<u>GEORGIA DOT RESEARCH PROJECT 17-19</u>

Final Report

CRITICAL ASSESSMENT OF HFST'S LONG-TERM PERFORMANCE IN GEORGIA UNDER DIFFERENT ROADWAY CONDITIONS

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16. Abstract:
The Georgia Department of Transportation (GDOT) uses high friction surface treatment (HFST) as a countermeasure to address curve-related crashes proactively and reactively. In the US, as of December 2020, Georgia has the highest number of pavement miles and curve sites that use epoxy-based friction improvement surface treatments (FIST). These sites include 342 curve sites with calcined bauxite HFST and 69 curve sites with phonolite TPO ("Wyoming bauxite"). Deteriorated epoxy-based materials will lead to a smooth and glossy surface that may lead to drivers running off the road. To mitigate this safety concern, this research project has the following objectives: 1) critically analyze real-world FIST friction deterioration behavior and spatial friction distribution in Georgia's local environments, and 2) develop practical guidance for GDOT to programmatically and proactively manage its FIST sites based on life cycle activities. Thirty representative FIST sites in Georgia were monitored for three years beginning in 2018. A Dynamic Friction Tester (DFT) was used during the monitoring period; friction at 60mph was used for analysis. Findings from of this research reveal calcined bauxite is performing well with friction greater than 0.65 after six years. Meanwhile, phonolite TPO friction dropped over 40% in the first three months and below 0.4 at certain sites after three years. Therefore, phonolite is not recommended for future application and requires close monitoring at existing sites. Additional monitoring for two to three years is strongly recommended to further study the end-of-life characteristics of calcined bauxite HFST. It is recommended to use performance measures based on aggregate loss with automatic survey methods to cost effectively screen sites for targeted friction testing and optimized condition evaluation.

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By
Yichang (James) Tsai, Ph.D., P.E., Professor

Zhonghua Wang, Ph.D., P.E., Senior Research Engineer

Cibi Pranav, Graduate Research Assistant

Pingzhou (Lucas) Yu, Ph.D., Graduate Research Assistant

Ronald W Knezevich, Graduate Research Assistant

Georgia Tech Research Corporation

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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LIST OF ABBREVIATIONS

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway Transportation Officials
ALP	Aggregate Loss Percentage
ASTM	American Association of State Highway Transportation Officials
BBI	Ball-bank Indicator
CFMD	Continuous Friction Measurement Device
CTM	Circular Texture Meter
DFT	Dynamic Friction Tester
DOT	Department of Transportation
EDC	Everyday Counts
ESAL	Equivalent Single Axle Load
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FIST	Friction Improvement Surface Treatment
GDOT	Georgia Department of Transportation
GIS	Geographic Information System
HFST	High Friction Surface Treatment
HFSTA	HFST Association
HMA	Hot Mix Asphalt
KYTC	Kentucky Transportation Cabinet
LCMS	Laser Crack Measurement System
LFD	Long-term Friction Deterioration
LWA	Lightweight Aggregate
LWD	Locked Wheel Device
MC	Middle of Curve
MPD	Mean Profile Depth
MR&R	Maintenance, Repair, and Replacement

MTD	Mean Texture Depth
NCAT	National Center for Asphalt Technology
NJDOT	New Jersey Department of Transportation
NZTA	New Zealand Transport Agency
PC	Point of Curve
PIARC	Permanent International Association of Road Congresses
PSV	Polished Stone Value
PT	Point of Tangent
ROR	Run Off Road
SCRIM	Sideway-Force Coefficient Routine Investigation Machine
SN	Skid Number
TPO	Thin Polymer Overlay
TTI	Texas Transportation Institute

EXECUTIVE SUMMARY

A disproportionally high number of serious vehicle crashes occur on curved roadway sections even though curves only represent a fraction of the roadway network (FHWA, 2021; Atkinson et al., 2016). High Friction Surface Treatment (HFST), composed of a thin layer of calcined bauxite aggregate on resin-binder, is used to improve friction on curved roadways, especially on curves that have a high friction demand and a history of roadway and lane departure crashes. The Georgia Department of Transportation (GDOT) uses HFST to address curve safety concerns proactively and reactively. Georgia has the highest number of miles (more than 90 accumulated centerline roadway miles) and curve sites (more than 411 curve sites) in the US (as of December 2020) that use epoxy-based Friction Improvement Surface Treatment (FIST) sites, including 342 curve sites with calcined bauxite HFST and 69 curve sites with phonolite TPO (phonolite aggregate, also called "Wyoming bauxite"). GDOT has also been exploring the use of lightweight aggregates (LWA) with emulsion as an alternate friction improvement treatment. HFST friction deterioration, especially due to loss of aggregates and exposure of slippery epoxy, is a serious safety concern because HFST is typically used on critical locations with high friction demand, such as horizontal curves.

The objectives of this project are as follows: 1) To critically analyze FIST friction deterioration behavior and spatial friction distribution in Georgia's local environments, including critical sections and wheel path positions in FIST curve sites and the factors that impact FIST curve sites' spatial and temporal friction deterioration (such as material, roadway geometry, prior pavement condition, construction quality, traffic, age, weather, etc.); 2) To develop practical guidance for GDOT to holistically and systematically manage its FIST sites based on their complete life cycle activities (including performance measures, sampling and testing locations and frequencies, maintenance trigger criteria, etc.) to establish an optimized, systemic, proactive, network-level FIST long-term performance monitoring and maintenance program. The developed procedure primarily uses a Dynamic Friction Tester (DFT) and also highlights the use of aggregate loss performance measures.

A GIS database was created to store the location and site information of the FIST sites based on the GDOT's FIST contract let packages. An experimental test design was used to select and monitor representative FIST sites in Georgia with diverse conditions and using a consistent data collection procedure with a DFT (including consistent criterion for selecting DFT friction testing spots) to study their temporal friction behavior and spatial friction distribution patterns. Thirty representative FIST sites in Georgia with diverse conditions were selected with the help of GDOT; friction at the 30 sites was monitored for three years using a DFT.

The three-year friction performance monitoring on **calcined bauxite HFST** showed very good long-term friction performance. Both the initial friction deterioration during the first three months after installation, and long-term over three years are small, with high friction values (0.6 - 0.8) after 2 million ESALs. This shows it is a good treatment for improving surface friction on sites with large friction demand. HFST is recommended for use in future projects. In addition, no significant difference in friction deterioration was found between manual and automated construction methods. Additional monitoring on current HFST sites to study the end-of-life performance is recommended. For future monitoring, it is recommended to perform annual DFT tests and to develop intelligent, low-cost alternatives, such as using loss of aggregates with smart phones and AI, which are proposed in this report, for safety risk screening.

The three-year friction performance monitoring on **phonolite/Wyoming bauxite** showed a poor long-term friction performance. The initial friction drop during the first three months after installation is significant: more than 40%. While the friction deterioration stabilized after that, the friction values are below 0.5 after only one million ESALs. Due to the poor friction performance, phonolite is not recommended to be used in future projects, and the current sites should be monitored closely, as the low surface friction poses safety risks.

The three-year friction performance monitoring on **lightweight aggregates chip seal** showed inconclusive results. While the sites monitored in this project showed good friction performance (0.6-0.75) after three-year monitoring, only two sites with low traffic volume were monitored. Due to the limited sample size, and the fact that the low traffic volume only reached 1.2 million ESALs on these sites, it is hard to draw any definitive conclusions. Therefore, it is recommended to perform additional long-term monitoring on sites that have diverse geometric and traffic conditions.

Technical and management needs were identified and synthesized based on a literature review, a national survey, field observations, and discussion with NCAT, FHWA, and state DOT experts. Based on the synthesized technical and management needs, a technical and managerial integrated framework with nine technical modules was developed to enable researchers and transportation agencies to cost-effectively manage the complicated life cycle activities of safety-sensitive epoxy-based friction surface treatments. Based on the developed integrated framework, this report also presents the recommended guidance for Georgia's network-level HFST (and FIST) long-term performance monitoring and maintenance program. The guidance provides recommendations on performance measures, testing locations and positions, frequencies, and performance evaluation and trigger criteria thresholds detailed in a systematic, eight-step procedure to support the optimized FIST long-term performance monitoring. Using this guidance, GDOT can better establish its FIST long-term performance monitoring and maintenance program using internal resources and/or external contactors.

CHAPTER 1. INTRODUCTION

BACKGROUND

Although curved roadways constitute only 5% of total roadway mileage, 25% of all roadway fatalities, about 8700 per year, occur on curved roadways (FHWA, 2021; Atkinson et al., 2016). Furthermore, nearly 70% of the curved roadway fatalities are associated with single-vehicle roadway departure crashes (FHWA, 2021). This disproportionally high number of fatal crashes makes curved roadways a high-risk to the public and very much concerns transportation agencies. Transportation agencies are seriously studying the safety concerns associated with curved roadways. Vehicles travelling on curved sections of roadways require a higher amount of sideways (lateral) friction to counter centrifugal forces than do vehicles traveling on straight roadway sections. Inadequate friction between vehicle tires and the pavement (for the driving speed and roadway geometrical design) is identified as one of the major contributing factors of roadway departure crashes (Atkinson et al., 2016). When there is inadequate pavement friction available to the vehicles due to poor pavement conditions (such as wet pavements) or when vehicle friction demand outweighs available pavement friction, a vehicle can skid and run off the road (ROR).

To improve the friction performance on roadways, the Federal Highway Administration's Everyday Counts (EDC-2) program recommends adoption of high friction surface treatment (HFST) to prevent/reduce crashes. HFST is composed of a thin layer of high-quality, polish-resistant aggregate (like calcined bauxite) bonded to the pavement surface with a polymer resin binder. The Georgia Department of Transportation (GDOT) has an active HFST program that applies HFST on specific curves. An image of HFST installation on a curved roadway and a close view of HFST over asphalt pavement is shown in Figure 1.

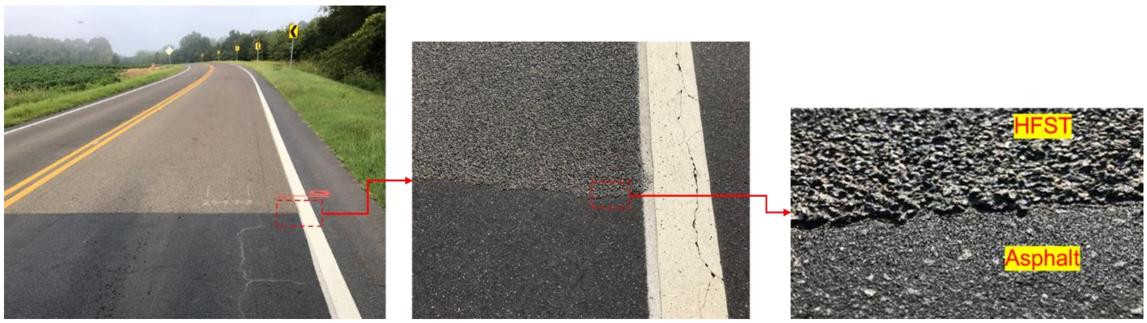


Figure 1 – Pictures. An example of HFST installed on a curved roadway and a close view of HFST over an asphalt pavement surface.

HFST has been used as a low-cost safety countermeasure that can be used instead of roadway build improvement (such as superelevation or alignment modification); it addresses curves with high friction demand where the available pavement friction is not adequate to support vehicle operating speeds. HFST increases the pavement friction value immediately and has been proven to significantly reduce the number of run-off-road (ROR) and wet-pavement crashes on curved roadways (Merritt et al., 2020).

The term “friction improvement surface treatment” (FIST) is used in this report to refer to the general category of friction improvement surface treatments, including calcined bauxite, phonolite, granite aggregates in an epoxy-resin binder, and lightweight aggregate chip seals, etc. Georgia has the highest number of miles (more than 90 centerline roadway miles) and curve sites (more than 411 curve sites) in the US (as of December 2020) that use epoxy-based friction improvement surface treatment (FIST) sites, including both calcined bauxite HFST and phonolite thin polymer overlay (phonolite, or “Wyoming bauxite,” aggregate is used in an epoxy-binder and is called thin polymer overlay (TPO) by the industry). GDOT has also been exploring low-cost, high-friction surface treatments using lightweight aggregates (LWA) with emulsion.

Properly constructed HFST on pavement in good condition typically maintains high friction value throughout its expected life (7-12 years), which is considered good long-term performance. Even though a well-constructed HFST surface shows good long-term performance, HFST friction deterioration due to aggregate loss, especially towards the end of its life cycle, is a serious safety concern; HFST is typically used on critical locations, such as horizontal curves, that require high friction. An HFST roadway surface with a severe loss of aggregate will have very low friction, which creates a dangerous situation for drivers, especially during wet weather.

So, transportation agencies must pay additional attention to HFST friction deterioration. However, there is no established trend for how real-world HFST friction decreases over time, especially in Georgia, in real-world roadway and traffic conditions. There is an urgent need to critically analyze HFST deterioration and longevity for transportation agencies to plan HFST application, monitoring, and replacement/maintenance actions (such as proactively performing detailed surveys, setting up warning signs, replacing and/or resurfacing pavements, etc.), especially when the HFST friction behavior is nearing the end of the HFST life.

Periodic monitoring is required to comprehensively study the friction deterioration at the epoxy-based FIST sites and to detect the friction deterioration so the potential hazardous situation can be identified before it occurs and timely maintenance, such as the replacement of a HFST surfaces, can be accomplished. However, it is impractical to periodically monitor the friction on 411 epoxy-based FIST sites using DFT, a sample/spot friction testing method used by GDOT (it is labor-intensive, traffic-disrupting, and time-consuming), as it takes nearly one hour to set up traffic controls and measure friction at five to six spots at each site; sometimes, it is dangerous, even with traffic controls. Therefore, there is an urgent need to develop targeted and optimal Dynamic Friction Tester (DFT) sampling and monitoring strategies, including optimal locations and frequencies, to test epoxy-based FIST curve sites. Besides, alternative or supplementary friction performance measures (such as aggregate loss area, texture, etc.), that are correlated to friction and have predictable deterioration are urgently needed for transportation agencies to carry out cost-effective and sustainable long-term HFST performance monitoring at high friction demand sites.

RESEARCH OBJECTIVES AND TASKS

Based on the above identified needs, the following are the research objectives of this project:

1. To critically analyze FIST friction deterioration behavior and spatial friction distribution in Georgia's real-world environments, including critical sections and wheel path positions in FIST curve sites and the factors that impact FIST sites' spatial and temporal friction deterioration (such as material, roadway geometry, prior pavement condition, construction quality, traffic, age, weather, etc.).
2. To develop a practical guidance for GDOT to holistically and systematically manage its FIST sites based on their complete life cycle activities (including performance measures, sampling and testing locations and frequencies, maintenance trigger

criteria, etc.) for establishing GDOT's optimized, systemic, proactive, network-level FIST long-term performance monitoring and maintenance program.

The major tasks to accomplish the project objectives include the following:

1. Conduct a comprehensive literature review; interview other state DOTs to discover their experience with HFST performance and their current HFST practices (Chapter 2).
2. Develop an experimental test design and collect field data to select FIST sites for long-term performance monitoring and data collection (Chapter 3).
3. Conduct long-term data collection and performance monitoring at selected sites.
4. Perform comprehensive data analyses (Chapter 4).
5. Develop guidance to address the needed components for a FIST monitoring and maintenance program (Chapters 5 and 6).
6. Summarize research findings and provide recommendations for safely managing the epoxy-based FIST sites throughout their life cycle activities (Chapter 7).

REPORT ORGANIZATION

This research project report is organized as follows. Chapter 1 presents the background, the needs, and the objectives of this research project. Chapter 2 presents a comprehensive literature review and a national survey to summarize the HFST performance and current state DOT HFST practices. Chapter 3 presents the experimental test design and field data collection plan for studying the long-term spatial and temporal friction behavior of Georgia's FIST curve sites. Chapter 4 presents a data analysis framework to analyze temporal and spatial friction deterioration; then it presents the preliminary findings, which are based on the data analysis framework developed after three years of monitoring 30 of Georgia's FIST sites. Chapter 5 discusses the technical and managerial integrated framework (consisting of nine technical modules), including its core contents and the critical steps and actions involved in establishing guidance for researchers and transportation agencies to perform enhanced epoxy-based FIST safety management actions. Chapter 6 recommends an optimized strategy and systematic procedure for developing Georgia's network-level HFST and FIST long-term performance monitoring and maintenance program. The program is based on the integrated framework. Chapter 7 presents conclusions and recommendations.

CHAPTER 2. LITERATURE REVIEW AND NATIONAL SURVEY

This chapter first presents the 2020 HFST National Survey that was conducted to gather inputs from state DOTs on their HFST practices and experiences with HFST. This chapter then discusses a) an HFST overview, including materials and construction, b) HFST advantages and crash reduction, c) HFST long-term performance, premature failures, and factors impacting friction deterioration, d) HFST aggregate loss characteristics and their relationship with friction, e) friction and texture measurement devices, f) spatial friction variation in curved sites, and g) current state DOT practices on HFST life-cycle activities, challenges, and needs based on the National Survey results and an intensive literature review. Finally, this chapter summarizes the literature review, and the research needs of this project.

2020 HFST NATIONAL SURVEY

An extensive survey was designed to gather inputs from state DOTs on their HFST practices and their experiences with HFST. Based on the survey results, state agency HFST practices and challenges were summarized; remaining needs to enhance the current HFST practices were identified. The survey questions were primarily based upon a literature review, then refined through meetings with various agency personnel from GDOT, FHWA, and NCAT. The final survey consisted of three sections: HFST site selections and construction practices, HFST performance and management practices, and HFST monitoring and forecasting of friction performance. Each section consisted of three parts. Table 1shows the overview of the three sections and their parts.

Table 1 – Three-section organization of the survey and their parts.

Section 1: HFST site selections and construction practices
1. Agency ‘s experience with HFST installations
2. HFST construction method
3. Alternate HFST aggregates and treatments
Section 2: HFST performance and management practices
1. HFST safety performance (crash reduction)
2. HFST pavement performance
3. HFST repair and replacement practices
Section 3: HFST monitoring and forecasting friction performance
1. Routine friction monitoring on HFST sites
2. Monitoring texture change on HFST sites
3. HFST friction performance forecasting

The key personnel related to HFST in each state were identified with the help of FHWA, and the survey was sent to them. They were informed that their responses would be presented as that of the agency. The survey was sent out to 46 states, which were identified with the help of FHWA’s Office of Safety in Spring 2020. Twenty-eight states out of 46 (61%) responded. Additionally, two county transportation organizations in Washington state, namely King County and Klickitat County, responded to the survey, resulting in 30 responses (as seen in Figure 2), although the intention of the survey was to get responses only from the state DOTs. Washington state has an active local program to implement safety improvements in the state, and, therefore, there were two responses from the local county transportation agencies.

