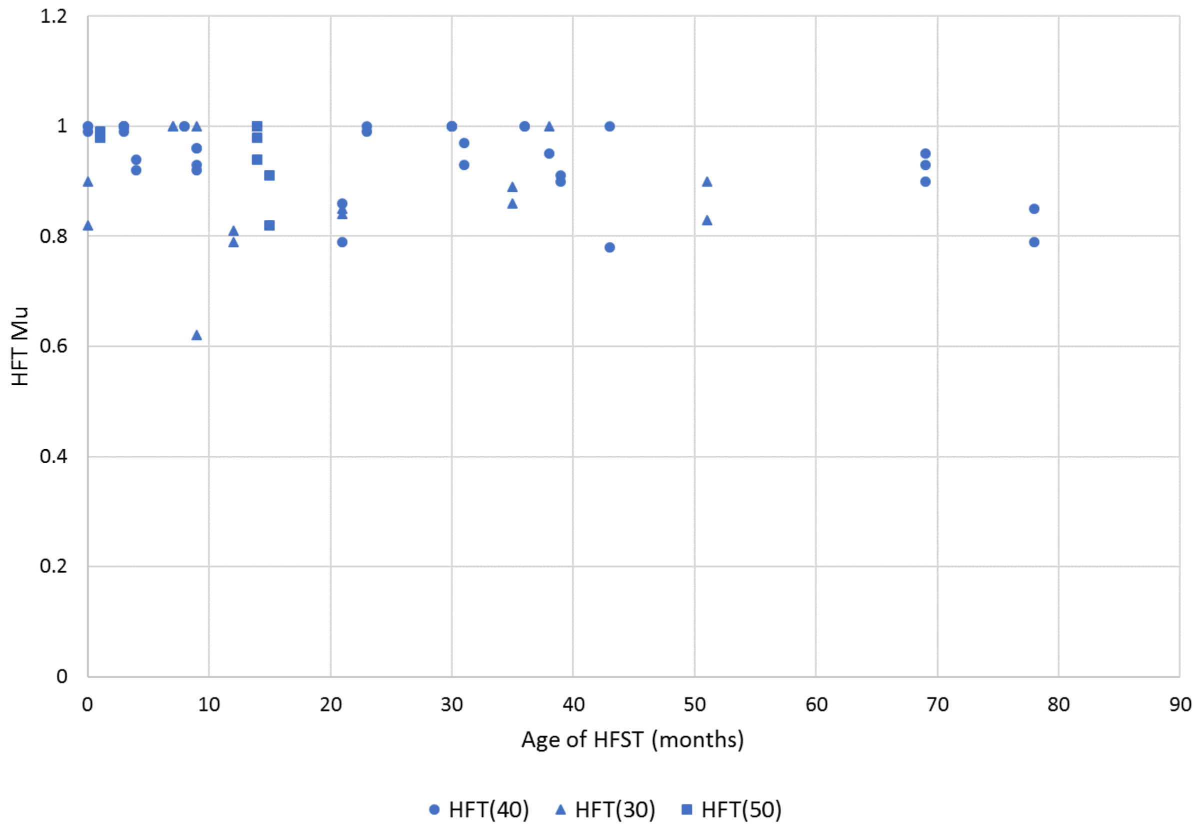
Table 6 summarizes the estimated friction change for the underlying pavement at each site. Pre-HFST friction data were available (within 1–2 mo before installation) for almost all sites except those indicated with an asterisk. For these sites, lead-in and lead-out friction data from the first round of HFT testing at the site were used to estimate initial underlying pavement friction. For sites H05 and H10 (eastbound (EB)), these data were collected approximately 8 and 9 mo after HFST installation, respectively. For site H11, these data were collected approximately 21 mo after HFST installation. For all sites, the pavement friction after HFST installation was estimated from lead-in and lead-out friction data. The number of months between tests, for which the friction change is reported, is shown for all sites regardless of whether the pavement friction data were collected before HFST installation.

Table 6. Estimated friction change for underlying pavement.

State	Site ID	Time Between Tests (mo)	Estimated Traffic Exposure (Millions of Vehicles)	Initial Pavement Friction (HFT Mu)	Pavement Friction Change (HFT Mu)	Friction Change (%)	Test Speed, Initial/Final (mph)
OK	H01, EB	43	0.84	0.59	−0.13	−22.0	30/40
	H01, WB	43	0.84	0.57	−0.10	−17.5	30/40
	H02, EB	43	0.36	0.80	−0.22	−27.5	30/35
	H02, WB	43	0.36	0.67	−0.08	−11.9	30/35
AL	H03	39	12.64	0.59	−0.01	−1.7	30
	H04	39	16.38	0.53	−0.10	−18.9	30/40
WI	H05, L1*	69	39.43	0.53	−0.01	−1.9	40
	H05, L2*	69	39.43	0.51	0.03	5.9	40
IA	H06, NB L1	69	22.42	0.59	−0.12	−20.3	50/40
	H06, NB L2	69	22.42	0.28	0.03	10.7	50/40
	H06, NB L3	69	22.42	0.40	0.03	7.5	50/40
	H06, SB L1	69	22.42	0.62	−0.19	−30.6	50/40
	H06, SB L2*	69	22.42	0.29	−0.03	−10.3	50/40
	H06, SB L3*	69	22.42	0.31	−0.03	−9.7	50/40
	H07	69	12.83	0.58	−0.15	−25.9	40
	H08	69	28.77	0.58	−0.19	−32.8	40
	H09	69	20.91	0.65	−0.22	−33.8	40
GA	H10, EB*	36	1.13	0.72	−0.05	−6.9	40
	H10, WB	36	1.13	0.82	−0.15	−18.3	40
MI	H11, L1*	30	4.11	0.54	−0.04	−7.4	30
	H11, L2*	30	4.11	0.50	0.01	2.0	30