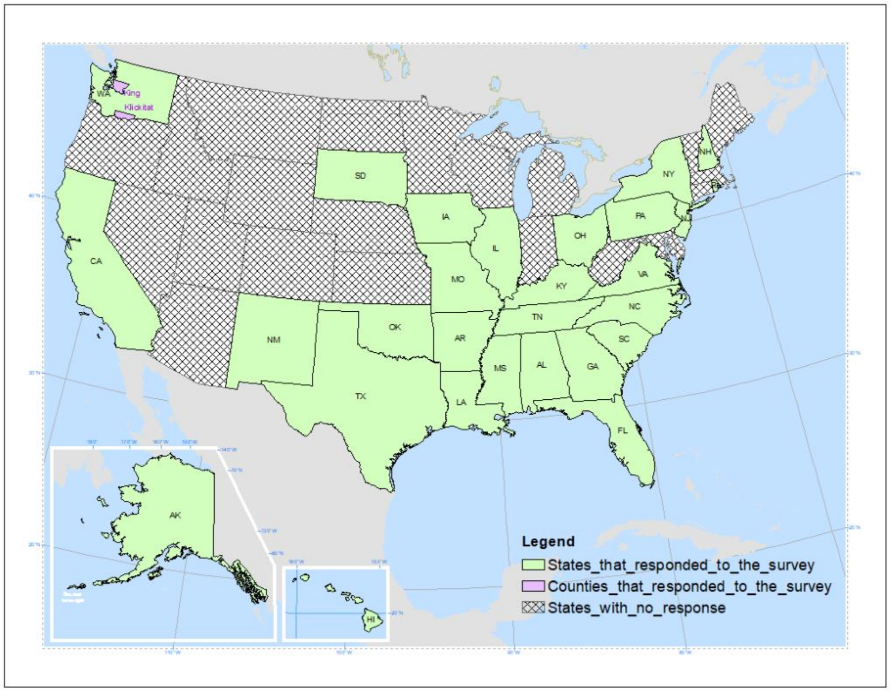


Figure 2 – Map. State and local DOTs responding to the survey.

HIGH FRICTION SURFACE TREATMENT OVERVIEW

High friction surface treatments (HFST) are pavement surfacing systems with high skid-resistant properties intended to enhance and maintain high friction on the pavement sections. HFST is composed of a thin layer of specially engineered, 3–4 mm nominal-size polish- and abrasion-resistant calcined bauxite aggregate embedded on the top of a thermosetting polymer resin binder – usually epoxy, modified polyester, or urethane (Atkinson et al., 2016). As of 2019, at least 45 states had at least one HFST installation; several states reported over 100 installations (including Georgia, Kentucky, and Pennsylvania), accounting for millions of square yards of HFST installed. Based on the National Survey, state DOTs have applied HFST as a safety treatment predominately on horizontal curves (90%), but they have also applied it to ramps and intersections. HFST is also used on bridge decks as preservation treatments, but this research is primarily focused on HFST used as a safety treatment on curves. The map in Figure 3 shows the status of HFST application on curves in the United States as of January 2020.

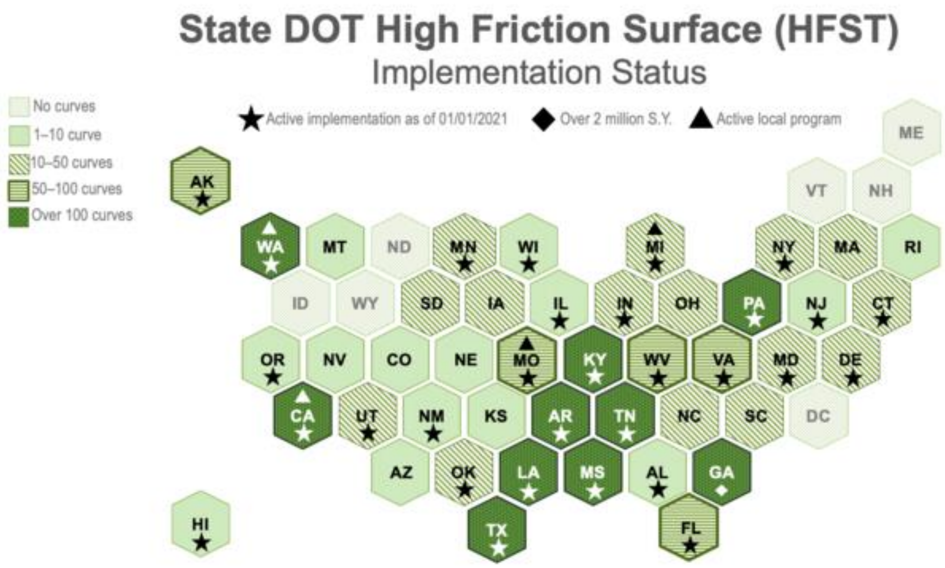


Figure 3 – Map. Implementation of HFST as of January 2020 (FHWA, 2021).

The majority of the states have applied HFST as a rural safety countermeasure. On rural roadways, state DOTs have mostly installed HFST on horizontal curves; in urban areas, state DOTs have mostly installed HFST on interchange ramps.

HFST materials and characteristics

HFST typically consists of two components: polish- and abrasion-resistant aggregates and a polymer resin binder. Although several aggregates have been evaluated for use with the epoxy binder, only calcined bauxite aggregate has consistently met the threshold for performance necessary to be used for HFST (Heitzman et. al., 2015; Woodward & Friel, 2017). “Calcined bauxite used for HFST is categorized as ‘non-metallurgical refractory grade,’ which comes from high-quality bauxite that is calcined, or heat treated, at 2900-3000°F to produce a dense, high-purity, stable aggregate.

Refractory grade calcined bauxite has a high-alumina (≥ 82 percentAl_2O_3), low-alkali content (≤0.4 percent) and a bulk density of ≥ 3.0 with very low residual moisture levels" (IMPACTS, FHWA). In addition, calcined bauxite has a high polished stone value (PSV) in the higher 60s or lower 70s (Izeppi et. al., 2010) that makes it very durable.

There are four types of binders that are available for special surfacing like HFST and colored pavement. They include epoxy-resin, polyurethane-resin, rosin-ester, and acrylic-resin (Nicholls, 1998). Traditionally, epoxy-resin has been used widely for high friction surfacing (Nicholls, 1998). Epoxy-resin binder consists of two components: a viscosity reducer (also called a diluent or polymer) and a curing agent (also called a hardener or ross-linking agent). Binder mixture plays a key role in the long-term durability. The type and percentage of the hardener and diluent impact the life and performance of HFST. Based on communication with epoxy-binder manufacturers, we learned that the hardener is the reactive component, and higher quantities of hardener increase binder life. However, higher quantities of hardener cure the binder faster, leaving inadequate time for aggregate embedment and aggregate bonding. Moreover, a strong binder mix design with a higher quantity of hardener can make the HFST thermally incompatible with the underlying asphalt and result in premature failure distresses, such as delamination or pop-off (discussed in "HFST premature failure, characteristics, and causal factors" section). Therefore, the binder composition must be designed appropriately and mixed with caution according to prescribed specifications to achieve HFST longevity.

HFST site preparation, installation, and acceptance testing

The general procedure for installing HFST starts with preparation of the existing pavement surface. The pavement surface must be clean, dry, and free from ice, frost, loose aggregate, oil, grease, road salt, and other loose matter likely to interfere with the bonding between the binder materials to the surface. This is accomplished using mechanical sweepers, high pressure air, and/or other methods approved by the transportation agency or the engineer. Drainage structures, curbs, and other utility services must be protected to prevent them from being clogged with epoxy and aggregates. Inadequately filled joints and cracks are to be filled with resin binder and allowed to gel. Figure 4 shows a) cleaning of an existing road surface using a scrubber and b) sealing of cracks.

Figure 4 – Pictures. Surface cleaning (top) and cracks sealing with epoxy (bottom).

After surface preparation, the surface temperature must be measured to ensure it is within HFST installation standards (for two-part resin, it is usually between 55°F and 105°F). After ensuring adequate surface preparation and pavement temperature, the two components of the binder are mixed in accordance with the manufacturer's recommended methods and placed uniformly over the original surface as per the specified in-place thickness (GDOT specifies 60 mils). The aggregates are then placed on the binder at a specified rate (GDOT specification: 13 pounds per square yard) before the binder reaches its gel time. Complete coverage of the binder with aggregates is necessary to achieve a uniform surface. HFST placement can be done manually or automatically; Figure 5 shows the automatic placement using a designated truck. Figure 6 shows the binder and aggregates placement operation closely. The binder is spread evenly on the pavement and the aggregates are dropped uniformly within 5 seconds.

Figure 5 – Picture. Designated truck in operation, automatically placing HFST binder and aggregates.

Figure 6 – Picture. Close up of automatic binder and aggregates placement.

The installation method is critical, especially at hotter temperatures. The aggregates must be embedded into the epoxy binder before the curing process is completed because the epoxy binder components, namely the hardener and polymer, form cross-links. If cross links are formed between the hardener and polymers before the aggregate embedment is complete, the aggregates bind poorly. High temperature accelerates the curing and, hence, this window for embedding the aggregates (one minute) becomes lower and delayed aggregate dropping can result in inadequate bonding and embedment. This can lead to premature failure due to aggregate loss. It is better to use automated methods to install HFST, especially in hot temperatures.

The HFST is allowed to cure for approximately three hours without any traffic intervention. Finally, all excess aggregate should be removed using either hand brooms, mechanical sweeping, or suction methods. After all operations are complete and excess aggregate is removed after curing, the treated surface is opened for traffic. Figure 7 shows excess aggregate removal with a mechanical blower.

Figure 7 – Picture. Excess aggregate removal with mechanical blower.

After HFST is installed, the friction and texture performances and site characteristics of HFST sites are tested for acceptance. The majority of state DOTs require that the HFST be tested within 60 to 90 days from the installation and meet a minimum requirement of a friction number (FN40R per AASHTO T 242) of at least 65 as measured by a locked-wheel skid testing device. Georgia DOT specifies testing with the Dynamic Friction Tester (DFT) within five days after placement and again at 90 days after placement, requiring a value greater than 0.9 at five days and a value greater than 0.8 required at 90 days. The Tennessee DOT and the Maryland state Highway Administration both require a minimum mean texture depth (ASTM E 965-15) or mean profile depth (ASTM E 2157) of 1.0 mm. Some state DOTs, like Florida and New Jersey, require additional testing of the in-place HFST for such surface characteristics as raveling, delamination, bleeding, etc.

HFST ADVANTAGES AND CRASH REDUCTION

HFST offers several advantages over large roadway realignment projects and other pavement treatments, including the following:

- Substantially low project cost compared to costly roadway realignment improvements. According to Atkinson et al., (2016), state DOTs have found 90 to 98 percent savings in project costs.
- Greater safety benefits than other low-cost safety measures, such as advanced curve warning signs, advisory speed plaques, pavement markings, chevrons, open-graded friction course (OGFC), open graded asphalt concrete (OGAC), and guardrails, when installed in appropriate locations.

- Quick implementation. HFST requires a relatively short planning process and installation timeframe compared to other alternatives (Atkinson et al., 2016). Some agencies have reported installation in as little as 10 days for small applications or 6 months for larger projects.
- Minimal impact to traffic during construction. HFST construction requires only one lane to be closed at a time, most often eliminating the need for a detour. HFST is quick to install, so roadways can be opened for traffic within a few hours.
- Durable high friction and long lasting. Well-constructed HFST on sound pavement surfaces has excellent pavement surface functional durability; it has an estimated service life from 7-12 years. Some vendors have reported a service life of 5 to 8 years at 15,000 vehicles per day, and up to 5 years at 50,000 vehicles per day (IMPACTS).

Merritt et. al., (2020) performed a state-of-the-art EB before–after methodology to evaluate the effects on various crash types (e.g., total, injury, wet-road, ROR, etc.) using data collected in Arkansas (ramps), Kentucky (curves and ramps), Pennsylvania (curves), and West Virginia (curves). The results for curves indicate significant crash reduction benefits of HFST in terms of low CMFs for each state and for Kentucky, Pennsylvania, and West Virginia combined; the CMFs are 0.430, 0.515, 0.279, and 0.168 for total crashes, injury crashes, ROR crashes, and wet road crashes, respectively. Besides crash reduction, Atkinson et. al., (2016) noted that HFST reduced stopping distance by 25-30%.

HFST LONG-TERM PERFORMANCE, PREMATURE FAILURES, AND FACTORS IMPACTING FRICTION DETERIORATION

This section summarizes 1) the long-term performance of HFST and 2) the review of HFST premature failures, characteristics, and failure causal factors, and 3) factors affecting HFST and epoxy-based FIST long-term friction deterioration.

Long-term performance of HFST

High friction surface treatment (HFST) has significantly increased friction on roadway sites when it is installed properly; treated sites have produced positive safety improvement. Based on the National Survey and NCAT observations, HFST life varies from 2-10 years because of various factors, including underlying pavement conditions, construction quality, material used, age, environmental conditions, truck volume, and geometric characteristics. A well-constructed HFST on a good underlying pavement can maintain high and stable friction for 7-12 years, which is considered good, long-term performance (IMPACTS, FHWA). A study by Anderson et al. (2017) showed that the friction values (skid numbers) were exceptionally high for the Tyregrip® (an HFST system involving calcined bauxite and epoxy-resin binder); values above the 70's were maintained throughout the five-year evaluation period of the study at a 17,000 AADT ramp in Washington state. Unlike Andersan et al., who studied single HFST sites over five years continuously, Scully (2016) analyzed Kentucky's HFST friction performance at the network level using different HFST sites to support his findings. Scully noted that the calcined bauxite HFST friction values were high and stable for five years based on the DFT friction measured in 2015 at several sites of different ages in Kentucky. Figure 8 shows a graphical representation of the DFT friction values (multiplied by 100) versus age in the wheel path (right wheel path, center of lane, and left wheel path) as measured in 2015. It must be noted that the one site with less than the 60 DFT friction number (multiplied by 100) is considered a micro-application; the aggregate is much smaller than typical calcined bauxite. This micro-application HFST site was observed to wear out much more quickly than other HFST sites, and there was aggregate loss observed in the wheel paths.

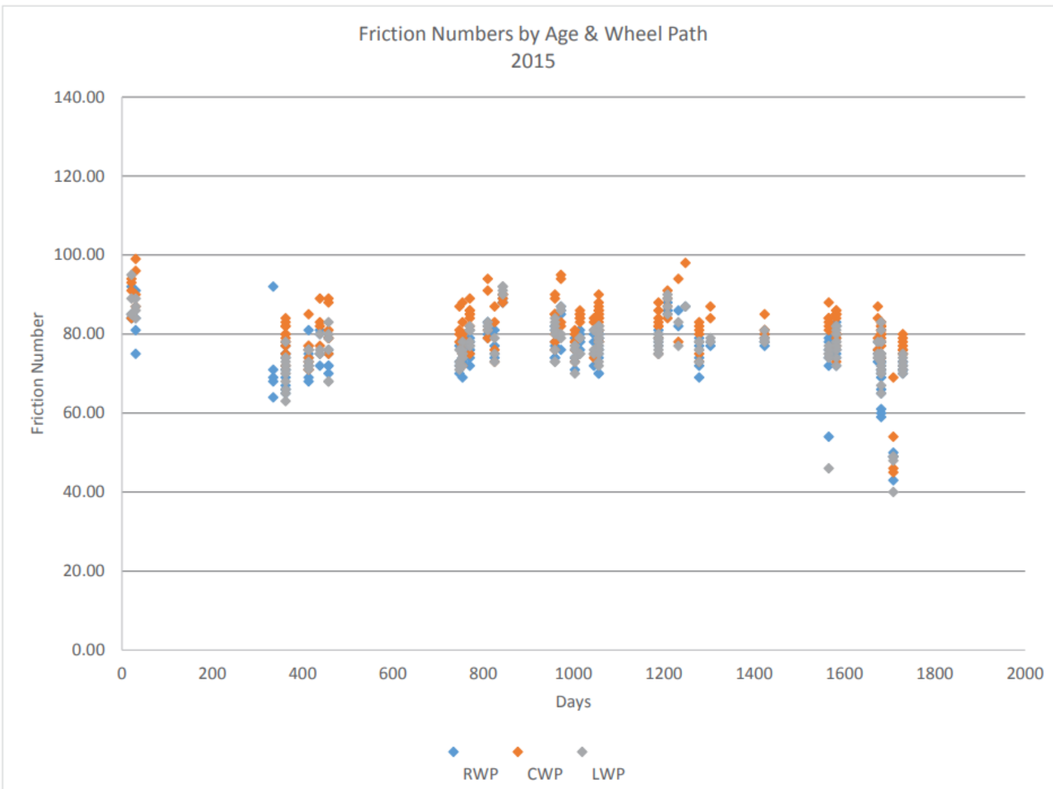


Figure 8 – Graph. Graphical representation of DFT friction numbers (multiplied by 100) measured in 2015 versus age at different wheel paths (Scully, 2016); image taken from a report shared by KYTC in 2020).

Heitzman et al. (2015) studied the friction performance of eight aggregates (granite, calcined bauxite, flint, basalt, silica, slag, emery, and taconite) applied on top of epoxy-resin binder at the NCAT test track. The test sections were subject to approximately 2.6

million ESALs (equivalent to 350,000 18-wheel tractor-trailer units) in six months. Granite, calcined bauxite, and flint aggregate sections were exposed to up to ten million ESALs, corresponding to 24 months of accelerated truck traffic. DFT friction (measured at 40 mph) and locked-wheel skid tester SN values showed an initial reduction that subsequently stabilized. It was found that the calcined bauxite sections maintained higher friction levels (more than 0.75 DFT40 friction) compared to the rest of the friction levels (less than 0.60 DFT40 friction) throughout the testing period.

Currently, there is no established trend for how real-world HFST friction decreases over time, especially towards the end of its life after giving good long-term performance. Only two HFST test sections at the NCAT test track were observed to reach their end of life. HFST friction dropped significantly and rapidly at the HFST's end-of-service life, even with good long-term performance. Figure 9 shows the plot of long-term friction performance (measured as a skid number (SN)) for calcined bauxite aggregates installed in 2005; the friction performance was measured with a skid trailer fitted with a ribbed tire and run at 40 mph. It is clearly seen that the SN drops rapidly after 9 years (in 2014).

Based on our discussions with engineers from NCAT, FHWA, and state DOTs and based on the observations at the HFST sites at NCAT, it was found that excessive calcined bauxite aggregate loss is one of the potential reasons for HFST friction deterioration. Towards the end-of-service life, the epoxy-resin binder used in HFST becomes brittle due to physical / chemical aging (Odegard & Bandyopadhyay, 2011) and/or mechanical deformation (Epoxy Technology, www.epotek.com) and loses its capacity to strongly bind the aggregates. Sustained shear stress at the tire-pavement interface forces the aggregates to be dislodged from the brittle epoxy. With the absence of bauxite aggregates, the smooth, glossy epoxy-resin layer (binder) and the underlying pavement surface are exposed, and the pavement becomes slippery (because of low friction). Towards the end of service life, when a significant amount of bauxite aggregate is being lost continuously from the wheel path, overall friction on the site drops rapidly; this creates a hazardous pavement surface for drivers.