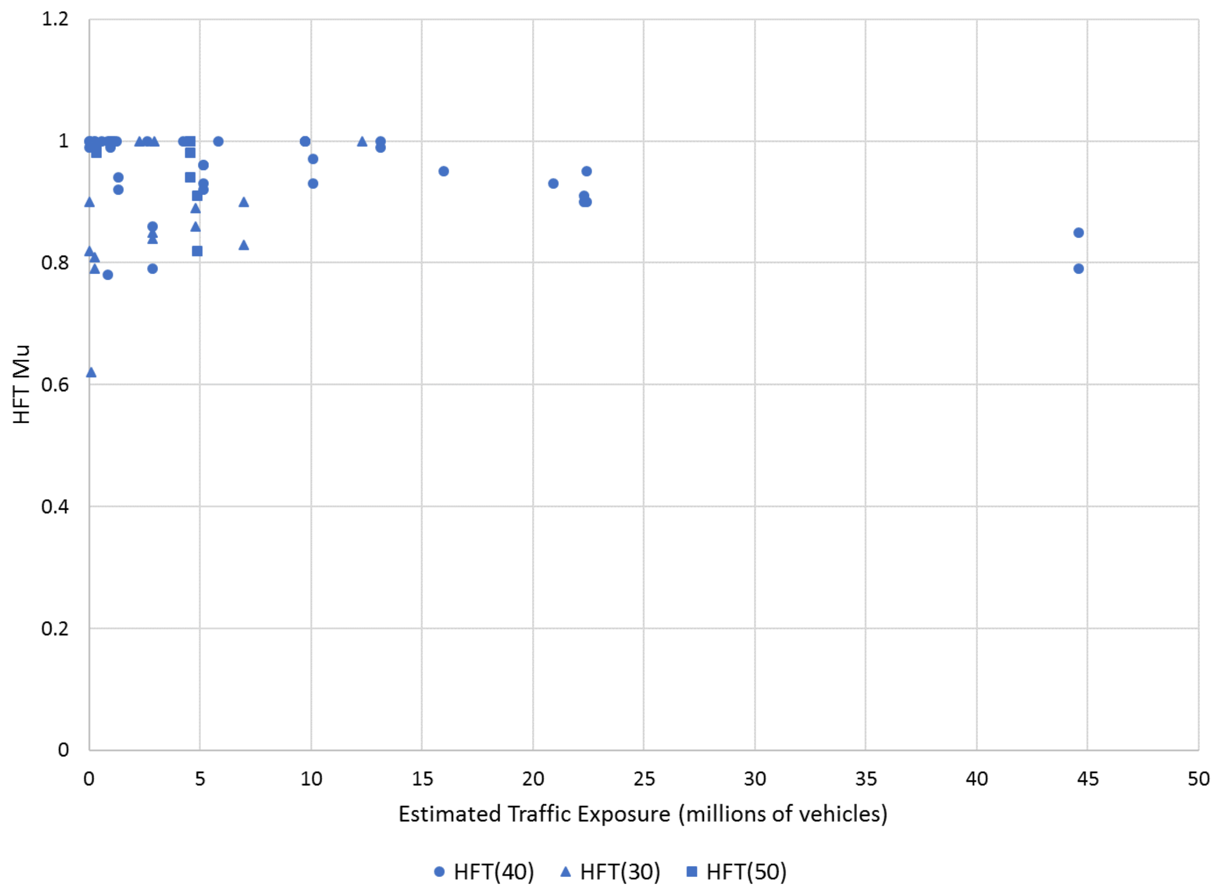
1 mph = 1.61 km/h.
*Sites where lead-in and lead-out friction data from the first round of HFT testing at the site were used to estimate initial underlying pavement friction.
L1 = lane 1; L2 = lane 2; L3 = lane 3; NB = northbound; SB = southbound; WB = westbound.

Figure 7 and figure 8 show HFST friction values versus age and total traffic exposure, respectively, for the sites with historical friction data. Friction values are shown for all friction data collected at various dates (table 4), including multiple measurements over time at a given location. Therefore, one site may be represented by several data points, depending on how many times the friction was measured. Note that friction data in both plots are delineated by test speed (30, 40, or 50 mph).



Source: FHWA.

Figure 7. Graph. HFST friction versus age for sites with historical friction data.



Source: FHWA.

Figure 8. Graph. HFST friction versus estimated traffic exposure for sites with historical friction data.

HFST Sites From Safety Performance Evaluation

The sites from the six States tested as part of the HFST safety performance evaluation were also evaluated for friction change over time. Although it was not possible to document actual friction change over time for these sites because only one set of friction data was collected, these sites indicate HFST friction variation with age and traffic because it is reasonable to assume that most of these sites would have had a friction value close to 1.0 when new. For the purpose of comparing friction values within a State and from State to State, only sites tested at a speed of 40 mph (±2 mph) were evaluated.

Table 7 summarizes the HFST sites included in this evaluation, including many that were tested just after HFST installation. The table shows the total number of sites by State and the number of those sites tested at 40 mph. For each State, the table shows the range and average values of the following measurements: friction, age of the HFST at the time of testing, AADT, and total estimated traffic exposure. Exact installation dates were not available for sites in Louisiana, but a range of estimated traffic exposure was provided based on an age range of 1–18 mo.

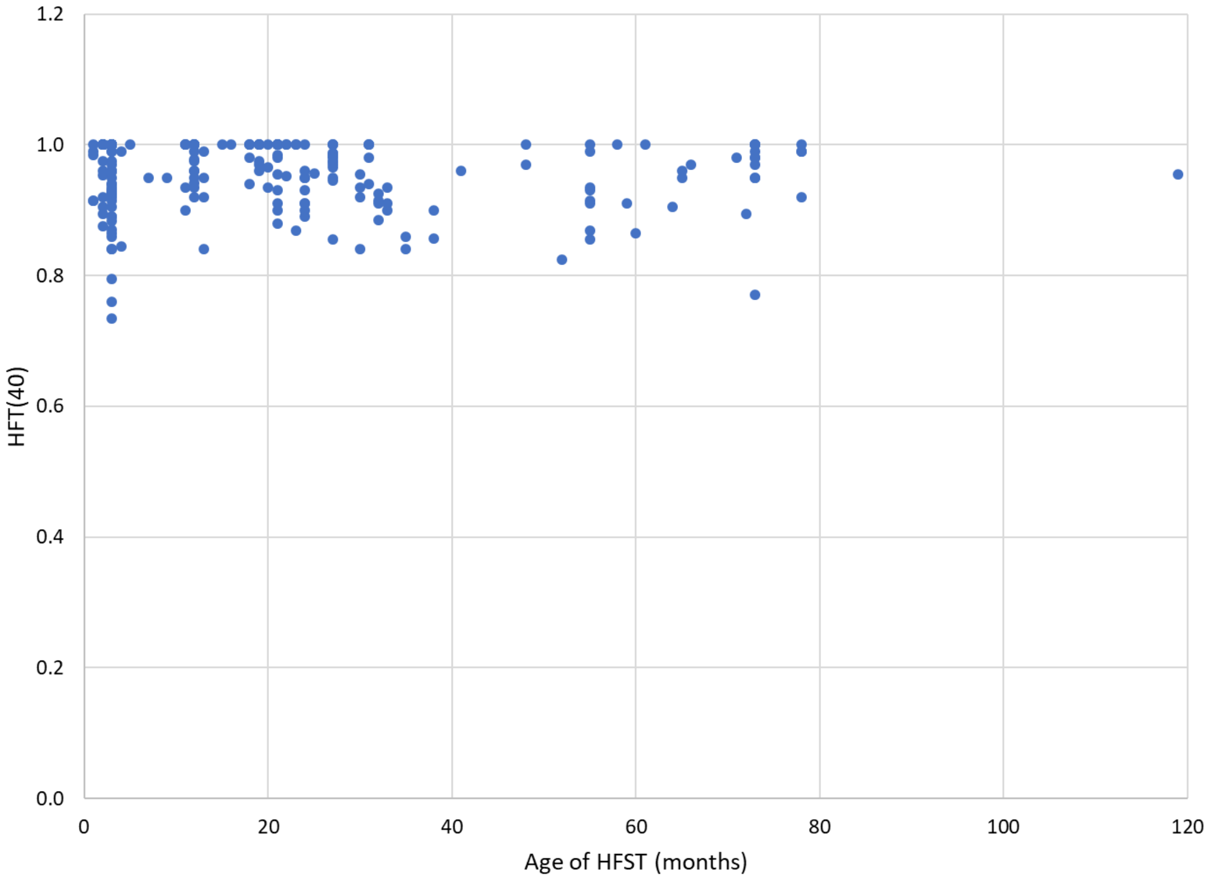
HFST sites ranged in age from 1 mo to nearly 10 yr, with the majority being less than 3 yr old. Estimated traffic exposure ranged from approximately 10,000 vehicles to more than 28 million. These variations provided a wide range of age and traffic exposure for evaluating HFST friction performance.

Table 7. Summary of safety performance evaluation HFST sites.