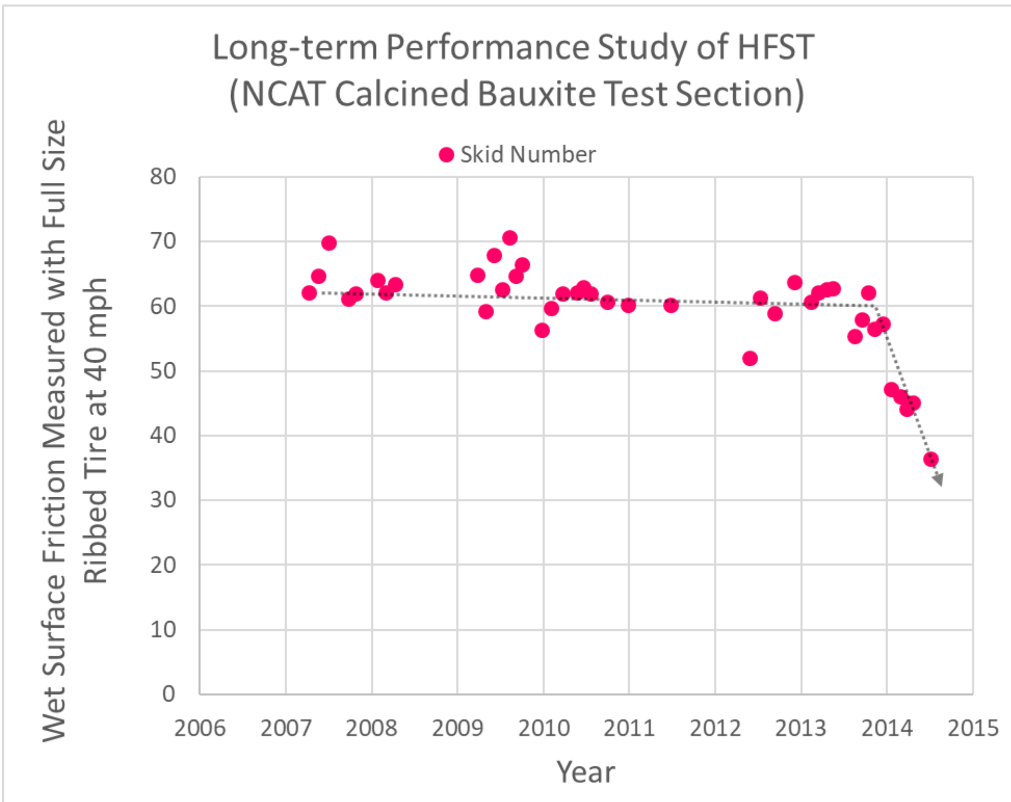


Figure 9 – Graph. Friction (measured as a Skid Number using a locked wheel skid trailer) drops substantially at the end of HFST life. Data courtesy of NCAT.

The chemical or mechanical aging can be prolonged by using the correct formulation of epoxy components (hardener and polymer) and, hence, delay the aggregate loss; however, like all pavements, HFST deteriorates over time. Since HFST is applied at critical locations with high friction demand, performance deteriorations are taken very seriously. Therefore, there is a need to monitor HFST sites over time for signs of aggregate loss and friction drop to proactively identify potentially risky sites and take appropriate maintenance actions.

HFST premature failure, characteristics, and causal factors

Based on the National Survey, the most common distresses observed by DOTs in the premature failure cases are excessive HFST delamination, HFST aggregate loss, and pavement pop-off with attached HFST. Figure 10 shows an example of these common distresses. According to DOTs, the top-three causes for HFST premature failures are the following: 1) inadequate surface preparation, such as not filling the cracks, clearing the dust, etc., 2) moist pavement during HFST application, and 3) incorrect HFST binder thickness.

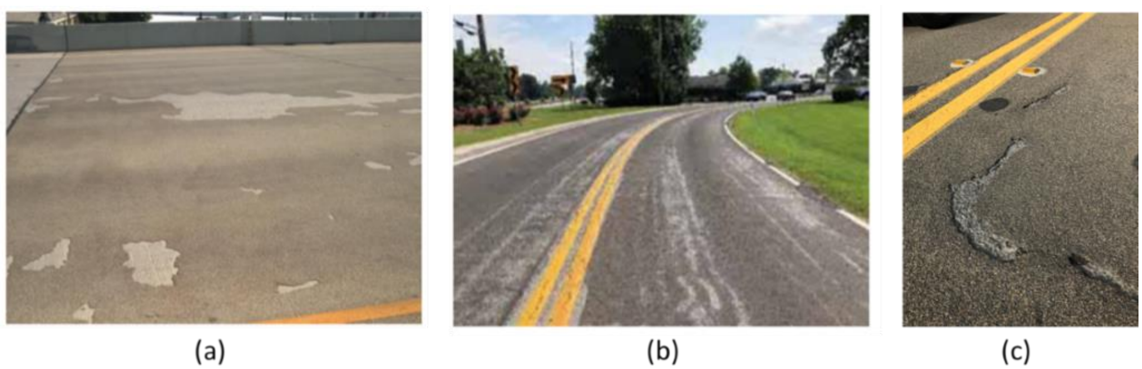


Figure 10 – Pictures. Examples of different HFST distresses: (a) HFST delamination (FDOT, 2019), (b) HFST aggregate loss (Courtesy of KYTC), and (c) Pavement pop-off with attached HFST (photographed by author).

Through this survey, we collected and compiled a list of premature failure causes (as shown in Table 2) and grouped them into three categories: construction factors, underlying pavement (below HFST) factors, and traffic and maintenance operation factors. It must be noted that not all the factors were observed by all the states. For example, Alaska DOT and New Jersey DOT reported snowplowing operations that were likely to have contributed to excessive aggregate loss and friction deterioration; however, other northern states did not report snowplowing as a problem.

Table 2– List of premature failure causal factors.

Category 1: Construction factors
1. Moisture on pavement surface before HFST is placed
2. Inadequate surface preparation (such as not filling the cracks, clearing the dust, etc.,)
3. HFST Binder thickness was too thin or too thick
4. Incorrect pavement temperature during epoxy placement
5. Incorrect proportioning of epoxy components
6. Non-uniform aggregate distribution
7. Calcined bauxite not clean or not dry
8. The pavement has a steep grade (epoxy flows down)
Category 2: Underlying pavement factors
1. Very old pavement
2. Pavements that have entrapped moisture (mostly seeping from underneath) and insufficient surface drainage
3. Extensive cracking on the pavement
4. Inadequate macro-texture on underlying pavement (e.g., flushing with asphalt results in weak bond with epoxy)
5. Newly resurfaced pavement within 30 days
6. Large number of voids (e.g., OGFC pavement)
7. Weak asphalt compared to epoxy (Incompatible tensile strength and coefficient of thermal expansion)
8. Moist pavement (part of roadway in constant shade)
Category 3: Traffic and maintenance operation factors
1. Vehicles use studded tires
2. Snowplow blades scraping the HFST surface

It is important to note that safety-compromising aggregate loss may occur not only at the end-of-service life, as in the NCAT observation, but it can also occur prematurely shortly after construction. The mechanisms in each case are different. The safety-compromising aggregate loss on the wheel path shortly after construction (especially in the first year or two), which exposes the smooth epoxy-binder, is associated with construction issues, such as insufficient binder thickness, poor surface preparation, or insufficient aggregate embedment depth. Some northwestern state DOTs, like Alaska DOT, reported that friction drop was a major concern on the HFST sites; it was accompanied by aggregate loss at many sites. Aggregate loss and friction deterioration in Alaska can be attributed to severe traffic conditions (i.e., studded tires), construction issues, and snowplowing operations. More specific distresses and remedial treatments can be found in the FDOT and NJDOT HFST guidelines.

Factors affecting HFST and epoxy-based FIST long-term friction deterioration. Factors affecting HFST and epoxy-based FIST long-term friction deterioration are needed to identify potentially high friction deterioration sites in the network to prioritize monitoring and maintenance activities.

FHWA (IMPACTS) noted that HFST wear is dependent on many factors, such as initial construction quality, friction demand, and traffic volume, as well as the severity of the climate and the weight and number of heavy truck axles using the roadway. However, there are only a limited number of studies that quantified the impact of these factors on long-term HFST and epoxy-based FIST friction deterioration. Li et al., (2016) analyzed the impact of material, age, traffic volume (AADT), precipitation, average temperature recorded as a Grip Tester friction number at 21 HFST and flint TPO sites using multi-variate analysis and identified that average temperature and installation age are significant factors impacting the friction number. Yang et al., (2019) found that higher traffic volumes seem to slightly increase the calcined bauxite HFST friction deterioration rates (over 9%) based on continuous monitoring of five sites over a two-year period.

Based on our discussions with engineers from NCAT, FHWA, state DOTs, epoxy-resin manufacturers, and contractors, and based on the observations at the HFST sites at NCAT, the additional factors impacting the long-term friction performance on well-constructed roadways displaying calcined bauxite HFST friction deterioration are identified as follows:

1. Epoxy composition. The type and percentage of hardener and diluent used in the epoxy can impact the chemical/physical aging and tolerance to mechanical stresses. Epoxy is the critical element holding the calcined bauxite, and any weakening of epoxy leads to potential aggregate loss and subsequent friction deterioration.
2. Daily traffic loading. Daily traffic loading impacts the stresses that is applied on the epoxy. A 15-20,000 traffic volume per day causes high, sustained stress on the epoxy, and according to one manufacturer, a 15-20,000 volume per day reduces the epoxy thickness by 10 mils each year; less than a 1,000-traffic volume per day does not impact significantly.
3. Age. The longer the age, the more chance for epoxy hardening due to chemical and physical aging processes. Age is also related to cumulative amounts of traffic loading.
4. Friction demand and lateral stresses. Curve geometry, including curve radius, super elevation, deviation angle, grade, and operating speeds on the curve impact the amount

of lateral stress on the wheel path. A sharp radius with a high speed imparts high lateral stress on the pavement. Similarly, inadequate superelevation for the friction demand also imparts higher lateral stress on the pavement.

5. Environmental conditions, especially the pavement temperature range. The coefficient of thermal expansion of the HFST is significantly higher than those of hot mix asphalt, which implies that thermal incompatibilities may exist between HFST and the underlying pavement. If the pavement temperature range is significantly large, unequal expansion of HFST and underlying asphalt pavement can cause delamination or worse: asphalt pavement pop-off.

The impact of factors, including aggregate and binder material properties, traffic volume and traffic type, age, friction demand, and environmental conditions on the long-term friction deterioration need to be quantitatively evaluated through actual field studies; the significant factors need to be prioritized.

HFST AGGREGATE LOSS CHARACTERISTICS AND THEIR RELATIONSHIP WITH FRICTION

HFST aggregate loss characteristics

Based on the discussions with state DOT, NCAT, and FHWA engineers and on our field observations, aggregate loss is an important contributor to friction deterioration at HFST sites, regardless of whether it is shortly after construction (due to insufficient aggregate embedment) or towards end of the HFST life (due to aging of epoxy binder). We identified useful characteristics to detect HFST aggregate loss and to establish the relationship between the aggregate loss and friction as listed below:

1. Occurrence of calcined bauxite aggregates on the sides of the lane,
2. Appearance of contrasting colors on the HFST surface due to change in calcined bauxite surface distribution and areas of exposed epoxy/background pavement. This is applicable if the calcined bauxite and epoxy or background pavement are different colors.
3. Flattened range (elevation) profile of the HFST aggregate loss surface based on high-resolution 3D profile data.
4. Change in macrotexture parameters, including height, shape, and density of asperities in 3D HFST surface data.

The details of these aggregate loss characteristics can be found in Pranav and Tsai (2021), and Pranav et al. (2021).

Relationship between aggregate loss characteristics and friction

We found that HFST (calcined bauxite) aggregate loss percentage area change (determined based on color contrast from 2D images) correlates strongly with the DFT60 friction coefficient value (Pranav & Tsai, 2021). Moreover, HFST (calcined bauxite) aggregate loss macrotexture parameters (including height, shape, and material volume) have shown reasonable correlations with friction and are able to reasonably distinguish different aggregate loss severity levels, such as low, medium, and high aggregate loss densities, roughly corresponding to less than 20%, 20-80%, and greater than 80% aggregate loss, respectively (Pranav et al., 2021).

These findings reveal that HFST surface friction deterioration is largely controlled by the calcined bauxite aggregate loss and the corresponding changes in the surface macrotexture. These findings show that HFST loss of aggregate is the key contributor of friction deterioration, and there is minimum impact on friction deterioration from calcined bauxite aggregate material polishing.

Based on these findings, DOTs can now view aggregate loss to study HFST friction deterioration. HFST aggregate loss can be used as a supplementary HFST safety performance measure to monitor friction performance.

FRICTION AND TEXTURE MEASUREMENT DEVICES USED BY THE U.S. TRANSPORTATION AGENCIES

A locked wheel device (LWD), as shown in Figure 11, is the most common friction measurement device used by state DOTs. ASTM E274 governs the method for measuring the skid resistance of paved surfaces with a locked wheel device. This test method utilizes a measurement representing the steady-state friction force on a locked test wheel as it is dragged over a wet pavement surface under constant load and at a constant speed (standard test speed is 40 mph). Skid testing is conducted using a smooth tire (ASTM E524) or a ribbed tire (ASTM E501). The primary advantage of this method is that no traffic control is required, and the friction is measured while the vehicle is moving. The output is a skid number (SN), which is the force required to slide the locked test tire at the stated speed divided by the effective wheel load and averaged over the testing area. SN values range from 0-100.

Figure 11 – Picture. Locked Wheel Skid Test Device (Source: Moravec, M. 2013).

ASTM E1911 covers the standard method for measuring the surface friction using the DFT. This method provides a measure of surface friction as a function of sliding speed. DFT measurement is a static measurement and requires traffic control to let the engineers place the device on the road and collect the measurements. The output is a friction coefficient (0-1) that is used to indicate the surface friction. Figure 12 shows a DFT.

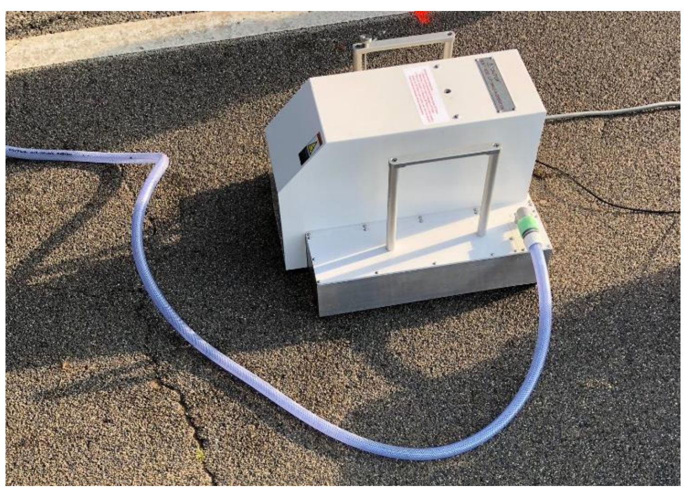
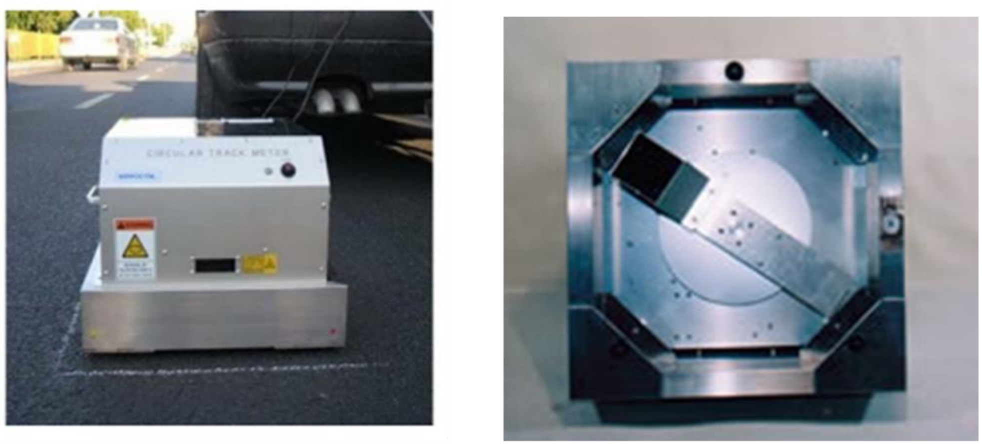


Figure 12 – Picture. Dynamic Friction Tester.

A circular testing machine (CTM) is one such standard device as shown in Figure 13. It consists of a laser that is mounted on an arm that rotates so that it follows a circular track having a diameter of 284 mm and the vertical displacement of the laser along the path is measured. The CTM is designed to measure the same circular track that is measured by the dynamic friction tester and report the mean profile depth (MPD) of the macrotexture profiles. ASTM E2157 covers the standards macrotexture measurement using the CTM and ASTM E1845-15 covers the standard practice for calculating pavement macrotexture MPD.



(a) (b)

Figure 13 – Pictures. (a) The CTM device during the measurement; (b) View of laser sensor (Source: Manufacturer).

Recently, continuous friction measurement devices (CFMDs), such as the Grip Tester and the Sideway-force Coefficient Routine Investigation Machine (SCRIM) are being explored by FHWA and some of the state DOTs for enhancing network level friction measurement and safety improvement programs. One advantage of a CFMD over the traditional locked-wheel skid tester is that friction is measured continuously rather than as an average value over several hundred feet (Izeppi et. al., 2017). The SCRIM is a continuous friction measurement device introduced to the U.S. in 2015. Besides measuring side force coefficient (at 1- to 20- meter averages), the SCRIM under evaluation (by FHWA and Virginia Tech Transportation Institute) uses a high-speed laser device to measure macrotexture, especially mean profile depth (MPD), road geometry (grade, cross slope, and horizontal curvature), and temperature (pavement, tire, and air) in 1- and 10-meter averages. The SCRIM has an operating speed between 15 and 55 mph, and a range of 150 miles per 2,200-gal tank of water. Data from the SCRIM are geolocated to enable integration with other data sets (Izeppi et. al., 2019). Currently, the specifications for deploying the SCRIM are being developed by AASHTO. Figure 14 shows an image of a SCRIM device.

Figure 14 – Picture. Sideway-force Coefficient Routine Investigation Machine (SCRIM). (Image source: VTTI).

SPATIAL FRICTION VARIATION IN CURVED ROADWAY SECTIONS

Burns et al. (2009) noted that curved roadways experience differential friction along the curve, since it is exposed to frequent and consistent acceleration and deceleration by the vehicles maneuvering the curved roadway. The resulting speed changes cause a greater rate of wear and polishing on relatively small, critical sections of the curve. A majority of the vehicles require higher friction at these critical locations to operate safely, and the friction available at these critical sections eventually decreases due to continuous wear and polishing. This creates differential friction within the curve site, which could become unsafe for drivers, especially if it is associated with high friction demand conditions, such as on sharp curves.

Besides, the differential friction can also arise in the transverse direction when the individual wheel paths have significantly different coefficients of friction. Burns et al. (2009) noted that transverse differential friction can cause significant problems for a braking vehicle. Pilgrim (2014) studied the impact of transverse differential friction on curved roadways and concluded that higher differences in the friction coefficient between the wheel paths requires lower driving speeds for drivers to safely maneuver around the curve.

Hence, both longitudinal and transverse friction differentials are potentially a safety concern on curved roadways. The differential friction on epoxy-based FIST sites can be more dangerous than normal pavement surfaces due to the potential exposure of a low friction epoxy layer towards the end of its life. Therefore, many aspects of friction differential, such as its location, magnitude, and other factors contributing to differential friction, need to be thoroughly investigated.

STATE DOT HFST PRACTICES ON HFST LIFE CYCLE ACTIVITIES

Based on the National Survey and a literature review, the state DOT HFST practices are categorized into four life-cycle activities: 1) HFST site selection, 2) HFST construction quality control, 3) HFST long-term performance monitoring, and 4) HFST maintenance treatments and replacement. The following section summarizes the state DOT practices, identifies some of the remaining challenges, and presents the needs to overcome the identified challenges in each life cycle activity.

HFST site selection

Two types of HFST site selection are observed in current practices: 1) the reactive approach, and 2) the proactive approach. The reactive site selection approach is based on crash history (especially ROR crashes, wet-weather crashes, curve crashes, and crash rate). This approach is adopted by most state DOTs. On the other hand, proactive site selection approach is based on identifying high-risk roadway features and treating all the locations in the network that have the high-risk criteria. For example, state DOTs, like GDOT, use the Ball-bank Indicator (a combined indicator that includes side friction condition, curvature, super-elevation, and driving speed) to identify high-risk roadway curves and high-risk criteria (BBI > 12˚ at speed limit) to proactively select HFST sites/projects.

State DOTs typically employ the following methods to determine the starting and ending points for HFST installation in the field, especially for the curve sites: 1) field judgement, 2) point of curve and point of tangent, 3) TTI recommendation or similar criteria based on distance required to decelerate safely to an advisory speed on the curve, or 4) a fixed distance in front of the curve, such as 100 ft. or 150 ft. from the beginning of the HFST curve (or point of curve).

Challenges:

- Current HFST site selection procedures are based primarily on the crash history (wet and run-off-the-road (ROR) crashes) and address only those sites with high crash numbers, which is a reactive approach. In addition, HFST provides the maximum safety benefit on sites that have high friction demand (including sharp curves, large speed differentials between posted and advisory speeds, etc.). Therefore, site selection criteria based on crash history alone may fail to select all the potential sites in the network that have high friction demand and low crash rates even though they may have a high potential for wet and ROR crashes.
- Applying HFST to pavements with unsuitable underlying pavement conditions (like a poor surface and sub-surface drainage, low macrotexture, etc.) can minimize the crash reduction benefit of HFST through premature failures and reduced performance life. Assessing the suitability of sites for HFST installation is often overlooked; however, more and more attention is being paid to this issue.
- Current methods to determine the starting and ending points of HFST installation with the TTI approach are conservative and apply HFST to the entire curve (or extend it several hundred feet before the PC), which may not be optimal.

Needs:

- Develop a systemic procedure to select sites for HFST installation that performs the following: (1) maximizes the safety benefit by including crash history (wet crashes, curve related crashes, etc.), (2) proactively addresses roadway risk factors (particularly characteristics associated with high friction demand, like sharp curves, inadequate superelevation, BBI, etc.), and (3) avoids premature failure-causing and unsound underlying pavement conditions (surface distresses like cracking, surface and sub-surface drainage, asphalt pavement age and thermal compatibility, etc.).
- Develop a method and guidelines for determining optimal beginning and ending points of HFST installation based on high friction demand locations in a curve site, vehicle dynamics (high lateral forces, vehicle run-off-the-road conditions, etc.), and driver behavior (acceleration and deceleration locations).

Construction

The general trend is moving from manual, hand-based installation to automatic truck-based installation to improve construction quality. The majority of state DOTs allow both manual (hand installation) and automatic (using truck-mounted epoxy and aggregate sprayer) HFST installation, but the manual installation is limited to 200-300 sq. yd. for most states. Some state DOTs allow only automatic installation.

There are very stringent HFST construction quality requirements for site preparation, binder mixing, binder application rate, binder thickness, binder application temperature, aggregate application rate, and aggregate embedment depth; these are well documented in FHWA guidelines and several DOT specifications. One of the significant construction quality control requirements is the aggregate embedment depth. Insufficiently embedded aggregates in the epoxy binder during construction can be dislodged easily by traffic, leading to premature failures and faster aggregate loss towards the end of the HFST life. State DOT HFST specifications require a binder thickness of 50-60 mils and a 50% – 67% calcined bauxite aggregate embedment depth as a part of construction quality control requirements (such as the Ohio DOT).

Challenge:

- However, there is a lack of an objective, cost-effective, and reliable method to assess aggregate embedment depth in HFST construction quality control. For example, there are specifications on the aggregate application rate (e.g., the aggregate spread rate of 12-15 pounds per square yard), but this specification does not reflect the actual aggregate embedment measurement. Moreover, there are manual methods of aggregate embedment depth measurement (such as the sand patch method), but it is time-consuming, and it is only a spot check that does not cover large areas for assessment.

Need:

- Develop automatic, accurate, reliable, and potentially real-time aggregate embedment depth measurement methods using automatic 3D pavement scanning technologies that can assess large areas of an HFST site to ensure good construction quality.

HFST long-term performance monitoring

There is minimal monitoring of HFST sites after installation, although there is a potential safety risk due to premature failures and end-of-life aggregate loss and friction deterioration on these sites. Only a few states, like Kentucky and Alaska DOT, perform long-term performance monitoring at the network-level. They use a dynamic friction tester to monitor friction. KYTC initially monitored friction every year for four years (2012 – 2015) and, since the friction values were quite high, KYTC then started to monitor friction once every two years. Recently, Kentucky developed and used a visual inspection process to evaluate all the HFST sites every year (DRAFT Research Report KTC-19-04). Their visual evaluation is based on distresses, such as cracking, rutting, aggregate loss, potholes, peeling, etc.

Challenges:

- Regarding performance monitoring technology, the current DOT monitoring practice of using DFT is expensive, requires traffic control, is laborious, and is time-consuming.
- Regarding performance-monitoring practices, there are currently no established network-level, cost-effective HFST condition survey protocols, nor is there an HFST condition rating system, which makes regular monitoring and performance evaluations of HFST sites difficult.

Needs:

- Develop an optimized, proactive, targeted, network-level FIST long-term performance monitoring that uses DFT.

- Develop supplementary and low-cost performance measures (like aggregate loss) and measurement methods, including visual inspection, 2D imaging, and 3D pavement scanning, to cost-effectively monitor the HFST deterioration performance.
- Explore alternative friction measurement technologies (like continuous friction measurement devices, such as a SCRIM or FHWA's Grip Tester) that do not require traffic control; develop corresponding testing protocols (where to measure, how to aggregate friction readings, what indicators to use for determining unsafe conditions, etc.) to monitor the friction based on continuous friction measurement (rather than sampled measurements).
- Develop a cost-effective HFST performance monitoring and rating system, for implementing long-term HFST performance monitoring and safely managing HFST at the network-level.
- Develop an accurate and reliable method for forecasting HFST performance or the risk level using friction, along with other supplementary measurements, like aggregate loss, texture depth, etc., and factors affecting deterioration (such as age, material used, traffic volume, curve geometry, etc.) to predictively identify HFST sites with potential safety risks at the network level.

HFST maintenance treatments and replacement

DOTs like PennDOT, FDOT, and WashDOT are developing specifications for HFST maintenance treatments to remedy HFST distresses; however, their approaches vary significantly. For example, FDOT recommends grinding to treat the distressed areas, while PennDOT recommends milling to the asphalt layer (milling only at the epoxy layer is hard as it is strongly attached to asphalt); WashDOT only recommends patching of the distress areas. Based on communicating with NCAT engineers, they performed a thin granite overlay on the entire site after their site experienced excessive aggregate loss.

Challenge:

- Currently there is a shortage of HFST maintenance treatments and no guidance on when to apply the treatment (the right time) or when the appropriate treatment (the right treatment type) should be applied to address the HFST deterioration.

Needs:

- Synthesize the success and failure cases of different HFST treatments and determine the different factors impacting the HFST MR&R treatment performance.
- Develop an HFST MR&R treatment and action decision-tree based on overall rating, pavement condition, deterioration, traffic volume to determine the right maintenance treatment timing and the right treatment method.

SUMMARY OF THIS PROJECT'S RESEARCH NEEDS

The following are the two main research needs addressed in this project:

1. **There is a need to establish an HFST long-term friction deterioration trend, study end-of-life characteristics, quantitatively analyze the factors impacting HFST friction deterioration, and study spatial friction distribution and variations inside epoxy-based FIST curve sites.**

a. Well-constructed HFST on good underlying pavement can maintain high and stable friction for 7-12 years. Currently, there is no established trend for how real-world HFST friction decreases over time, especially towards the end of its life after giving good long-term performance. Additional studies are required to periodically monitor HFST friction in real-world conditions to establish long-term performance trends, confirm the NCAT's rapid friction deterioration observation, and study the symptoms right before its end of life to take proactive actions.

b. For well-constructed HFST and epoxy-based FIST on sound pavements, factors such as age, traffic volume, type, and climatic conditions are identified to impact their long-term friction deterioration. However, there are only a limited number of studies that quantify the impact of these factors. Consequently, more studies are needed to confirm the impact of these factors and rank them by their significance. In addition, factors including FIST material and friction demand-related factors (curve radius, super elevation, deviation angle, grade, operational speed) need to be quantitatively evaluated to determine the impact on friction deterioration. Quantitative analysis of these factors affecting HFST, and epoxy-based FIST long-term friction deterioration are needed to a) identify and prioritize potential high friction deterioration sites in the network for monitoring and maintenance activities, and b) develop accurate and reliable friction forecasting models.

c. Curved roadway pavements experience higher forces during vehicle cornering and braking/acceleration actions and tend to wear and polish pavements non-uniformly in both longitudinal and transverse directions. This results in differential friction values in longitudinal and transverse directions along the curved roadways, which can be unsafe for drivers. With the potential exposure of low friction epoxy at the epoxy-based FIST site towards end of life, the differential friction on these sites can be more dangerous than normal pavement surfaces. Therefore, there is a need to study the spatial distribution of friction on the curve sites to a) identify if there is differential friction, b) determine the critical sections and wheel path positions where the friction is lowest, and c) analyze the factors (such as curve geometry, operating speeds, etc.) contributing to the differential friction.

2. **There is a need to develop a technical and managerial integrated framework to manage epoxy-based FIST safety throughout a pavement's lifecycle activities and to develop the preliminary version of a guide based on the developed framework to assist state DOTs with epoxy-based FIST sites' safety management.** Based on the National Survey and the literature review, technical and management needs were identified for safe and cost-effective management of FIST sites. However, these identified needs are fragmented and complicated. Therefore, there is a need to extract the core components of the needs into key technical modules, connect and organize these technical modules into a logical and integrated framework that will assist researchers and state DOTs in holistically understanding the key technical modules involved in the safety management of epoxy-based FIST life cycle activities. This will help establish practical guidelines for safe and cost-effective operations and good management of epoxy-based FIST sites throughout their lifecycle activities.

Accordingly, there is a need to develop a practical guidance document for GDOT with a systematic procedure to establish an optimized, proactive, targeted, network-level FIST site long-term performance monitoring and maintenance program that uses DFT and aggregate loss performance measures.

CHAPTER 3. EXPERIMENTAL TEST DESIGN AND FIELD DATA COLLECTION

This chapter presents an experimental test design and a field data collection process using consistent procedures for studying real-world FIST friction deterioration behaviors and spatial friction distribution at Georgia's FIST curve sites.

The purpose of this analysis is to study Georgia's FIST long-term spatial and temporal friction deterioration behavior and to study the factors that potentially impact the long-term friction deterioration. The factors to be studied include different materials used (calcined bauxite HFST, phonolite TPO, and LWA), construction methods (manual and automatic), different regions, traffic conditions (AADT and truck percentage, posted speeds, and advisory speeds), curve geometry (curve radius, superelevation, and deviation angle), different sampling "sections" within the curve, and sampling positions (wheel path and non-wheel path). First, Georgia's FIST program is summarized, and a GIS database is prepared. Second, a data collection design is developed describing the frequency, number, and positions for collecting DFT data at FIST sites. Third, representative FIST curve sites for periodically collecting data were selected; they covered diverse friction deterioration factors. Fourth, the data were collected in the field using a consistent data collection procedure. The data collection commenced in May 2018 and was completed in September 2021.

SUMMARY OF GEORGIA'S FIST AND GIS DATABASE

Georgia applied FIST using three different FIST material types in Districts 1, 2, 3, 4, 5, and 6 sites as follows:

1. Calcined bauxite HFST (342: 42 sites were installed in 2014 in Districts 5 and 6; 300 sites were installed in 2017 in Districts 3, 4, 5, and 6).
2. Phonolite TPO (69 sites were installed in 2017 in District 1).
3. Light weight aggregates (a continuous chip seal application was installed at 10 sites in 2017 on State Route 16 in District 2).

A GIS database was created to store the location and site information of the FIST sites. The location data (mile log information for starting and ending limits of the FIST site) for each FIST site were extracted from GDOT's FIST contract package and converted to GIS format by linear referencing of the FIST locations in GDOT's State Route shapefile; ESRI's ArcGIS software was used. In addition to the location and state route information, the curve geometry information for each site was extracted using "Smart-CIE," an ArcGIS-based automatic curve information extraction tool developed by the author for another project (Tsai et. al., 2016). The curve geometry information includes the locations of the point of curve (PC) and the point of tangent (PT), and geometry information on the curve radius, deviation angle, and curve length. The GIS database also included information on contractor(s), material sources (aggregate and polymer binder), construction method (automatic or manual), date of installation, AADT, truck percent, speed limits, dynamic friction test results at 5 and 90 days after installation, and initial pavement surface conditions.

DATA COLLECTION DESIGN – FREQUENCY, NUMBER, AND POSITIONS FOR DFT TESTING

Ideally, all the FIST sites need to be tested regularly to understand the long-term friction behavior and the various factors affecting its deterioration. However, due to the limitations of logistics (travel to different sites with equipment) and expensive traffic control operations required at each site, monitoring all the sites statewide is not practically possible. Therefore, based on discussions with GDOT, 30 representative FIST curve sites in Georgia were selected for the long-term performance monitoring. Sites that were expected to have faster friction deterioration rates were classified as primary sites, and sites with relatively slower deterioration rates were classified as secondary sites. The primary sites were those sites that had higher traffic volumes and high friction demand (sharp curves and/or high posted speeds) and were expected to show faster friction deterioration. Secondary sites were expected to show slower deterioration and typically consisted of low traffic and relatively less friction demand (wide curve radius). Since primary sites were expected to deteriorate faster, they were assigned more frequent and spatially dense data collection. In this test design, 10 out of 30 sites were identified as primary test sites, and the remaining 20 sites were identified as secondary sites.

At each of the 10 primary sites, 8 or more testing spots were dedicated, and data was collected every 3 months. For the 20 secondary sites, 6 testing spots were dedicated, and data was collected once in 6 months (less frequently because of their lower deterioration rate). In this study, the primary sites were further divided into 3 types:

1. Intensive test sites
2. Single-lane sites
3. Two-lane sites

The purpose of intensive testing was to identify which regions of curves were the weakest link or the locations that were deteriorating faster. Intensive test sites will contain 16 spots along one lane measured at several spots, including on adjacent asphalt pavement before the curve and after the curve, on the point of curve, point of tangent, middle of curve, and intermediate points on the inner and outer wheel path positions. Two non-wheel path positions were also collected as control data. In primary single-lanes, 8 points were collected only at points such as the point of curve, point of tangent, middle of curve, and non-wheel path positions, which are representative of the entire curve. In primary two-lane sites, only 8 points were collected, similar to primary single lanes but in both directions. The purpose of the two-lane sites was to assess the impact of the curve radius and to determine if the direction of the curve affected the friction deterioration differently.

In Figure 15, the top row shows the details of the data collection spots on primary sites. The bottom row shows the details of the data collection spots on secondary sites.

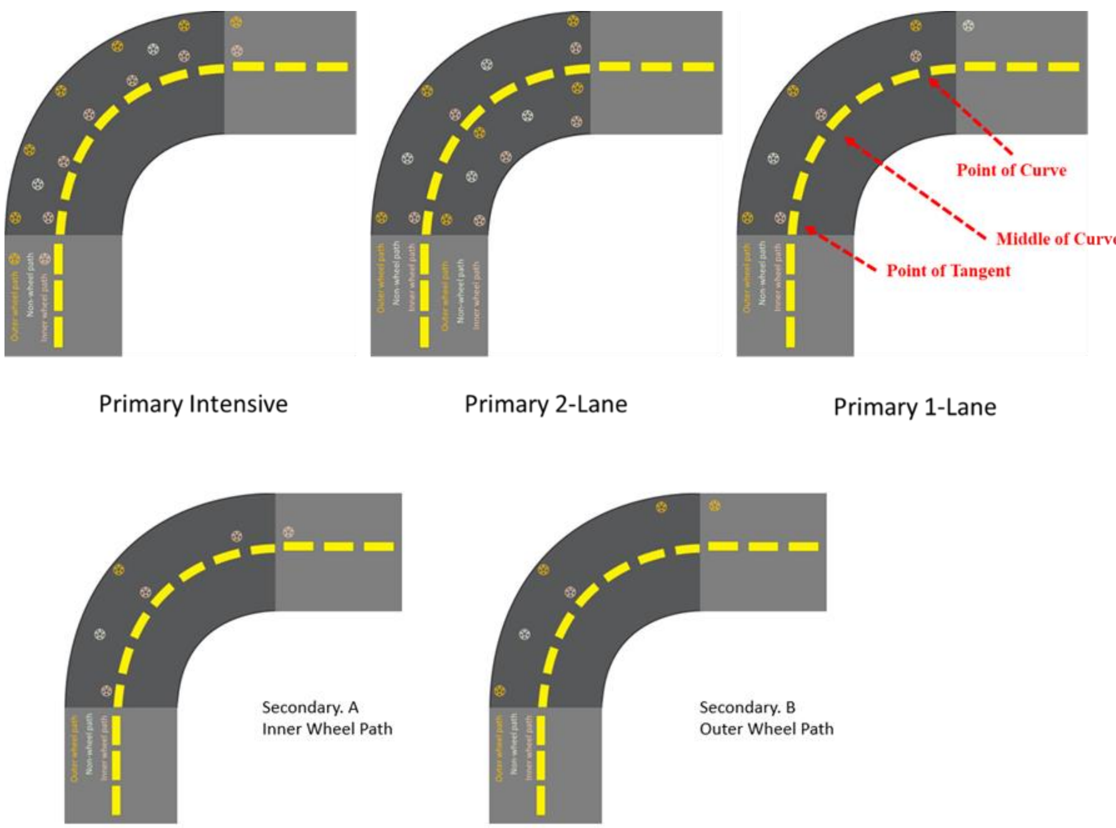


Figure 15 – Illustration. Spot testing locations for different primary sites (top row) and secondary site (bottom row).