State	Total Number of Sites	Number of HFT(40) Sites	HFT(40) Friction Range and Average	Age of HFST at Testing (mo)	AADT for HFST Sites	Estimated Total Traffic Exposure (Millions of Vehicles)
AR	19	17	0.84–1.0 Avg. = 0.95	11–24 Avg. = 16	1,700–30,000 Avg. = 9,635	0.39–5.85 Avg. = 2.62
GA	127	125	0.74–1.0 Avg. = 0.97	2–27 Avg. = 7	160–15,600 Avg. = 2,540	0.01–5.35 Avg. = 0.51
KY	62	44	0.84–1.0 Avg. = 0.97	18–78 Avg. = 49	1,024–69,619 Avg. = 7,897	0.51–28.31 Avg. = 5.6
LA	27	27	0.89–1.0 Avg. = 0.97	<18	1,190–4,800 Avg. = 2,412	0.04–2.59*
PA	112	61	0.84–1.0 Avg. = 0.95	1–119 Avg. = 23	1,080–219,752 Avg. = 10,074	0.04–25.27 Avg. = 2.54
WV	29	11	0.77–1.0 Avg. = 0.90	5–73 Avg. = 44	2,335–107,000 Avg. = 36,890	0.32–20.33 Avg. = 8.2

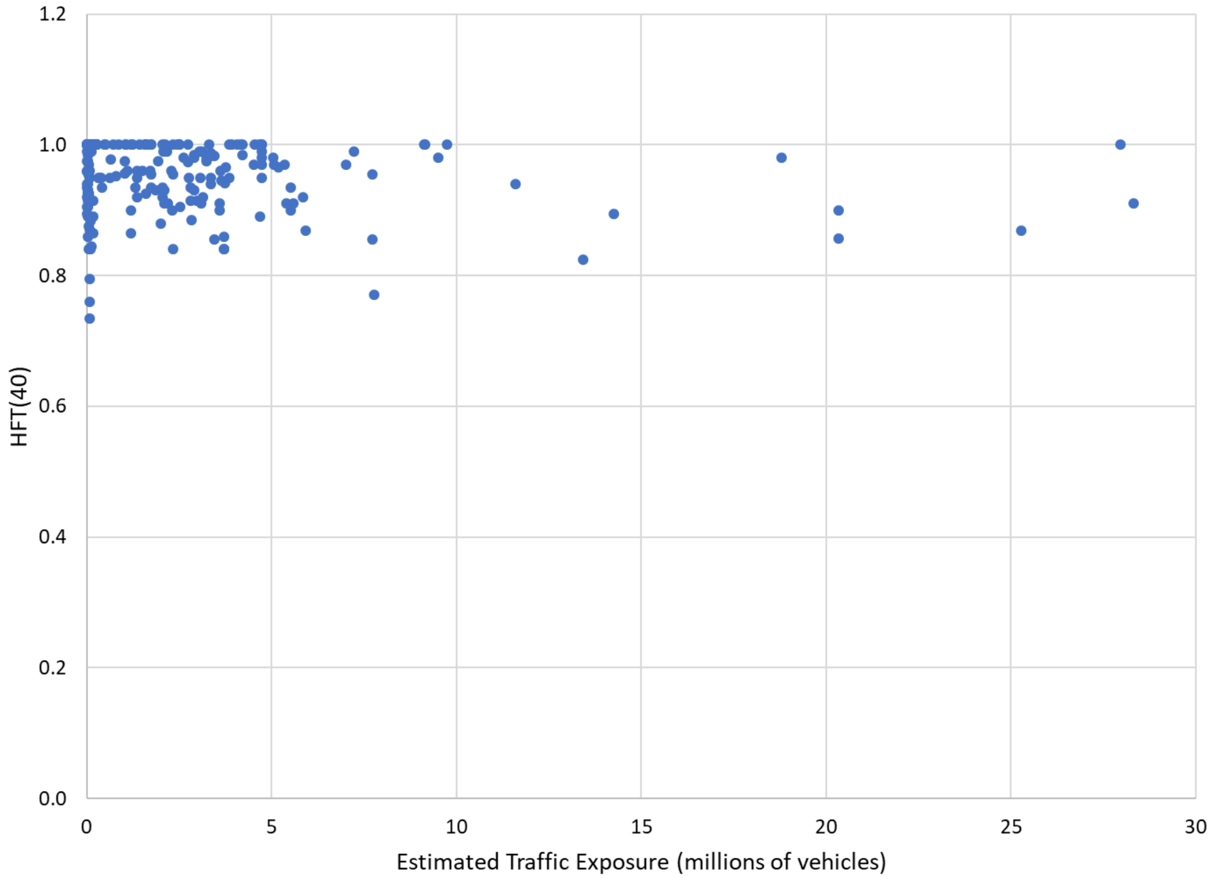
*Based on estimated age range for HFST installations because exact installation dates were not available to determine exact age.
Avg. = average.

Figure 9 shows a plot of friction values by age (at the time of friction testing) for the sites in table 7. Figure 10 shows a plot of friction values by estimated traffic exposure (in millions of vehicles) for these sites, and figure 11 shows a truncated version of the data in figure 10 for sites with less than 3 million vehicles. The 27 sites from Louisiana are not included in figure 9 through figure 11 because of the unavailability of actual installation dates.



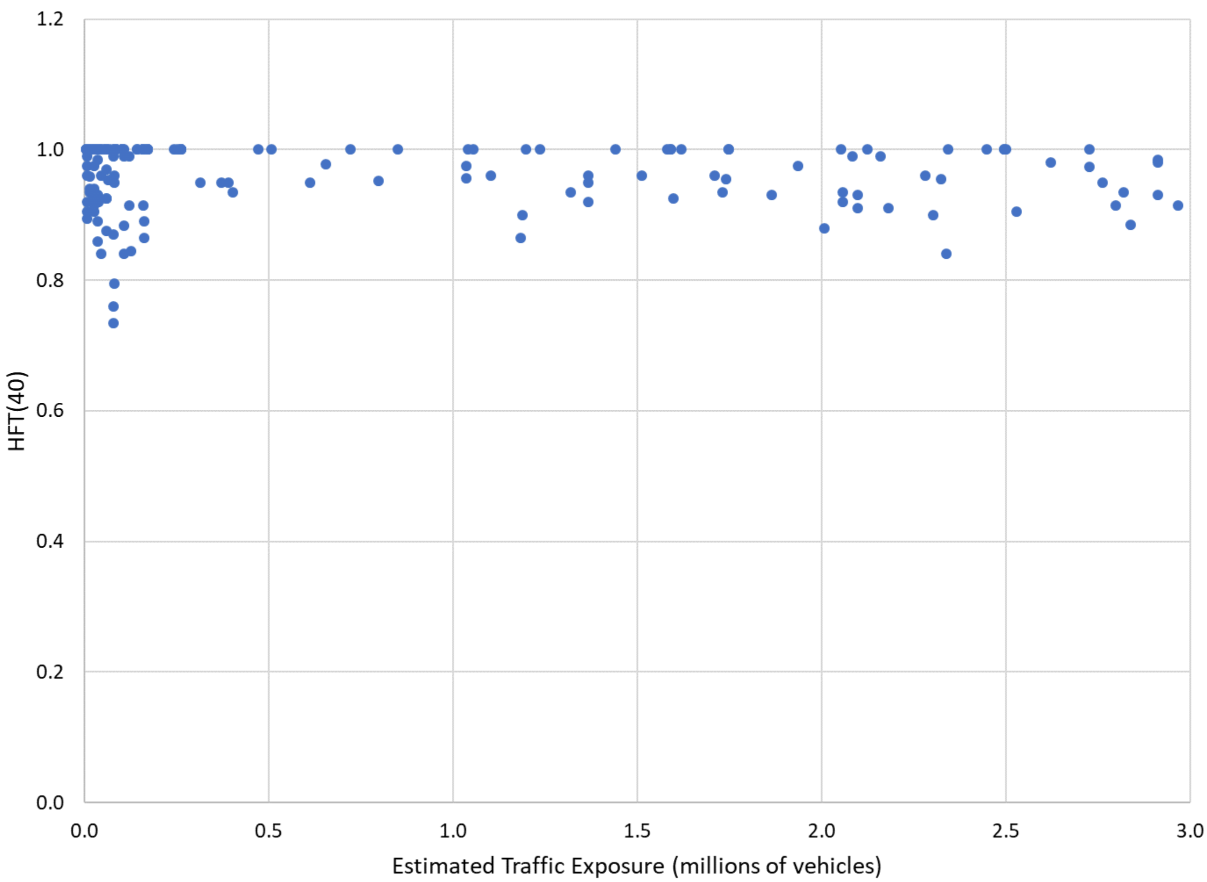
Source: FHWA.

Figure 9. Graph. HFST friction versus age for safety performance evaluation sites.



Source: FHWA.

Figure 10. Graph. HFST friction versus estimated traffic exposure for all safety performance evaluation sites.



Source: FHWA.

Figure 11. Graph. HFST friction versus estimated traffic exposure (safety performance evaluation sites with less than 3 million vehicles).

OBSERVATIONS

The following are some of the key observations from the evaluation of friction change over time.

- This evaluation of HFST sites with historical friction data and HSFT sites from the safety performance evaluation revealed that HFST maintained a high level of friction over time and after exposure to high traffic volumes.
- For the sites with historical friction data, HFST friction change varied, with some sites even showing a slight increase in friction. The majority of sites showed a decrease in friction, but most decreases were less than 10 percent over periods ranging from 2.5 to 5.5 yr with varying levels of traffic exposure.
- The largest decrease in HFST friction was a 17.7-percent decrease (HFT Mu value of −0.17) over a nearly 6-year period with exposure to more than 39 million vehicles, demonstrating exceptional long-term friction performance under heavy traffic.

- For sites tested as part of the safety performance evaluation, HFST friction was generally between 0.8 and 1.0 HFT Mu from a few months after application through nearly 10 yr. Although there did appear to be a decrease in friction with age, this was not unexpected, and the latter-age friction was still very good.
- Likewise, HFST friction based on traffic exposure remained high (between 0.8 and 1.0 HFT Mu) in even the highest traffic exposure condition, which was more than 28 million vehicles.

CHAPTER 4. FRICTION CHANGE WITHIN CURVES

EVALUATION OVERVIEW

This chapter discusses observations from a limited evaluation of friction change within curves for HFST sites tested as part of the safety performance evaluation. The purpose of this evaluation was to see whether any obvious change or variation in friction occurred within curves as a result of higher wear due to higher friction demand in curves. Because the HFT provides a continuous measurement of friction reported every 0.30 m (1 ft), it is possible to measure friction variation within a curve.

A limited number of sites were evaluated for friction change within curves. The data collected were generally found to be inadequate to state conclusively how much friction change occurs within a curve, even with 91.44–152.40 m (300–500 ft) of lead-in or lead-out friction data. The focus of this evaluation was existing pavement tested before HFST installation because the lead-in or lead-out pavement friction cannot be compared to the pavement friction in the curve. In addition, detecting friction change within HFST sections was found to be more difficult because of the limited amount of data from such short sections of HFST.

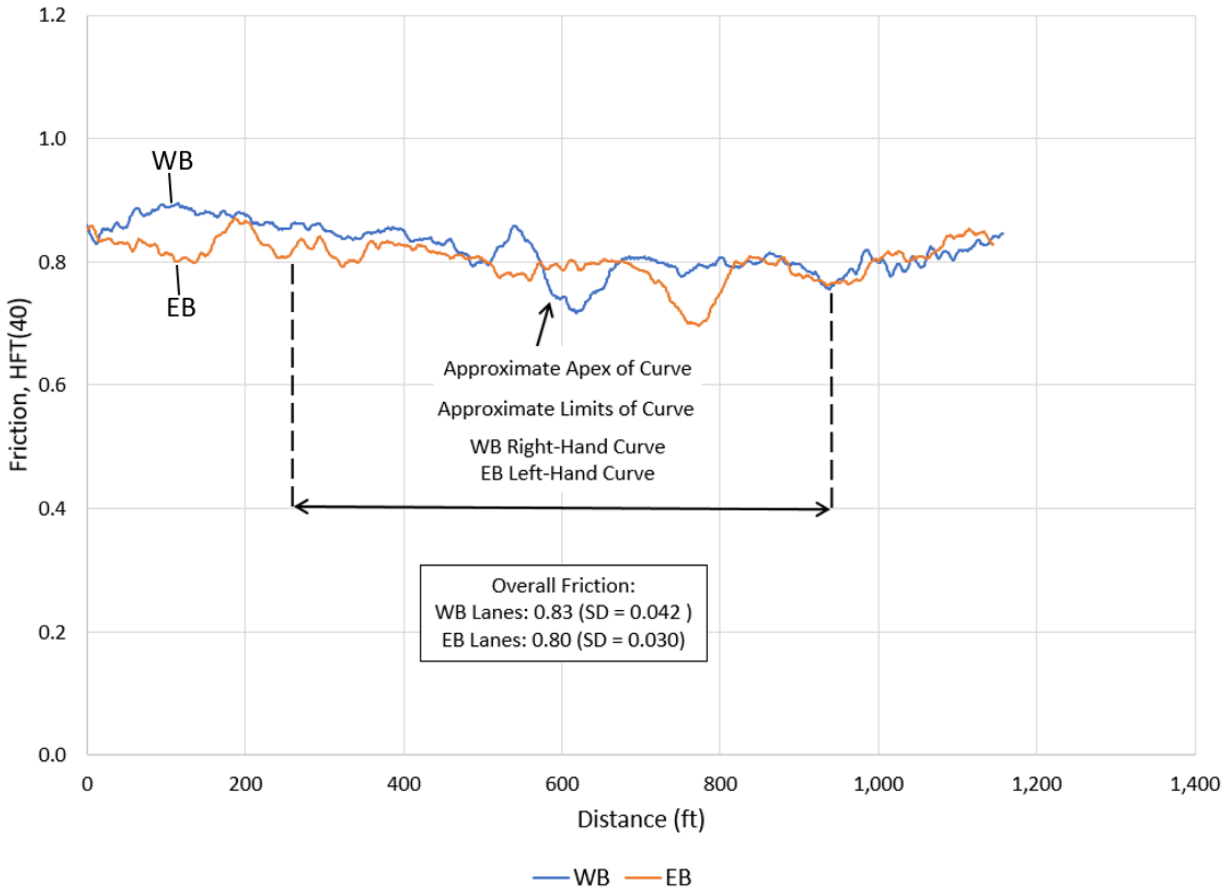
Because the majority of sites tested were low-volume rural road curves, tire-induced wear on these curves was likely not as significant as it could be on higher volume roadways. Unfortunately, pavement age and superelevation data were not available for these sites to assess the impact of these factors on friction change.

A key observation from the HFT data was that friction measurement appeared to be influenced by the direction of the curve (right-hand versus left-hand). This influence may have been caused by the dynamics of the HFT when it traversed tight-radius curves coupled with the fact that the test wheel was on one side of the vehicle in the left wheel path. Further discussion on this observation is provided in the next section.

For comparison, sites selected for evaluation were those tested at a consistent speed of 40 mph (±2 mph).