These data were collected and analyzed from the 30 sites; they provide quantified information on friction deterioration, identify factors impacting friction deterioration, and identify locations of faster friction deterioration. The findings from the data analysis will be used for refining this experimental test design and developing the guidance for GDOT's optimized network-level, long-term FIST performance monitoring program (discussed in Chapter 7).

REPRESENTATIVE SITE SELECTION

The FIST sites were first grouped systematically (in three steps) based on the FIST GIS database to select representative sites covering diverse friction deterioration impacting factors, including different materials used (calcined bauxite HFST, phonolite TPO, and LWA), construction methods (manual and automatic), different regions, traffic conditions (AADT and truck percentage and posted and advisory speeds), and curve geometry (curve radius, super elevation, and deviation angle).

Step 1: FIST sites were first grouped by GDOT's Working District, which already accounted for diversity in age, weather conditions, construction method, and materials. FIST sites in each District were executed by the same contractor. The first step in the grouping process resulted in five groups (Working Districts 1,3,4,5 and 6 had installed HFST at the beginning of this project; District 1 also had installed phonolite TPO). The sixth group was District 2 where lightweight aggregate chip (LWA) seal was installed.

Step 2: The sites in each group in Step 1 were grouped by their state routes; this approach considered that it was optimal for GDOT to provide traffic control along the same route rather than set up traffic control in spatially dispersed locations. Each state route was analyzed for diversity of curve geometry and traffic conditions, and six state routes (one in each of the parent group in Step 1) were selected to represent diverse curve geometry and traffic conditions.

Step 3: Finally, the sites along each route were grouped together by their curve geometry (curve radius, in this case) and traffic volume. The curves with radiuses less than 1000 feet and the curves with radiuses over 1000 feet were grouped and further grouped by the traffic volume (less than 1000 AADT, 1000-5000 AADT, greater than 5000 AADT), resulting in six groups within the six larger groups identified in Step 2. The sites that had a curve radius of less than 500 feet, a curve radius of between 500 and 1000 feet, and a traffic volume greater than 5000 AADT were grouped as primary site candidates; other sites were grouped as secondary site candidates.

After grouping the sites in the office, the research team performed field investigations of the candidate sites in each group (from Step 3) with the assistance of GDOT engineers, and representative sites for long-term friction performance monitoring were selected.

Based on the experimental test design described in the previous section and after consulting with GDOT, 30 sites from among the 421 sites were selected as representative sites for long-term performance monitoring with DFT, which is less than 8 percent of the total sites (30/421). The following summarizes the 30 sample sites:

1. Calcined bauxite HFST (19/342 sites in Districts 3 (4 sites), 4 (2 sites), 5 (4 sites) and 6 (9 sites))
2. Phonolite, or “Wyoming bauxite,” (9/69 sites installed in District 1)
3. Light weight aggregates (2/10 sites in District 2)

Figure 16 below shows the 421 curve sites with calcined bauxite HFST, phonolite TPO, and LWA. In Figure 16, the FIST sites are color coded by project let package, and the number of sites in each let package is indicated in the brackets. Inverted triangles show the 30 sites that were selected as representative sites for long-term performance monitoring with DFT. Figure 17 (Table) shows the site characteristic details of these 30 representative sites.

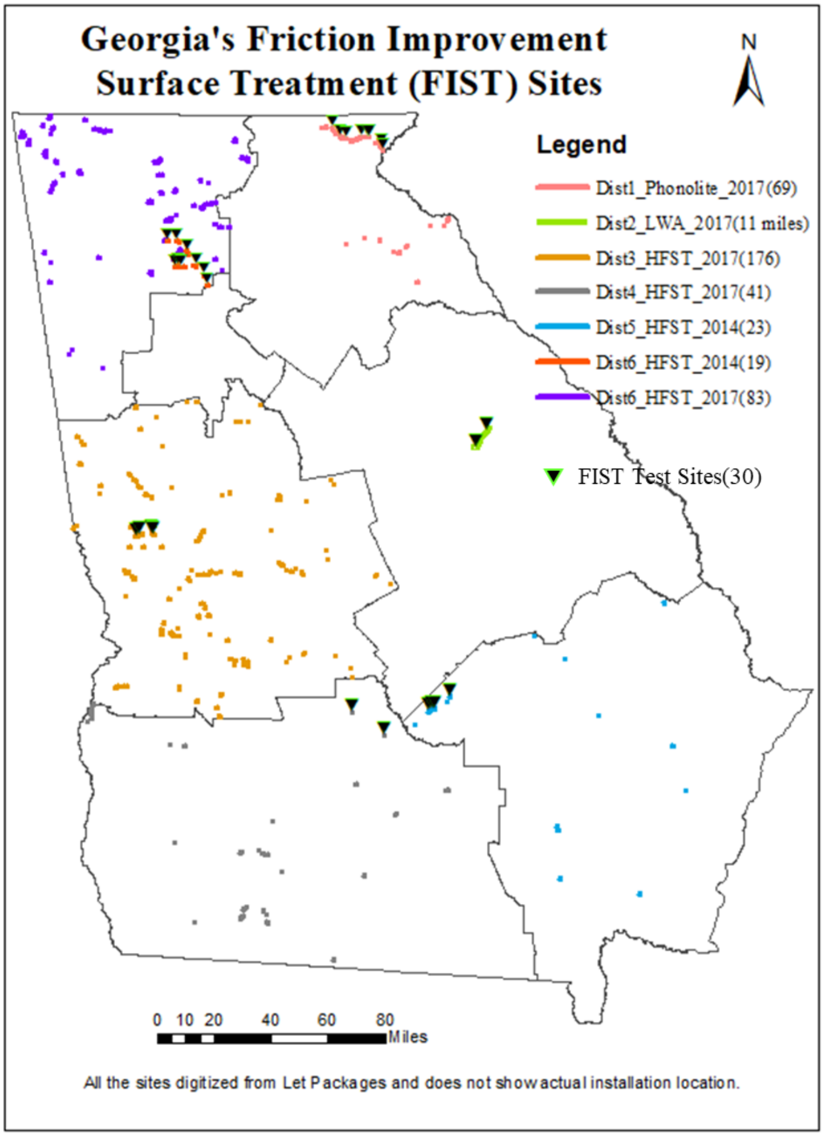


Figure 16 – Map. Georgia's FIST, including calcined bauxite HFST, phonolite TPO, and lightweight aggregate chip seal, constituting 421 curve sites and the 30 representative FIST test sites.

SiteID	Construction Method	Material	Installation Date	Annual Average Daily Traffic Volume	Annual Average Daily Truck %	Posted Speed	Difference between posted and curve advisory speed	Curve Radius (feet)	Length (feet)	Super Elevation at Curve Apex (%)	Deviation Angle (degree)
1-6-P	Manual	Calcined bauxite	Sep-2014	13600	11	55	10	1000	400	4.6	100
2-6-P	Manual	Calcined bauxite	Sep-2014	13600	11	55	20	970	2000	3.4	NA
3-6-S	Manual	Calcined bauxite	Oct-2014	13600	11	55	20	950	1000	4.1	60
4-6-P	Manual	Calcined bauxite	Jul-2014	14850	6	50	15	700	1000	4.8	80
5-6-P	Manual	Calcined bauxite	Jul-2014	17400	8	45	10	400	550	5	80
6-6-S	Manual	Calcined bauxite	Jul-2014	17550	8	45	10	1100	800	4	45
7-6-PE	Manual	Calcined bauxite	May-2014	2100	18	55	20	600	650	5.3	50
7-6-PI	Manual	Calcined bauxite	May-2014	2100	18	55	20	300	650	8	140
7-6-PW	Manual	Calcined bauxite	May-2014	2100	18	55	20	600	700	4.3	50
8-6-S	Manual	Calcined bauxite	May-2014	6100	8	55	10	1500	1100	1.7	50
9-6-S	Manual	Calcined bauxite	Jun-2014	8100	5	55	10	1100	1150	3.9	60
10-1-P	Automated	Phonolite	May-2017	850	12	45	20	520	800	6.7	110
11-1-P	Automated	Phonolite	Nov-2016	1550	14	45	10	175	450	5.6	150
12-1-S	Automated	Phonolite	Nov-2016	2250	12	35	0	600	600	NA	70
13-1-S	Automated	Phonolite	Oct-2016	4400	13	35	10	750	720	3.9	55
14-1-S	Automated	Phonolite	Oct-2016	8000	12	35	0	250	300	5.2	60
15-1-P	Automated	Phonolite	Oct-2016	8000	12	25	0	320	370	3.6	90
16-1-PE	Automated	Phonolite	Nov-2016	8000	12	35	0	210	300	5.6	80
16-1-PW	Automated	Phonolite	Oct-2016	8000	12	35	0	210	300	4.7	80
17-1-P	Automated	Phonolite	Jun-2016	2300	9	55	10	750	850	5.8	80
18-1-S	Automated	Phonolite	Jun-2016	2300	9	45	10	500	850	4.8	110
19-3-S	Automated	Calcined bauxite	Sep-2017	1950	7	45	20	550	500	6	50
20-3-S	Automated	Calcined bauxite	Sep-2017	300	6	45	10	650	550	2.6	50
21-3-S	Automated	Calcined bauxite	Sep-2017	400	6	45	10	350	600	5.6	100
22-3-S	Automated	Calcined bauxite	Sep-2017	400	6	45	10	700	400	4	40
23-4-S	Automated	Calcined bauxite	Apr-2017	3000	22	55	10	1500	800	2	30
24-4-S	Automated	Calcined bauxite	Apr-2017	230	7	45	0	1200	1300	7.4	70
25-5-S	Manual	Calcined bauxite	Nov-2014	350	12	45	0	1000	800	2.4	40
26-5-S	Manual	Calcined bauxite	Nov-2014	350	12	45	0	1200	700	4.2	35
27-5-S	Manual	Calcined bauxite	Dec-2014	350	12	55	0	1500	700	3	25
28-5-S	Manual	Calcined bauxite	Dec-2014	500	25	40	0	900	650	4	45
29-2-S	Automated	Lightweight aggregate	Sep-2017	2500	20	55	0	2000	1200	4.1	35
30-2-S	Automated	Lightweight aggregate	Sep-2017	2500	20	55	0	2000	1350	4.6	40

NA – Not available

Figure 17 – Table. Georgia's thirty representative FIST test sites used in this study and their site characteristics.

DATA COLLECTION TIMELINE

Three years of friction and limited texture data were collected from the representative FIST sites across Georgia from May 2018 to February 2021 in seven rounds, as shown in Table 3. It must be noted that data was collected at some sites in all seven rounds (especially primary sites), while in many secondary sites, data were collected only three times. Through this multi-round data collection effort, 1174 friction measurements were obtained.

Table 3– DFT data collection rounds in different districts.

Round #	Period	Districts
1	May-July 2018	1,2,3,4,5,6
2	September-November 2018	1,6
3	February-May 2019	1,2,3,4,5,6
4	August-October 2019	1,6
5	December 2019 - March 2020	2,6
6	July 2020	1,2,3,4,5,6
7	February 2021	1,2,6

FIELD DATA COLLECTION PROCESS

The consistent data collection process includes three steps: 1) traffic control, 2) locating and marking the testing spots in the site, 3) pavement friction, texture, and site condition data collection. These steps are presented below.

Traffic control:

Traffic control is a critical requirement for data collection, as all the data collected use spot measurements. GDOT was very supportive in establishing the traffic control. Typically, the lane in which the data is being collected is closed while the opposite lane is kept open for traffic. A pilot car and flagger control one-way movement of traffic in either direction. Figure 18a-b shows the traffic control of the curve site for the data collection.

(a) (b)

Figure 18 – Pictures. Traffic control activity: (a) Lane closure with flaggers at the beginning of the lane closure, (b) Pilot car to guide traffic on one lane while the other lane is closed.

The data collection activities start only after the GDOT traffic control crews give their approval.

Locating and marking testing spots in the site:

In the field, the PC point is located with the help of GPS and a visual survey. The rest of the spots are located with respect to the PC point using a measuring wheel. Once the spots are located, markings are made with paint on the side of the shoulder to identify the same spot for the next data collection round (as shown in Figure 19). At each round, the marking on the shoulder was repainted so it would be visible for the subsequent round of data collection.

Figure 19 – Picture. Identification of spots in the middle of the curve site using a measuring wheel and a marking on the shoulder indicating the spot to collect data, I - Left wheel path, O - Right wheel path, X - non-wheel path.

To support the analysis of spatial distribution, each spot is assigned a unique spot ID within each curve using a consistent naming convention, as shown in Figure 20.

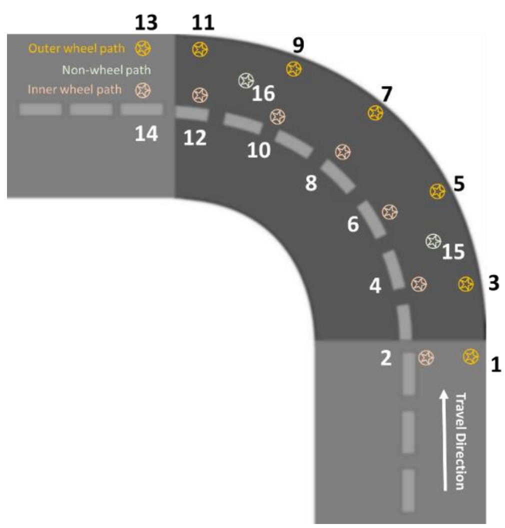


Figure 20 – Illustration. Consistent spot IDs assigned to the different position of testing spots within a curve.

From Figure 20, the dark region of the curve corresponds to the HFST surface. Spots 1, 2, 13, and 14 are outside of the HFST and belong to the underlying asphalt pavement surface. Spots 15 and 16 are on the non-wheel path locations within the HFST surface. The remaining spots belong to the wheel path – odd numbered spot IDs occur on the right wheel path (close to the shoulder) and even numbered spot IDs occur on the left wheel path (close to the roadway centerline). The purpose of this naming convention is to help analyze the spatial trends of friction deterioration.

Pavement friction, texture, and site condition data collection:

At each site, the following steps were followed to collect friction and site condition data:

1. Locate the correct position of the wheel path and non-wheel path and mark the appropriate spots at each site with chalk.
    a. The wheel path and non-wheel path locations are diligently located by visual inspection. Diligent effort is especially needed to identify the wheel path and non-wheel path on the curves because the vehicle generally tends to drift closer to the center pavement marking (left curve) or shoulder pavement marking (right curve), and the wheel path and non-wheel path shifts accordingly. The non-wheel path has a slightly different appearance (it is rougher and has a slightly different color than the wheel path); this visual cue is used to locate the non-wheel path.
2. Take photographs of the spot.
3. Take at least three cross slope measurements using the meter-long straight edge level and record the average value.

4. Measure the 3D scan of the spot (using an LS-40 high resolution scanner) in such a manner that it captures a homogeneous surface of the spot (avoid cracks, oil spills, other contaminations, etc.).
5. Record the pavement temperature using the infrared thermometer placed roughly 2 feet above the pavement.
6. Measure the DFT readings on the testing spot. If the recorded friction measurement is not smooth at different speeds (fluctuating widely), slightly move the DFT (by less than an inch) and repeat the measurement. Replace the DFT rubber slider after 3-5 measurements when it becomes worn-out. Figure 21 shows an example of a new DFT rubber slider and a worn-out rubber slider; it can be clearly seen the worn-out rubber slider is flat and has several cuts across it.

Figure 21 – Picture. Comparison of a new DFT rubber pad with the worn out DFT rubber pad after four measurements on calcined bauxite HFST.

7. Take the photographs of the shoulder, and
8. Finally record the observed distresses on the pavement.

Figure 22 shows photos of data collection and testing performed on a test site based on the testing procedure discussed above.

(a) (b) (c)

Figure 22 – Pictures. Photos of data collection and testing performed on a test site. (a) Cross slope measurement using straight level and recording an image of the marked spot with smart phone, (b) LS-40 high resolution 3D surface data collection, and (c) Friction data collection using DFT.

Appendix A shows an example page (field data sheet) from the data collection notebook to record the site and testing information, including the spot ID, ambient temperature, pavement temperature, cross slope, distress information, DFT, and 3D scans.

DATA MANAGEMENT

There are multiple site information and testing data collected through this project. To make the data manageable, two tables are generated to store the different types of data. The two tables are 1) the site information table that contains FIST Site ID, installation data, construction method, material used, location data, initial DFT measurements, roadway characteristics associated with the site (curve radius, length, deviation angle, traffic volume, and truck percentage), and 2) the DFT measurements and testing condition table, which contains a running list along with the site ID, spot ID, installation date, data of testing, ambient and pavement temperatures, cross-slope information, and its age. The site ID and spot ID are designed and used as the key items for linking the two different tables. A sample from the DFT measurements and testing condition table is shown in Table 4.

Table 4 – A sample of DFT measurements and testing condition table.

Site ID	Installation Date	Spot ID	Cross slope (degrees)	Ambient Temp (ºF)	Date	Pavement Temp (ºF)	μ (60 kph)	Age (Months)
11-1-P	11/14/16	3	0.3	83	7/8/2020	105	0.47	37
11-1-P	11/14/16	4	0.3	83	7/8/2020	109	0.45	37
11-1-P	11/14/16	7	5.6	83	7/8/2020	101	0.38	37
11-1-P	11/14/16	8	5	83	7/8/2020	100	0.39	37

CHAPTER 4. ANALYSIS OF GEORGIA FIST'S DETERIORATION BEHAVIOR UNDER LOCAL ENVIRONMENT

In this chapter, a friction data analysis framework is developed to analyze the long-term DFT friction data and site characteristics data to understand the real-world temporal friction deterioration behavior, spatial friction distribution and variations, and factors impacting the friction deterioration. The developed framework, along with the analysis methodologies, is presented in Section 4.1. Based on the developed data analysis framework, the preliminary findings from three years of monitoring 30 of Georgia's FIST sites are presented in Section 4.2. Sites with potential friction concerns and premature failures are identified and presented in Section 4.3. Finally, results and findings of Georgia's FIST deterioration behavior is summarized in Section 4.4.

FRICTION DATA ANALYSIS FRAMEWORK AND METHODOLOGIES

The proposed friction data analysis framework and methodologies analyze 1) the long-term DFT friction deterioration behavior of different FIST materials and the factors impacting the long-term DFT friction deterioration, 2) the spatial DFT friction distribution and the factors impacting the spatial distribution, 3) the spatial variation of DFT friction inside FIST curve sites and the factors impacting the spatial friction variations, and 4) the end-of-life FIST's DFT friction deterioration behavior and its attributes. Accordingly, the friction data analysis framework is divided into four components, and each component consists of corresponding analysis methodologies. This analysis framework can assist researchers and DOTs to a) systematically and comprehensively study the long-term friction behavior, b) establish friction deterioration curves and forecasting models, and c) develop strategies to monitor friction at FIST sites at optimal frequencies and perform DFT testing at targeted, critical locations within the curve site. The four components of the friction data analysis framework and its corresponding analysis methodologies are discussed below.

Analysis of long-term DFT friction deterioration behavior of different FIST materials and the factors impacting the long-term DFT friction deterioration.

This analysis component consists of three parts: 1) analysis of long-term DFT friction deterioration behavior of different FIST materials, 2) comparison of long-term friction performance on wheel paths and non-wheel paths, and 3) analysis of the factors impacting the long-term DFT friction deterioration. The detailed steps and methodologies for the analysis are discussed in the following sections:

1. Analysis of long-term DFT friction deterioration behavior of different FIST materials.

The purpose of this analysis is to understand the long-term friction deterioration and the deterioration trend of FIST materials. Three different friction plots are analyzed based on time, age, and cumulative loading. The median DFT friction value (measured at 60 kph) of the wheel path in each site is used for this analysis.

1.1. Time-plot: The median wheel path DFT60 values are plotted against time to analyze the current friction values at each of the sites. These results are useful for determining if the FIST sites have good friction values and for recommending safety actions if the current friction values are low and continuously deteriorating.

1.2. Age-plot: The median wheel path DFT60 values are plotted against age to study the long-term deterioration trend for each material. Since the sites of different ages are mixed, the time-plot may not reveal the age-related friction deterioration trend. Presenting the friction as a function of age can give continuous information about the long-term friction performance.

1.3. Cumulative loading plot: The median wheel path DFT60 values are plotted against cumulative truck traffic loading as measured by equivalent single axle loads (ESALs) to study the loading-related deterioration trend. Since the sites experience different daily traffic volumes, they may not deteriorate equally, even in the same age group. Therefore, the cumulative loading prior to each measurement at the respective site is calculated, and the friction is plotted against it. Based on Oh et al. (2010), surface friction is found to correlate more closely with the number of commercial vehicles (such as trucks) than with the total number of all vehicles (trucks and passenger cars). Therefore, truck related ESALs are used for measuring the cumulative loading. The ESAL is calculated from the annual average daily traffic (AADT) and truck percentage. For this analysis, a truck factor, (i.e., ESALs per truck) of two ESALs per truck is used for calculating the cumulative traffic loading.

$$ESAL\ (at\ DFT60\ measurement) = 2\ \times\ (AADT)(Truck\ Percentage)(Age) \tag{4.1}$$

where Age is the number of days since FIST installation at the time of DFT60 measurement.

It is noted that the truck factor of two ESALs per truck may not be consistent for all roadways because the nature of the loads carried on each roadway is different (e.g., some sites may contain fully loaded trucks, while other sites may contain empty trucks). To further enhance the cumulative loading calculation, it is recommended that the actual truck factor at each site be obtained.

2. Comparison of long-term friction performance on wheel path and non-wheel path.

The purpose of this analysis is to compare the difference between the wheel path and non-wheel path friction and to study how the difference changes over cumulative traffic loading (in terms of ESALs). The wheel path median DFT friction and non-wheel path DFT friction are plotted against ESALs. Trend lines are introduced in the plot to study the change in DFT friction over ESALs and to display the generalized long-term DFT friction performance.

3. Analysis of factors impacting the long-term DFT friction deterioration.

The purpose of this analysis is to identify the factors that impact long-term friction deterioration and quantify their impact using descriptive statistics (scatter plots and box plots) and inferential statistics (correlation coefficients).

In this analysis, the long-term friction deterioration (LFD) is first computed for each site. Second, the LFD is compared with the factors, including cumulative traffic loading, curve geometry (radius, deviation angle, super elevation), operating speeds, and construction methods; it uses scatter plots and box plots to show the relationship between the LFD and the factors. Third, the correlation tests and regression tests are conducted to analyze the strength and impact of each factor on the LFD.

3.1. Determine long-term friction deterioration (LFD)

Long-term friction deterioration is defined as the difference between the first DFT friction measurement on the wheel path immediately after construction at a site and the most recent wheel path DFT friction measurement at the same site. For the most recent wheel path DFT friction measurement, the site's average wheel path DFT60 friction measurement is used. It is noted from the field measurements that the wheel path and non-wheel path DFT friction values do not have a smooth deterioration trend and are fluctuating, which may have been caused by the variations in the friction measurement conditions (like pavement and ambient temperature, DFT device used, seasonal variation, etc.). Therefore, there is a need to correct this trend before obtaining the most recent wheel path friction measurement. For correcting this trend, the non-wheel path DFT60 friction is assumed to be constant, as it changes minimally over time (since there are no vehicle loads acting on the non-wheel path). So, the average of the non-wheel path DFT60 friction over time is computed, and the change in the non-wheel path DFT60 friction with respect to the average non-wheel path DFT60 friction value is computed for each time stamp (at each different age). This change is called the correction factor (Ç). The site's average wheel path DFT60 friction at different ages is adjusted by adding a correction factor to it.

$$\text{Ç}\,(\mathbf{i}) = \textbf{average non wheel path DFT60 friction over time} - \textbf{non wheel path DFT60 friction}\,(\mathbf{i}) \qquad (4.2)$$

where i is the age of the FIST site.

An example correction is shown in Table 5. Based on Table 5, the long-term friction deterioration is calculated to be 0.14, i.e., 0.86 (initial friction measurement) – 0.72 (friction measured at the most recent age of 70 months).

Table 5 – An example computation of corrected average wheel path friction.

Age (in months)	0	43	48	55	59	62	70	Average non-wheel path friction over time (Age 43-70 months): 0.79
Site's average wheel path average Mu	0.86	0.68	0.70	0.74	0.65	0.71	0.73	
Non-wheel path Mu	0.86	0.77	0.78	0.85	0.73	0.81	0.80	
Correction factor		0.02	0.01	-0.06	0.06	-0.02	-0.01	
Corrected site's average wheel path Mu		0.70	0.71	0.68	0.71	0.69	0.72	

3.2. Select factors to analyze its impact on long-term friction deterioration.

The factors selected for this analysis include (but are not limited to) traffic loading, curve geometry (radius, deviation angle, super elevation, and length), operating speeds, average precipitation, and construction methods.

3.3. Visualize the relationship between LFD and selected factors.

Scatter plots are generated to show the relationship between the LFD and continuous value factors, such as traffic loading, radius, deviation angle, length, and operating speeds; box plots are generated to show the relationship between nominal value factors, such as construction method (automated or manual).

In each analysis, the LFD is first plotted against traffic loading (ESALs) to verify the impact of loading on the LFD. If there is an impact of loading on the LFD, other factors are analyzed by normalizing the LFD with ESALs (LFD/ESALs). If there is no impact of loading on the LFD, other factors are analyzed directly with the LFD.

3.4. Analyze the strength of correlation and the importance of selected factors on the LFD.

In this analysis, the strength of the correlation between the LFD and selected continuous value factors is calculated using a Pearson correlation coefficient (assuming a linear relationship), and a t-test is performed to compare the impact of the nominal value factors. To compare the relative importance of the factors, first a multilinear regression is performed between the standardized values of the LFD and the standardized values of the selected factors. The resulting standardized regression coefficients are compared to determine the relative importance of each variable by identifying which factors have the larger standardized regression coefficient. The purpose of the standardization of values is to bring the factor values to the same scale so they can be compared. For example, super elevation range is 0-10 %, while the radius is 150-1500 feet, and comparing the regression coefficient of superelevation and radius without standardization will be misleading.

Analysis of spatial DFT friction distribution inside the FIST curve and the factors impacting the spatial distribution.

The purposes of this analysis are a) to understand the spatial friction distribution inside a FIST curve and reveal if there is differential friction, b) to identify the critical sections and wheel path positions with the lowest friction inside the FIST curve, and c) to determine the site characteristics that contribute to the lowest friction section and wheel path positions.

1) Analysis of spatial distribution of spot DFT friction.

The purpose of this analysis to reveal if there is differential friction within the FIST curve sites. Box plots of DFT60 friction are generated for each unique spot (1-16) inside the FIST curve (established in Figure 23) to visualize the spatial distribution of DFT60 friction. The box plots are presented for primary-intensive FIST curve sites in which 16 DFT friction measurements were recorded. The box plot is generated for each unique spot using the multiple DFT measurements collected during the three-year monitoring period.

2) Analysis of critical curve section with the lowest friction and the site characteristics contributing to the low friction.

The purpose of this analysis is to identify the routinely observed lowest friction section (beginning of curve-PC section; middle of curve-MC section; or end of curve-PT section) in the FIST curve sites and study the site characteristics that contribute to the lowest friction in the critical section. Figure 23 illustrates different sections used in this analysis.

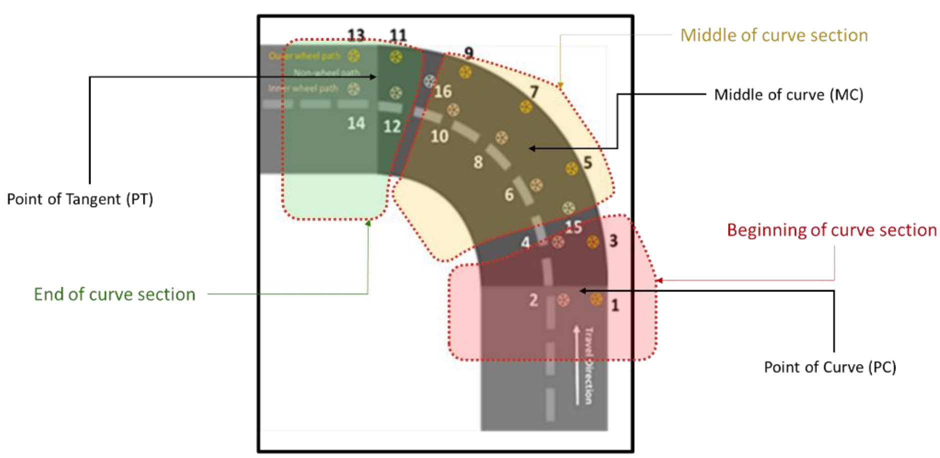


Figure 23 – Illustration. Location of different sections used for analyzing the lowest friction section in a curve.

The procedure used to identify the lowest friction section is described as follows:

1. Identify and record the Spot IDs of the three lowest friction spots on each curve for every time stamp at which the data is collected.
2. Count the total number of occurrences of each Spot ID at the minimum friction value (lowest friction value spot) in each specific curve.
3. Select the Spot ID with highest frequency and assign it to the "Beginning," "Middle," or "End" section of the curve. If there is equal frequency, count the second lowest friction spot.

Two examples to illustrate this procedure are shown in Figure 24.

Example 1

7-6-PE	Lowest Friction Spot		
Age	Min	2nd	3rd
47	4	8	7
52	8	11	12
59	8	12	4
63	8	7	12
67	8	7	11
74	8	7	12

Count of lowest friction Spot IDs:
Spot ID 8 – 6 times, Spot ID 4 – 1 time

Highest frequency lowest friction Spot ID: 8

Lowest friction section: Middle of the curve

Example 2

1-6-P	Lowest Friction Spot		
Age	Min	2nd	3rd
43	7	3	8
48	3	7	4
55	11	7	8
59	11	12	8
62	8	11	7
70	11	7	8

Count of lowest friction Spot IDs:
Spot ID 11 – 3 times, Spot ID 8 – 1 time, Spot ID 7 – 1 time, Spot ID 3 – 1 time

Highest frequency lowest friction Spot ID: 11

Lowest friction section: End of the curve

Color code	
3	Beginning
4	of curve
7	Middle of
8	curve
11	End of
12	curve

Figure 24 –Illustration. Examples showing how the lowest friction section in each curve is identified in each curve.

After identification of the lowest friction sections in each FIST site, the site characteristics, including STOP sign locations, presence of intersections or driveways along the curve, etc., are analyzed to determine if these site characteristics contribute to the lowest friction at the identified low-friction sections.

3) <u>Analysis of critical wheel path position with the lowest friction and the site characteristics contributing to its low friction</u>.

The purpose of this analysis is to identify the routinely observed lowest friction wheel path position (left or right) in the lowest friction section in a curve and to study the site characteristics that impact the lowest friction wheel paths.

Typically, the left wheel path and right wheel path are common terms used to describe the wheel paths. The terms "left" and "right" wheel path may not mean much for the analysis, as they cannot identify which wheel path is on the higher and lower sides of the superelevation (which is critical for a curve). Therefore, "inner radius" or "outer radius" is used to describe the wheel path positions; the inner radius wheel path corresponds to the lower side of the superelevation, and the outer radius wheel path corresponds to the higher side of the superelevation. Figure 25 illustrates the outer and inner wheel paths with respect to the superelevation.

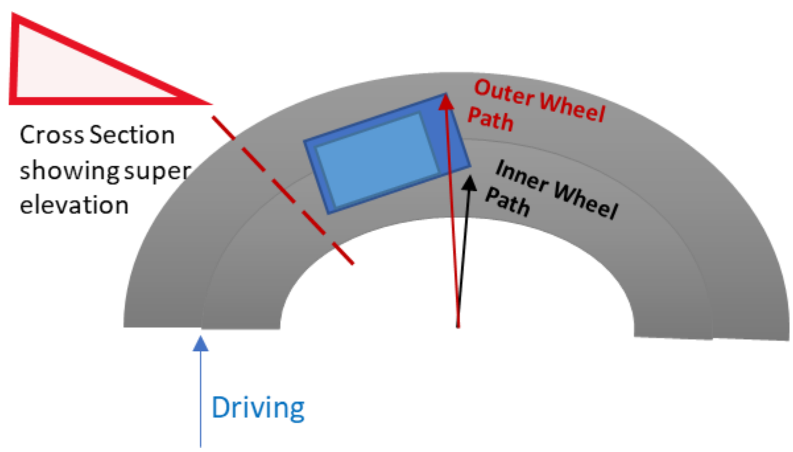


Figure 25 – Diagram. Illustration of outer and inner wheel paths with respect to superelevation.

The procedure to identify the lowest friction wheel path position in each curve site is as follows:

1. Identify the lowest friction section (based on Analysis Item 2 in this sub section).
2. Count the total number of occurrences of the lowest friction Spot IDs in the lowest friction section.
3. Select the spots with highest frequency and assign them to the "Left" or "Right" wheel path of the curve. If there is equal frequency, count the frequency in the second-lowest friction section.
4. Classify the lowest friction wheel path as "Outer" or "Inner" radius based on the curve direction. The right wheel path is the inner radius wheel path in the case of a right-turning curve and the outer radius wheel path in case of a left-turning curve.

An example to illustrate this procedure is shown in Figure 26.

7-6-PE	Lowest Friction Spot		
Age	Min	2nd	3rd
47	4	8	7
52	8	11	12
59	8	12	4
63	8	7	12
67	8	7	11
74	8	7	12

Lowest friction section = Middle of the curve

Count of lowest friction Spot IDs in the lowest friction section:
Spot ID 8 – 6 times, Spot ID 7 – 4 times
→ Left wheel path predominately low friction

Turn direction = Right turn

Lowest friction wheel path = Outer radius wheel path

Figure 26 – Illustration. An example showing how the lowest friction wheel path is identified in each curve.

After identification of the lowest friction wheel path positions in each FIST site, the site characteristics, including superelevation, operating speeds, and pavement conditions (such as aggregate loss, etc.) are analyzed to determine if the site characteristics contribute to the lowest friction wheel path position at the identified low friction sections.

Analysis of spatial variation of DFT friction inside FIST curve sites and the site characteristics impacting the spatial friction variations.

The purpose of this analysis is to identify the factors associated with non-uniform friction deterioration within the curve by analyzing the spatial friction variability and investigating the site characteristics of the FIST sites with significant spatial variability.

Spatial friction variability is computed based on the average friction range in each site. Friction range is defined as the difference between the maximum and minimum wheel path DFT60 friction values in each site. Spatial friction variability is defined as the average of computed friction ranges inside the site measured at different ages. A larger value of average friction range indicates non-uniform deterioration within the site.

Sites whose spatial friction variability is greater than 0.1 DFT60 are selected for further investigation to identify the key site characteristics contributing to non-uniform friction deterioration within the curve. The site characteristics considered for this analysis are curve radius, superelevation, presence of intersections/driveways, curve type (simple, compound, or reverse curve), and presence of pavement distresses, such as aggregate loss, delamination, aggregate pop-offs, cracking, and vegetation in the cracks.

Analysis of the FIST's end-of-life DFT friction deterioration behavior and its attributes.

The purpose of this analysis is to study friction deterioration behavior and deterioration attributes right before the epoxy-based FIST reaches its end of life. These attributes can serve as symptoms to detect the end of life and can be potentially used to develop trigger criteria for taking proactive actions, such as detailed surveys, setup of warning signs, replacement and resurfacing, etc. Based on NCAT observation, the FIST's end of life can be defined as the situation in which friction drops below its stable value. The DFT friction deterioration attributes to observe during the end of life are 1) dropped friction value, 2) friction drop percentage, and 3) friction deterioration or friction drop rate over consecutive measurements. Figure 27 illustrates the above-mentioned potential end-of-life DFT friction deterioration attributes from a synthetic DFT friction performance plot. This analysis is not pursued in this research study, as the DFT friction in the Georgia FIST sites is stable; an additional two to three years of monitoring is needed to observe end-of-life friction deterioration behavior.