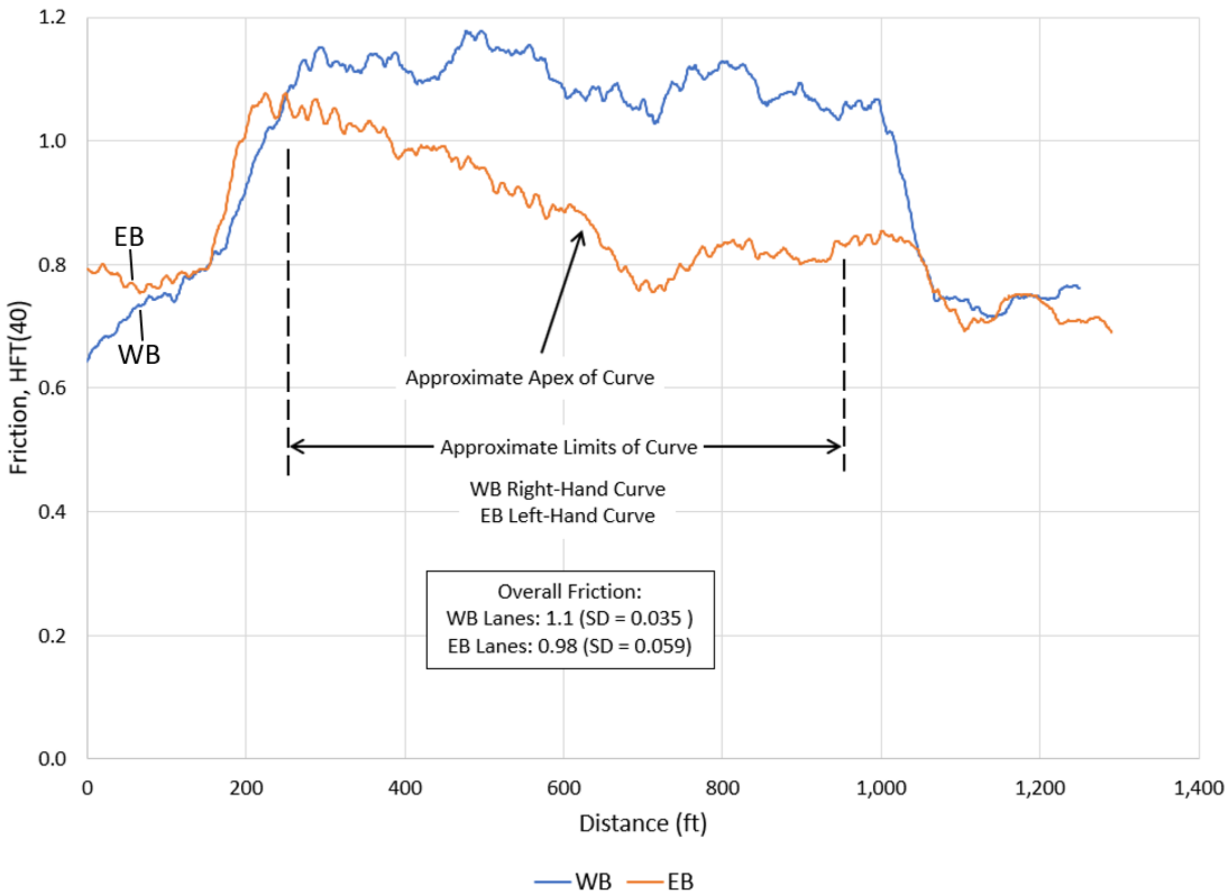
DATA SUMMARY

Figure 12 shows an example of friction change within a curve for a site tested before HFST installation. This site had asphalt pavement with a curve radius of approximately 182.88 m (600 ft) and an AADT of 210. There appeared to be a slight drop in friction through the middle of the curve in both directions, but the variability of friction measurement and the limited amount of data outside of the curve made quantification of the friction change difficult to establish with certainty. Figure 13 shows friction data from this same curve after HFST installation. There was no obvious change in friction within the curve, although there was a slight decrease in friction over a short area in both directions just past the apex of the curve. The friction of the EB lane was highly variable, making it difficult to identify friction change within the curve. The lower friction in the EB lane was likely due to the lower friction of the HFST but may also have been partially influenced by the dynamics of the HFT device, which generally measures lower friction on left-hand curves.



Source: FHWA.
1 ft = 0.30 m.
SD = standard deviation; WB = westbound.

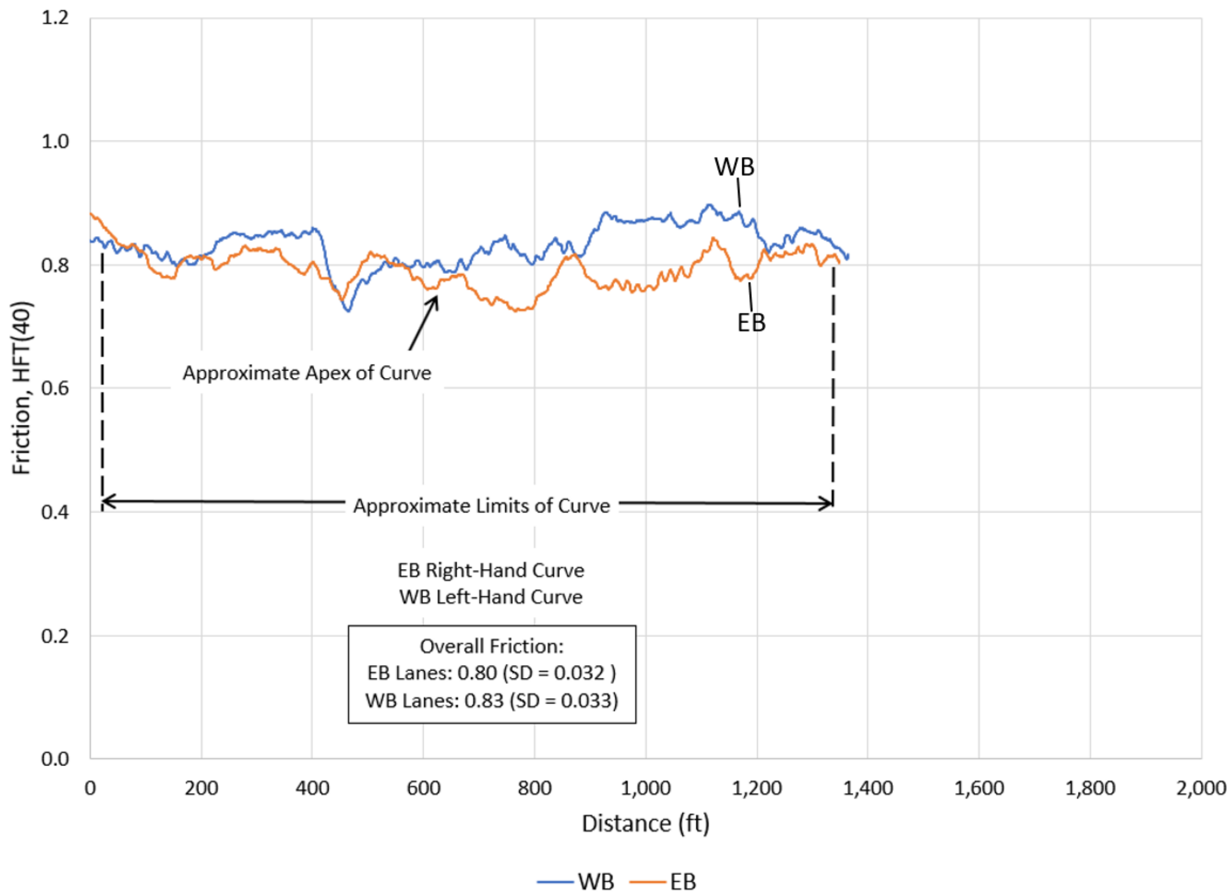
Figure 12. Graph. Friction measurement within a curve before HFST installation.



Source: FHWA.
1 ft = 0.30 m.
SD = standard deviation; WB = westbound.

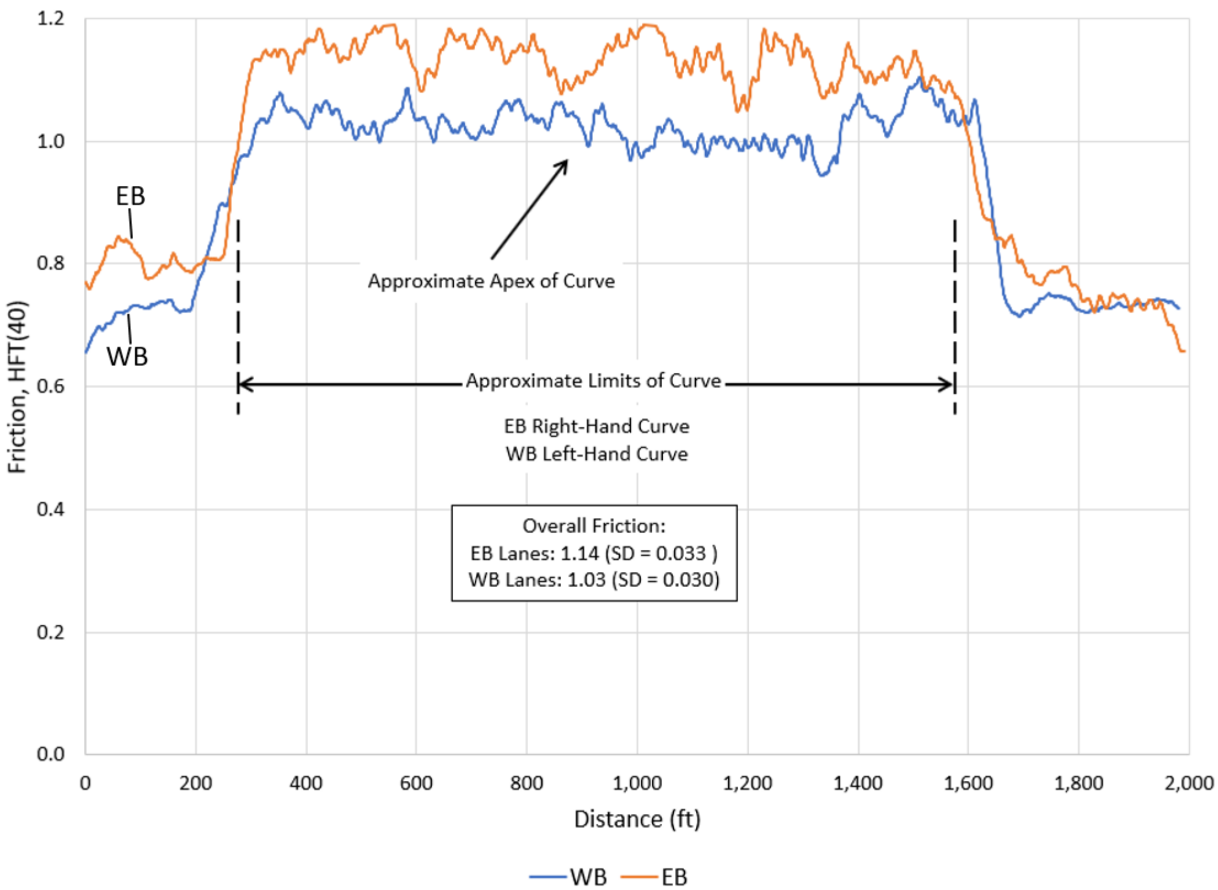
Figure 13. Graph. Friction measurement within a curve after HFST installation.

Figure 14 shows an example of friction change within a curve with a slightly larger curve radius (approximately 304.8 m (1,000 ft)) and the same traffic volumes. This curve turned in the opposite direction (i.e., the left-hand curve was in the westbound (WB) direction). Any change in friction within the curve was less noticeable at this site, possibly because of the larger curve radius. Figure 15 shows this same curve after HFST installation, and there was no obvious change in friction within the curve. However, WB friction was lower than EB friction, which was likely caused by the slightly lower friction of the HFST but may also have been influenced by the HFT measurement being lower on left-hand curves.



Source: FHWA.
1 ft = 0.30 m.
SD = standard deviation.

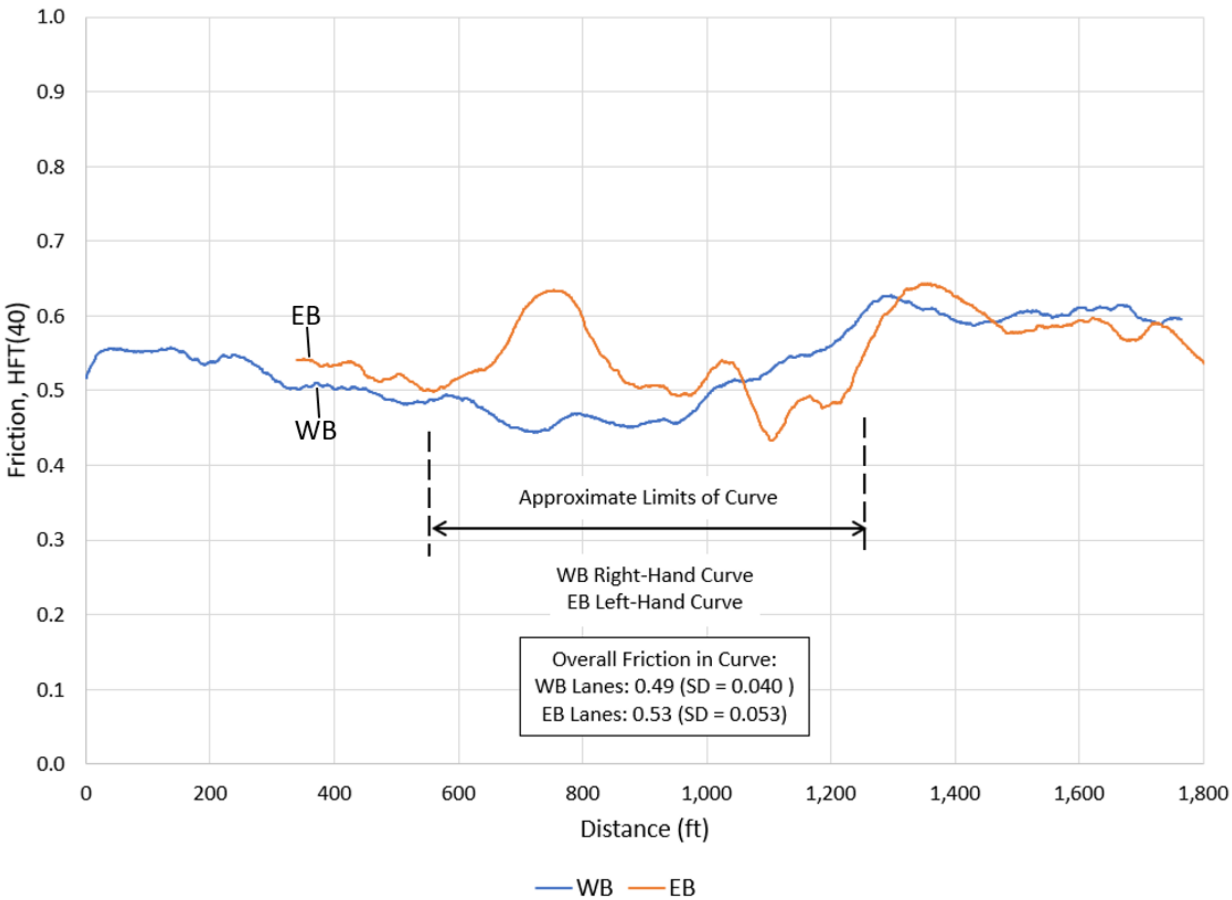
Figure 14. Graph. Friction measurement within a curve (larger curve radius) before HFST installation.