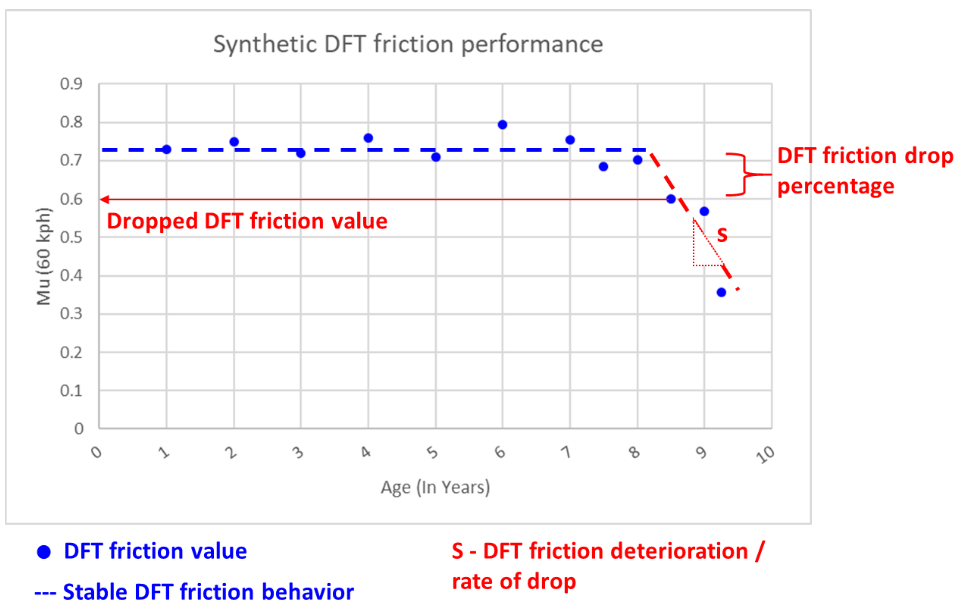


Figure 27 – Graph. Illustration of potential end-of-life DFT friction deterioration attributes, including 1) dropped friction value, 2) friction drop percentage, and 3) friction deterioration or friction drop rate over consecutive measurements on a synthetic DFT friction performance plot.

DATA ANALYSIS AND PRELIMINARY FINDINGS OF TEMPORAL AND SPATIAL FRICTION DETERIORATION BEHAVIOR

This section presents the data analysis and the preliminary findings of temporal and spatial friction deterioration behavior based on the developed data analysis framework used at 30 of Georgia's friction improvement surface treatment (FIST) sites. Georgia

FIST curve sites include a) calcined bauxite HFST, b) phonolite TPO (phonolite "Wyoming bauxite" aggregates used on epoxy), and c) lightweight aggregates (LWA) chip seal. The DFT friction values measured immediately after construction on these sites were obtained from GDOT. The DFT friction values and site condition data were continuously collected by the Georgia Tech research team from these 30 sites during a three-year monitoring period (May 2018-February 2021).

Long-term DFT friction deterioration behavior of the Georgia FIST materials.

Based on the analysis described in previous section, DFT friction is plotted against time, age, and cumulative loading. Figure 28 shows the median wheel path friction (DFT60) for all the friction measurements (including available 5-day and 90-day friction tests of the selected FIST sites) on the three FISTs plotted against time (the date of friction measurement). Figure 29 shows the median wheel path friction (DFT60) for all the friction measurements on the three FISTs plotted against age (in months). Figure 30 shows the median wheel path friction (DFT60) for all the friction measurements on the three FISTs plotted against a million ESALs. Table 6 summarizes the observations based on Figure 28, Figure 29, and Figure 30.

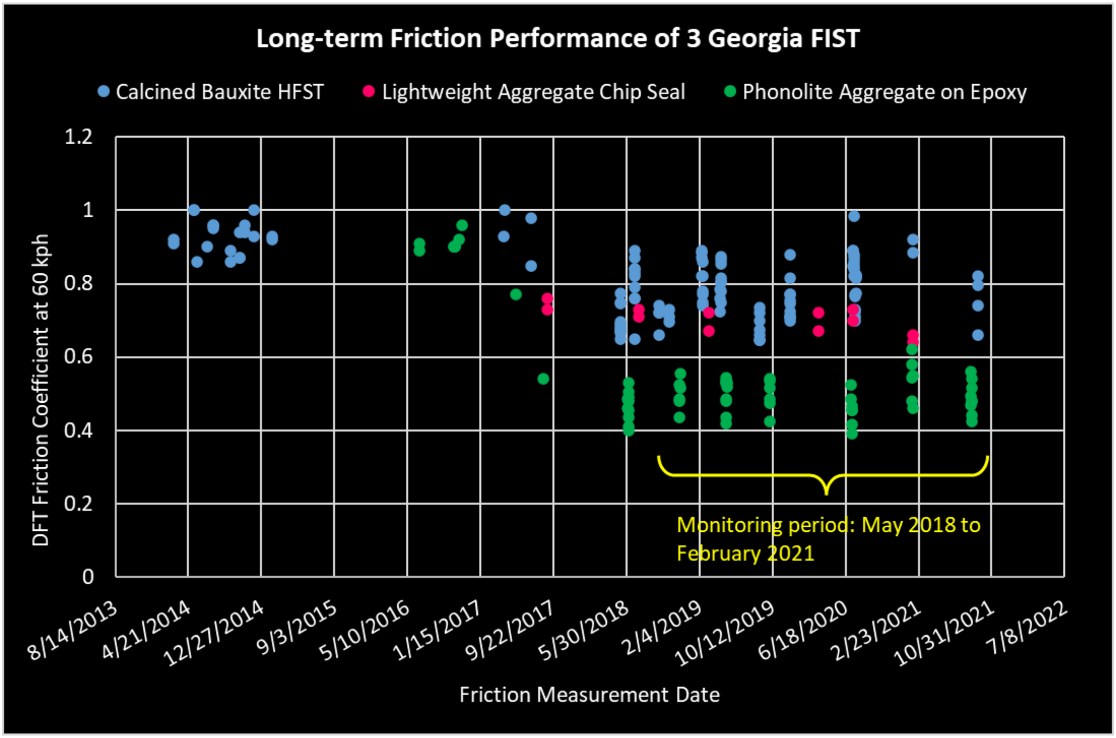


Figure 28 – Graph. Long-term DFT friction (60 kph) performance for the calcined bauxite, phonolite aggregate and LWA chip seal on the wheel path corresponding to the date of friction measurement.

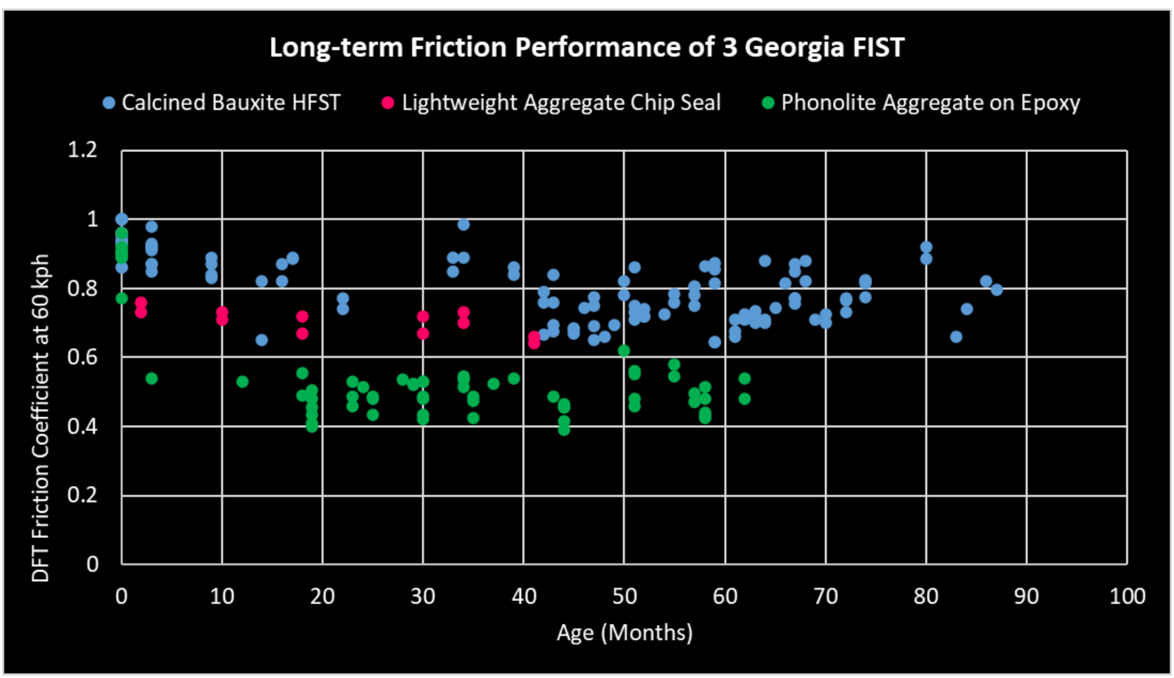


Figure 29 – Graph. Long-term DFT friction (60 kph) performance for the calcined bauxite, phonolite aggregate and LWA chip seal on the wheel path as a function of age.

Table 6 – Summary of observed long-term friction performance of calcined bauxite, phonolite aggregate and LWA chip seal in different stages after construction.

Calcined bauxite HFST		Drop from construction friction value
Construction friction value:	0.85 – 1.00 Mu	
3 months friction value:	0.85 – 1.00 Mu	10%
1 year friction value:	0.80 – 0.85 Mu	15%
Phonolite aggregate on epoxy (Phonolite TPO)		
Construction friction value:	0.85 – 1.00 Mu	
3 months friction value:	0.55 Mu	40%
1 year friction value:	.35-0.55 Mu	40%
Lightweight Aggregate Chip Seal		
Construction friction value:	0.75 Mu	
3 months friction value:	~ 0.75 Mu	
1 year friction value:	~ 0.7 Mu	7%

Based on Figure 28, Figure 29, and Table 6, it is observed that the DFT friction dropped drastically on phonolite TPO sites (close to 40%) in first three months; calcined bauxite HFST and lightweight aggregate (LWA) friction dropped less than 10% in the same time. Such drastic friction reduction at phonolite sites in the first three-months can, potentially, be due to excessive aggregate loss from the surface or excessive polishing of the phonolite aggregate. The mechanism for the rapid friction deterioration needs to be studied further. Finally, the DFT friction is observed to have stabilized at 0.7 Mu, 0.45 Mu, and 0.7 Mu for calcined bauxite HFST, phonolite aggregate on epoxy, and LWA, respectively, after the 1-year period. The difference in performance of calcined bauxite and phonolite aggregate could be potentially attributed to the difference in their alumina content. Calcined bauxite with high alumina content (87%) performed well compared to phonolite alumina content (<20%).

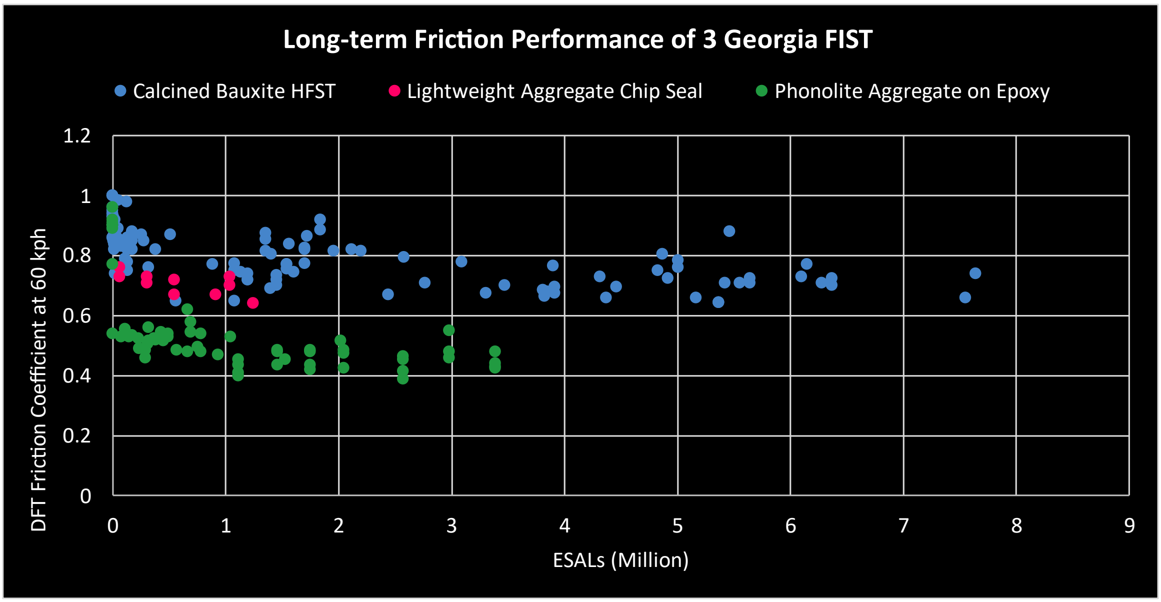


Figure 30 – Graph. Long-term DFT friction (60 kph) performance for the calcined bauxite, phonolite aggregate and LWA chip seal on the wheel path as a function of ESALs.

The observations from Figure 30 are summarized below:

1. Calcined bauxite HFST friction predominately stayed over 0.8 in the early stages of loading (less than 500 thousand ESALs). After one million ESALs, the majority of the calcined bauxite HFST friction measurements dropped below 0.8, and after two million ESALs, friction stabilized at 0.6-0.8.
2. Phonolite aggregate on epoxy (Phonolite TPO) friction predominately stayed between 0.5-0.6 in the early stages of loading (less than 500 thousand ESALs). After one million ESALs, the majority of the friction dropped below 0.5 and there is a tangible deterioration trend,

3. Lightweight aggregate friction performance was stable (0.7-0.75) until one million ESALs. The latest friction measurement showed friction dropping close to 0.6 at 1.2 million ESALs and mild flushing and aggregate loss are observed at these sites.

Comparison of long-term friction performance on the wheel path and the non-wheel path at the Georgia FIST curve sites.

This section analyzes the long-term friction performance on the wheel path and the non-wheel path of the three different FIST materials based on using the analysis method described in previous section.

Figure 33 show the median wheel path DFT60 friction and non-wheel path DFT60 friction behavior for calcined bauxite HFST 2014 sites, phonolite TPO sites, and LWA chip seal sites, respectively, as a function of ESALs during the monitoring period. To study the change in friction over ESALs, linear trend lines were introduced to display the generalized long-term friction performance.

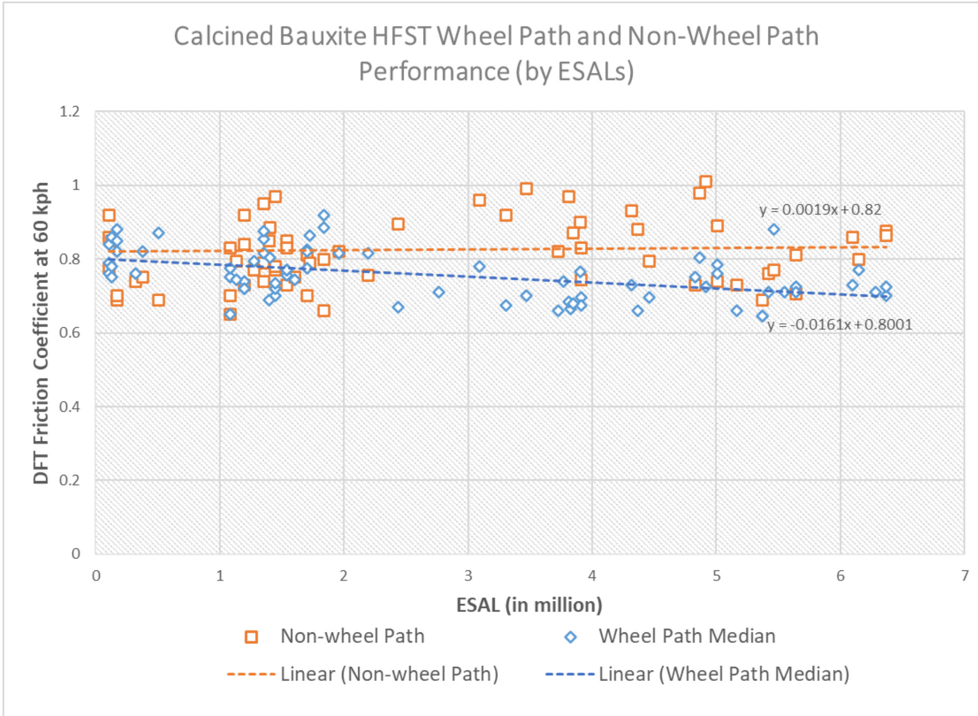


Figure 31 – Graph. Wheel path friction and non-wheel path friction behavior for calcined bauxite HFST in 2014 at calcined bauxite HFST sites.

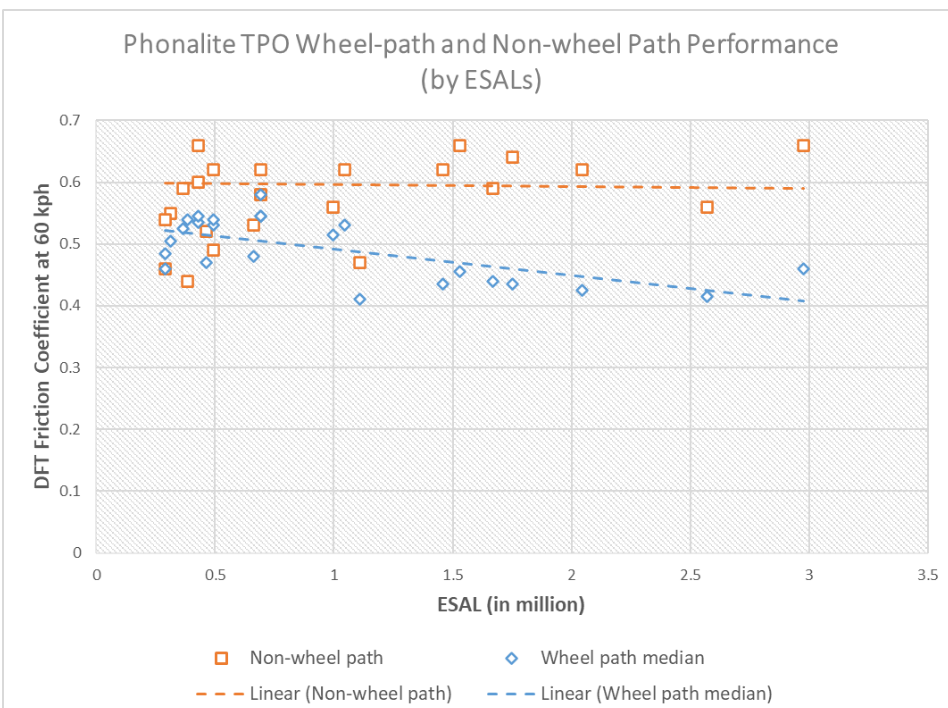
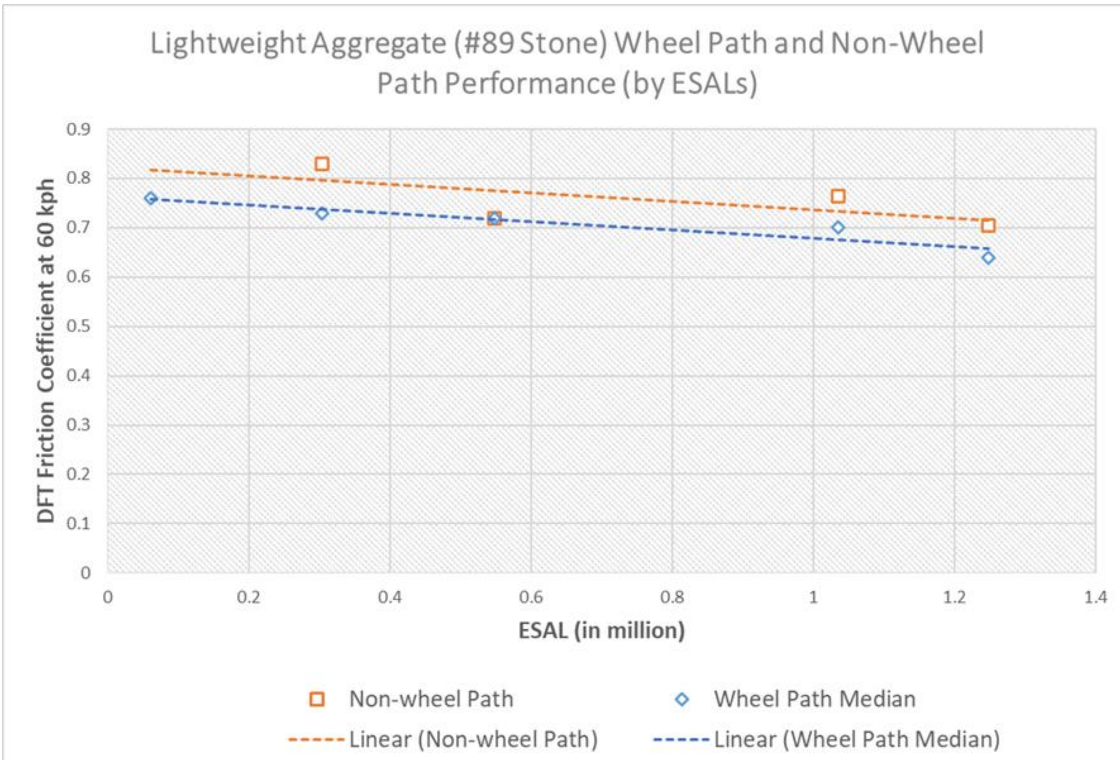


Figure 32 – Graph. Wheel path friction and non-wheel path friction behavior for phonolite TPO sites.