Source: FHWA.
1 ft = 0.30 m.
SD = standard deviation.

Figure 15. Graph. Friction measurement within a curve (larger curve radius) after HFST installation.

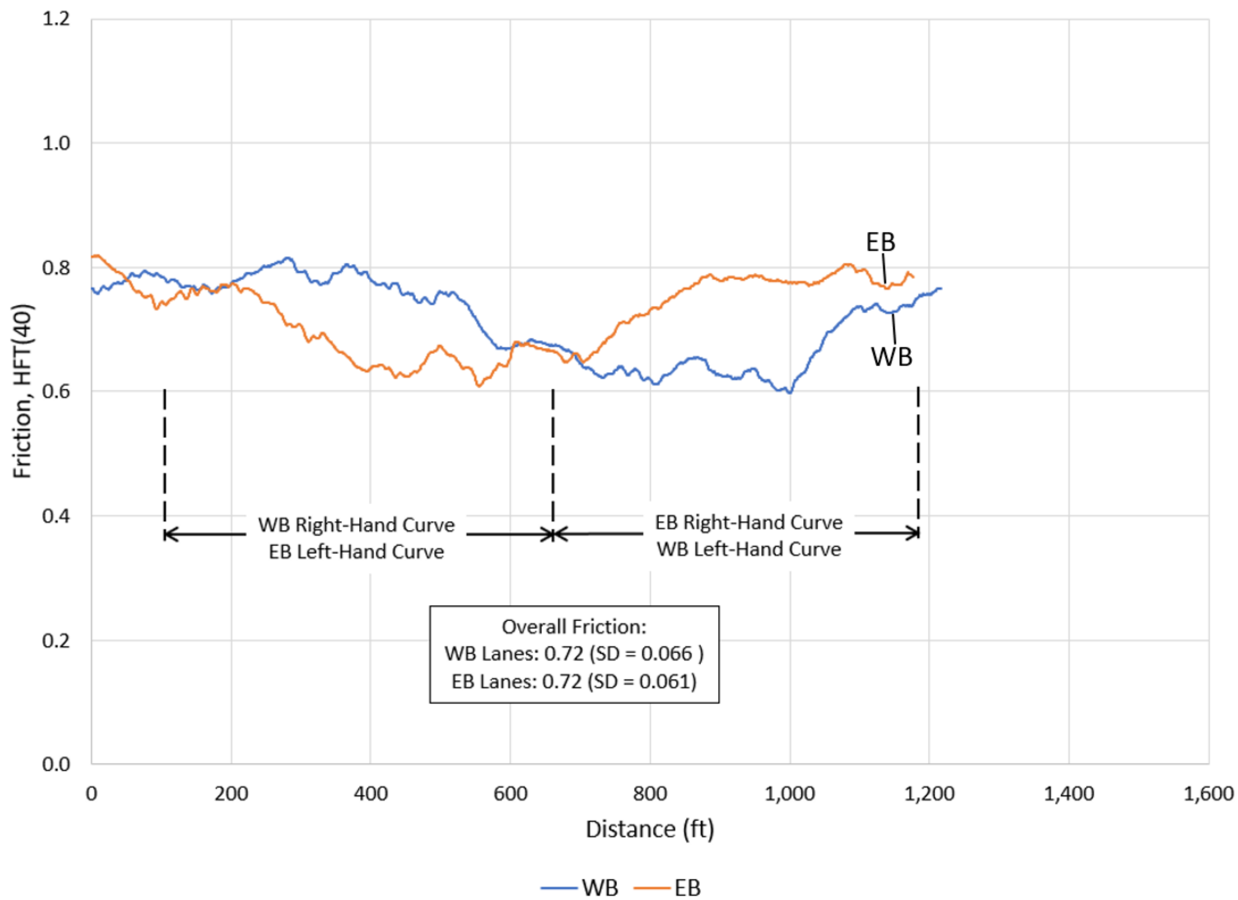
Figure 16 shows an example of friction change from asphalt pavement (before HFST installation) within a curve with a radius of approximately 121.92 m (400 ft), which is one of the lowest curve radii of the sites tested, and a higher AADT of approximately 3,300 vehicles per day. There appeared to be a slight drop in friction within the curve that was more noticeable in the WB direction, but the variability of the measurements in the EB lanes made it difficult to determine the change in friction exactly.



Source: FHWA.
1 ft = 0.30 m.
SD = standard deviation.

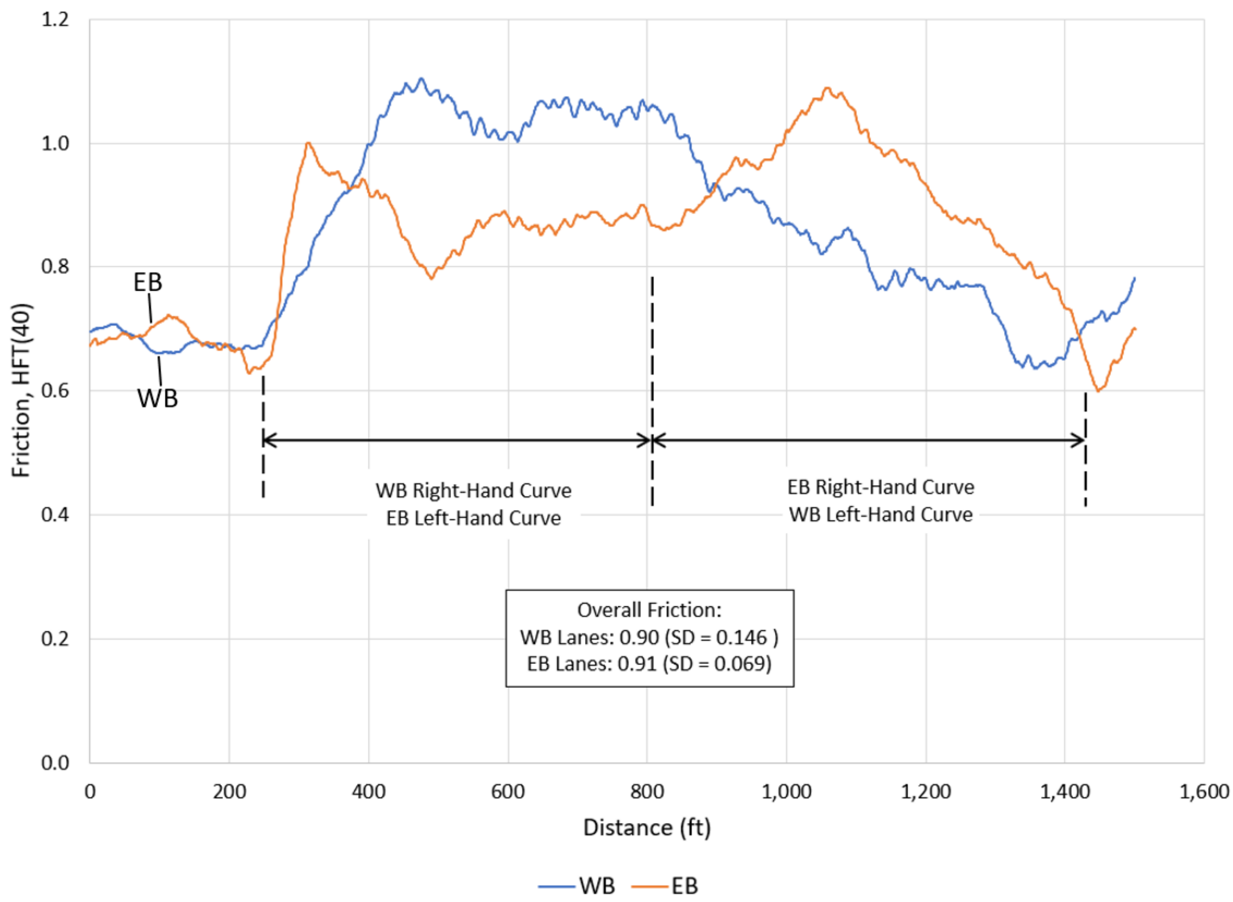
Figure 16. Graph. Friction measurement within a curve (asphalt pavement) before HFST installation.

To further explore the effects of the HFT configuration on friction measurements, figure 17 and figure 18 show friction data for an S-curve before and after HFST installation, respectively. Figure 17 shows friction data for the underlying asphalt pavement on a low-volume (210 AADT) S-curve with a radius of approximately 124.97 m (410 ft). Figure 18 shows friction data for this curve after HFST installation. Both figures show a difference in friction based on the direction of travel and direction of the curve; the line of the curve reverses when transitioning from a left-hand to a right-hand curve or vice versa. Lower friction was measured on left-hand curves, regardless of the direction of travel. Figure 19 shows a similar trend for another S-curve tested before HFST installation. This S-curve had a higher traffic volume (6,200 AADT) and a slightly larger curve radius of 201.17 m (660 ft).



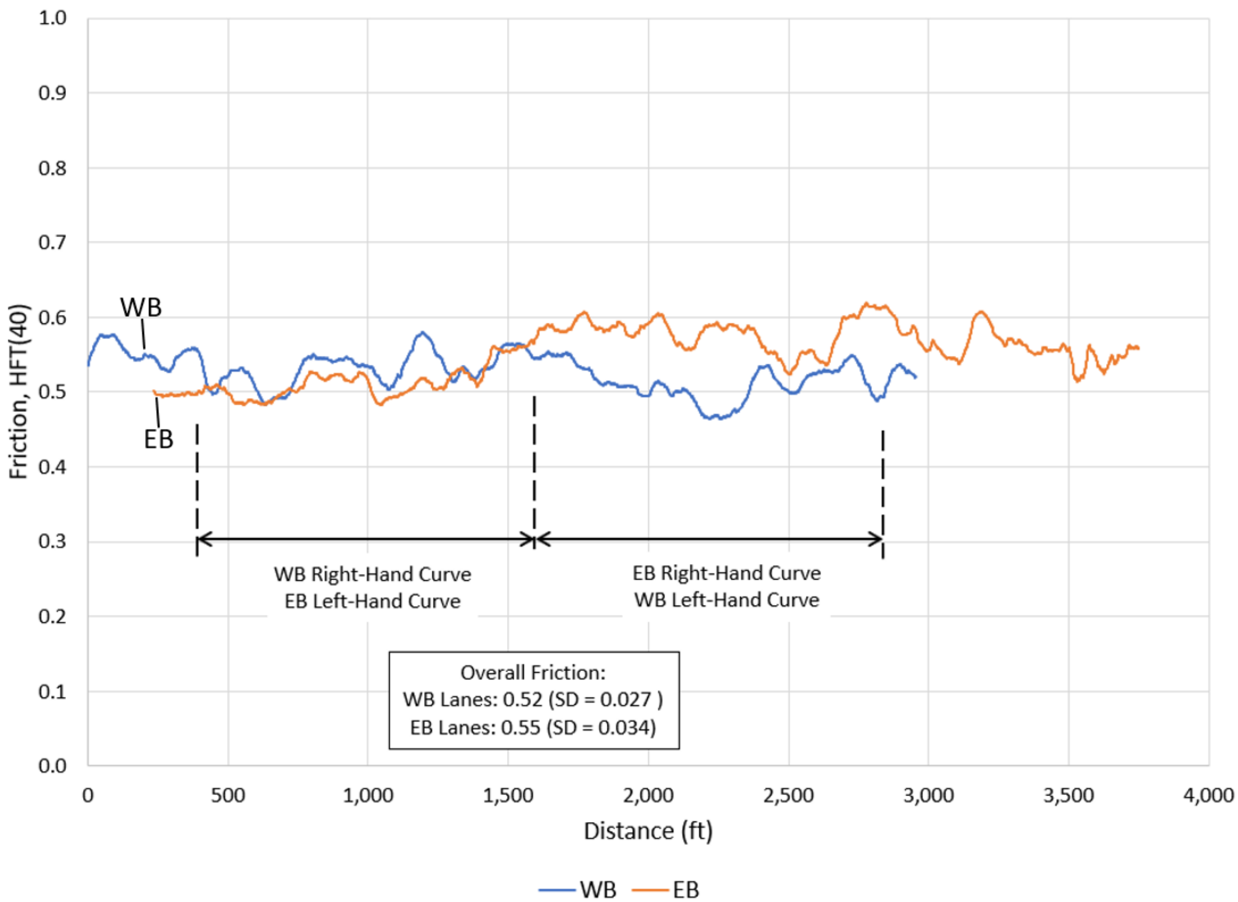
Source: FHWA.
1 ft = 0.30 m.
SD = standard deviation.

Figure 17. Graph. Friction measurement within an S-curve (lower AADT volume) before HFST installation.



Source: FHWA.
1 ft = 0.30 m.
SD = standard deviation.

Figure 18. Graph. Friction measurement within an S-curve (lower AADT volume) after HFST installation.



Source: FHWA.
1 ft = 0.30 m.
SD = standard deviation.

Figure 19. Graph. Friction measurement within an S-curve (higher AADT volume) before HFST installation.

OBSERVATIONS

The following are key observations related to friction change within a curve based on the limited amount of data collected with the HFT for this study.

- The cause of the variation in friction based on direction of curvature is not known for certain but could be inherent to the configuration of the HFT measurement device. Side forces on the test wheel, located on the left side of the HFT, coupled with the HFT's shifting center of gravity around tight-radius curves, likely affect friction measurement, as observed from analysis of friction data within S-curves. However, this observation is one of the reasons friction data were summarized as the average value over the curve in both directions in earlier chapters.

- An analysis of friction data from a select number of curve sites before HFST installation revealed possible variation in friction within the curve, but this variation was not consistent across all sites. Whether this variation in friction is caused by increased traffic wear in the curve cannot be determined with certainty. Unfortunately, the age of the asphalt pavement, and therefore the total traffic exposure of the pavement, was not available for inclusion in the evaluation.

- For the limited analysis of friction data, curve radius and traffic volume did not appear to correlate with possible friction variation within a curve. However, superelevation and pavement age were not factored into the evaluation. Further investigation on roadways with higher volumes, varying curve radii, known superelevation, and pavements of similar age may reveal clearer relationships between pavement friction, geometry, and traffic exposure.

- An analysis of friction data from sites after HFST installation was also inconclusive in terms of whether variation in friction was the result of traffic wear or lower initial friction of the HFST surface itself, particularly when there were differences based on direction of the curve.

- In summary, although there appeared to be some variation in friction within curves, it is not known whether the variation is actual change in pavement friction or caused by the variability of friction measurements using the HFT device. Further investigation to compare measurements from different fixed-slip and full-slip devices and under varying conditions, including different grades, superelevations, curve radii, and pavement types, may provide more insight on friction change within curves.

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