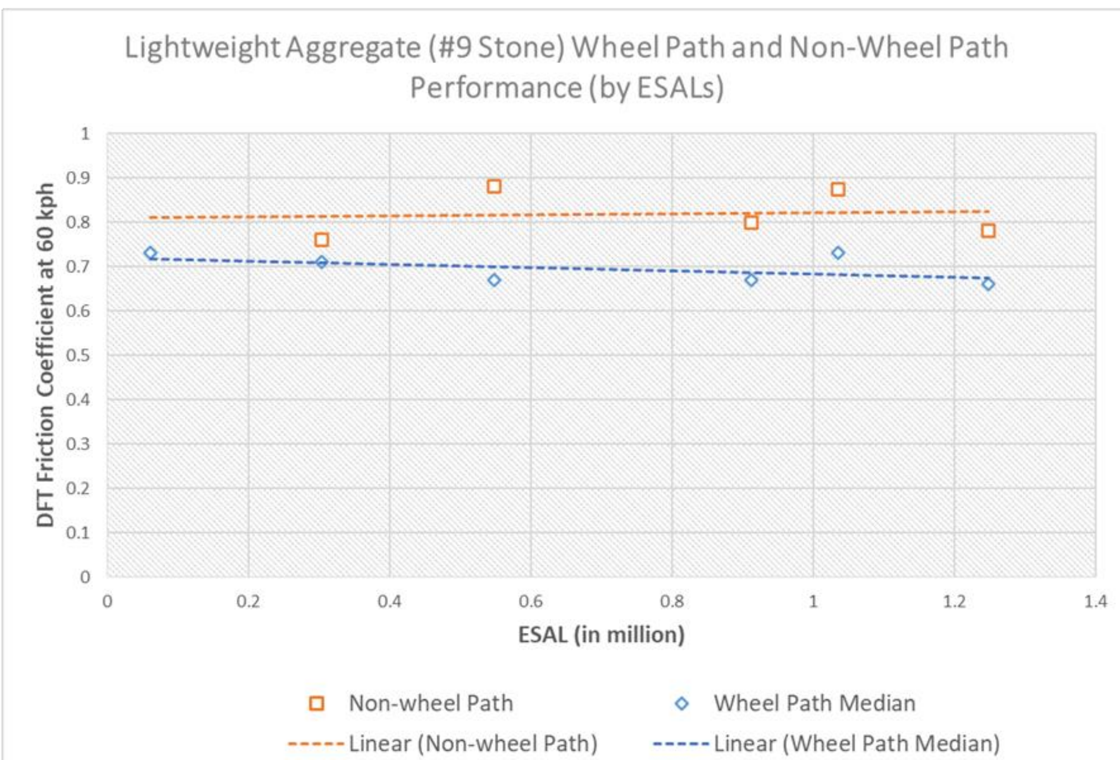


Figure 33 – Graph. Wheel path friction and non-wheel path friction behavior for LWA chip seal. Separate plots for the stone type used in the top layer – #89 and #9 stones.

It is noted that five of the phonolite TPO sites were removed from this comparison. At two sites, the non-wheel path friction was lower than the wheel path (DFT60 less than 0.5). These two sites are predominately located in urban areas close to the city of Clayton, which has slow-moving traffic (25 mph) and were observed to contain dust, dirt, and oil accumulated from the slow-moving traffic on the non-wheel path. The remaining three sites contained strong aggregate loss (based on visual identification) on the wheel path and non-wheel path, and they had similar friction values on the wheel path and non-wheel path (DFT60 around 0.55).

Based on Figure 31, Figure 32, and Figure 33, we can observe the following:

1. For the 2014 calcined bauxite HFST sites, the non-wheel path friction is predominately high compared to the wheel path friction. The trend line indicates stable non-wheel path friction (DFT60 slightly over 0.8) and shows continuous but steady deterioration of the wheel path friction; the difference between the wheel path and the non-wheel path is increasing with accumulated traffic loading (less than 0.05 DFT60 difference at 0.1 million ESALs to 0.1 DFT60, approximately a 12% difference at six million ESALs).
2. For the phonolite TPO sites with no strong aggregate loss, the non-wheel path friction is predominately high compared to the wheel path. The trend lines indicate stable non-wheel path friction (DFT60 at 0.6) and continuous friction deterioration of the wheel path friction; the difference between the wheel path and the non-wheel path is increasing widely with accumulated

traffic loading (less than 0.1 DFT60 difference at 0.5 million ESALs to 0.15 DFT60 and 25% difference at three million ESALs).

3. For lightweight aggregate, the non-wheel path measured consistently higher friction than the wheel path on both the test sites (7% on the #89 stone site and 14% on the #9 stone site). For the #89 stone site, the trend lines on the wheel path and the non-wheel path show slight long-term deterioration. However, for the #9 stone sites, the trend line is stable for the wheel path and the non-wheel path, indicating minimal long-term deterioration.

Besides this comparison of wheel path and non-wheel path friction, it must be noted that the phonolite TPO non-wheel path DFT friction dropped from 0.9 after construction to 0.6 in the first few months of service. This is contrary to our assumption that there is minimal deterioration on the non-wheel path; therefore, there is a need to further analyze the reason for non-wheel path friction drop.

Analysis of factors impacting the long-term DFT friction deterioration on Georgia FIST sites.

In this section, the relationship between long-term friction deterioration (LFD) and different factors, including cumulative traffic loading (ESALs), curve geometry (radius, superelevation, and deviation angle), operating traffic speeds, speed differences between the posted and the advisory speeds, and construction methods, are analyzed for calcined bauxite HFST (2014 sites) and phonolite TPO. Calcined bauxite HFST sites constructed in 2017 and lightweight aggregates are not analyzed due to the lack of the initial DFT friction data immediately after construction, which is needed to compute the long-term deterioration value. The LFD is computed based on the latest DFT friction measurement in late 2020 and early 2021, which represents close to six years of service life for the calcined bauxite HFST and close to four years of service life for phonolite TPO sites.

Visualization of the relationship between long-term deterioration and selected factors on calcined bauxite HFST.

Impact of cumulative loading: Figure 34 presents the plot of LFD vs. ESALs when the LFD is measured for the 2014 calcined bauxite HFST sites (14 sites) after approximately six years of service life. Based on Figure 34, there is no clear LFD correlation with loading. However, we can see two clusters (above six million ESALs, and below two million ESALs). In these clusters, we can observe that they have different LFDs (ranging from 0.14 to 0.23 in the cluster with six million ESAL), although they have the same ESAL level. This indicates that traffic loading has no conclusive impact on LFD, and other variables impact the LFD more strongly.

To further investigate if there were an impact caused by traffic loading on LFD over time, the LFD on two sites with similar, initial DFT60 (0.96) was analyzed at different ESAL values: one site carried four million ESALs, and one site carried less than one million ESALs. The results are shown in Figure 35. The LFD has a vertical trend, indicating the LFD did not change significantly at different ESAL values (clearly seen for site 4-6-P). This confirms that cumulative traffic loading does not have a clear correlation with the LFD. Since there is no clear LFD correlation with loading, the LFD is used without ESAL normalization for subsequent impact analysis of other factors, such as curve geometry.

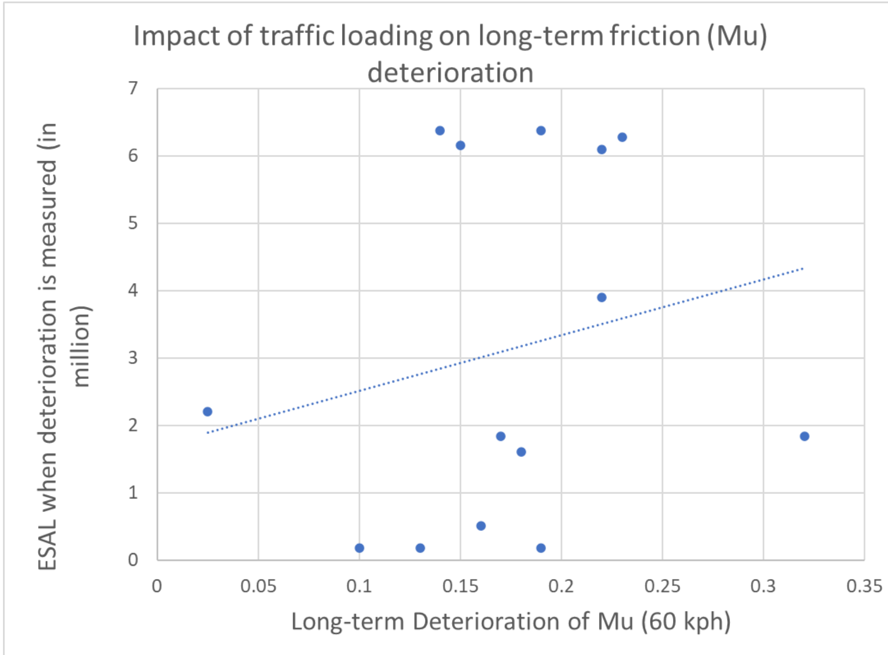


Figure 34 – Graph. Long-term friction deterioration vs. ESALs for calcined bauxite HFST.

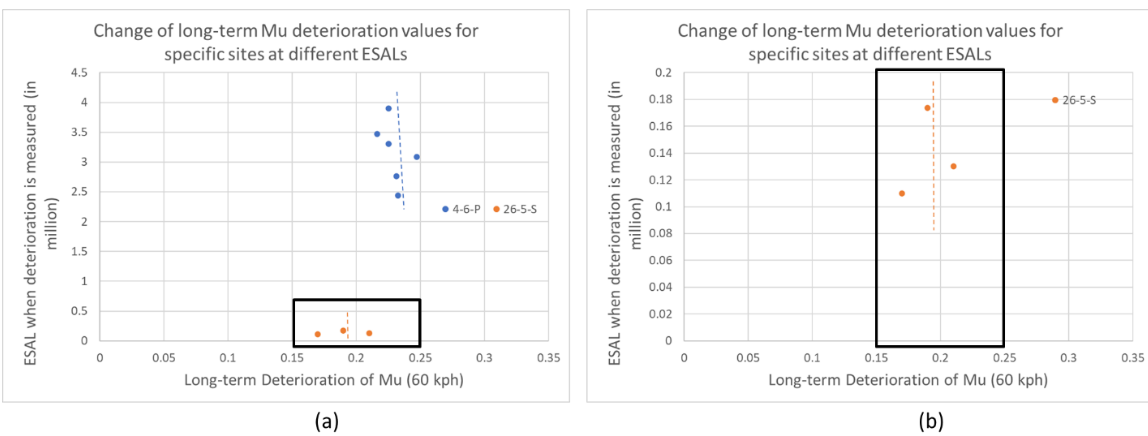


Figure 35 – Graph. Long-term friction deterioration values for two calcined bauxite HFST (4-6-P and 26-5-S) at different ESALs of loading.

Impact of curve radius: Figure 36 presents the plot of the LFD versus the curve radius. Based on Figure 36, there is an inverse relationship between the LFD and the radius. Short radius curves tend to have higher friction deterioration than do long radius curves. This outcome is reasonable because the short radius curves tend to have higher friction demand, and vehicle tires impart high lateral stresses on the pavement, which leads to the possibility of higher aggregate loss.

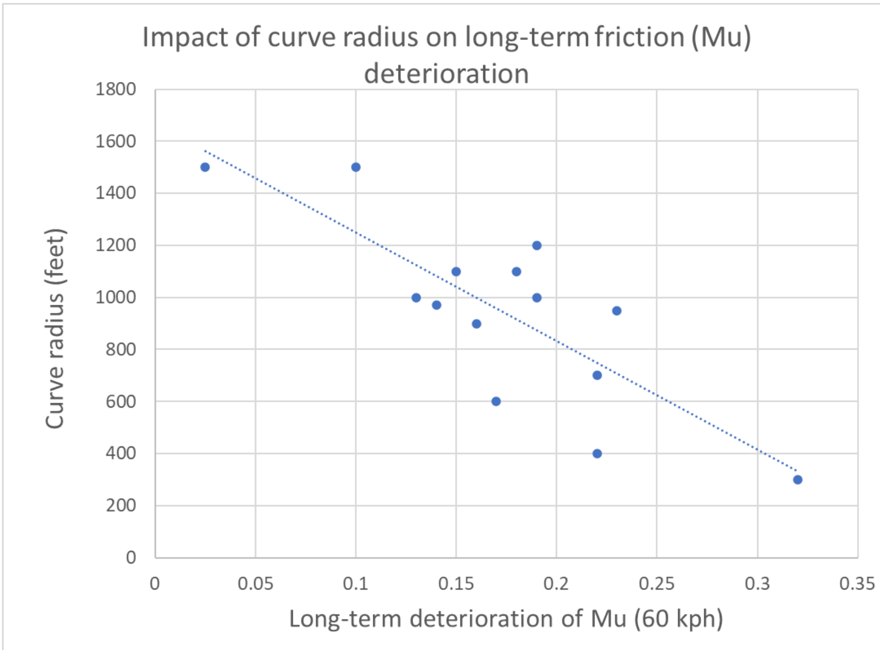


Figure 36 – Graph. Long-term friction deterioration vs. curve radius for calcined bauxite HFST.

Impact of curve superelevation: Figure 37 presents the plot of the LFD vs. the curve super elevation. Figure 37 shows a positive relationship between the LFD and superelevation. Smaller superelevation curves tend to have lower friction deterioration than do larger superelevation curves. This outcome is not intuitive because, at lower superelevation curves, vehicles are likely to impart more lateral stresses on the pavement to balance the lateral forces during the turn, which results in a higher LFD. Therefore, it is important to study the curve's geometrical design to make sense of the unintuitive impact of super elevation on the LFD. Typically, a curve with a shorter radius is designed to have higher superelevation to compensate for high lateral forces during the turn. It is observed that a curve with a short radius has a higher LFD (as shown in Figure 36), and a curve with a short radius also has a higher superelevation, so larger super- elevation curves tend to have a higher LFD, as shown in Figure 37. This is further confirmed by the strong negative correlation (-0.83) between the radius and super- elevation values.

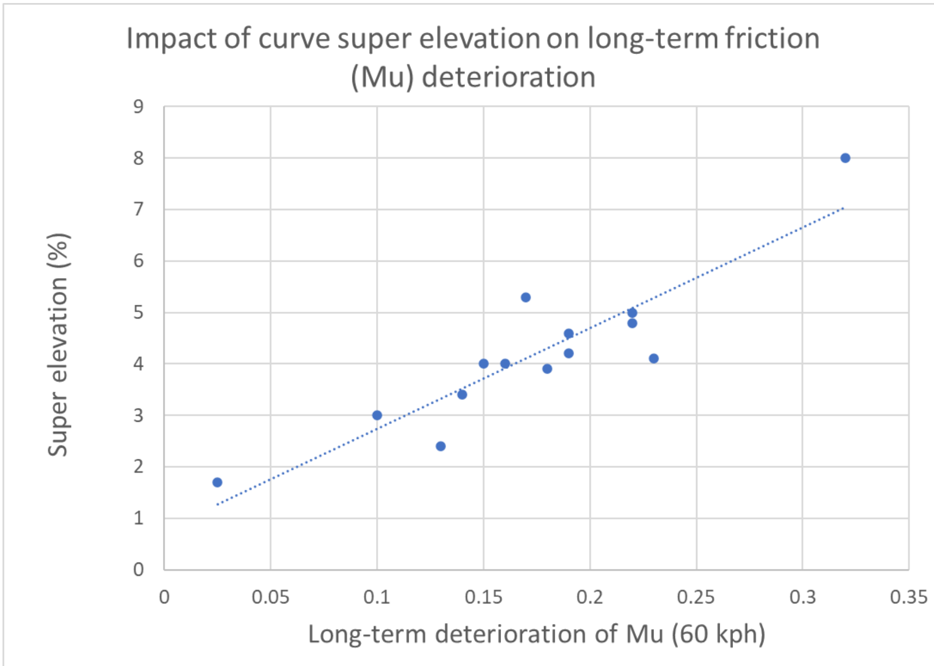


Figure 37 – Graph. Long-term friction deterioration vs. curve superelevation for calcined bauxite HFST.

Impact of curve deviation angle: Figure 38 presents the plot of the LFD versus the curve deviation angle. Based on Figure 38, the LFD shows a positive correlation with a curve deviation angle. The LFD increases with an increasing deviation angle. It is possible that at higher deviation angles, vehicle tires need to maintain a turned position (at an angle with respect to the direction of travel) for a longer time than a lower deviation angle because more lateral stresses are imparted to the pavement. Additional research using simulations is required to verify the observed trend.

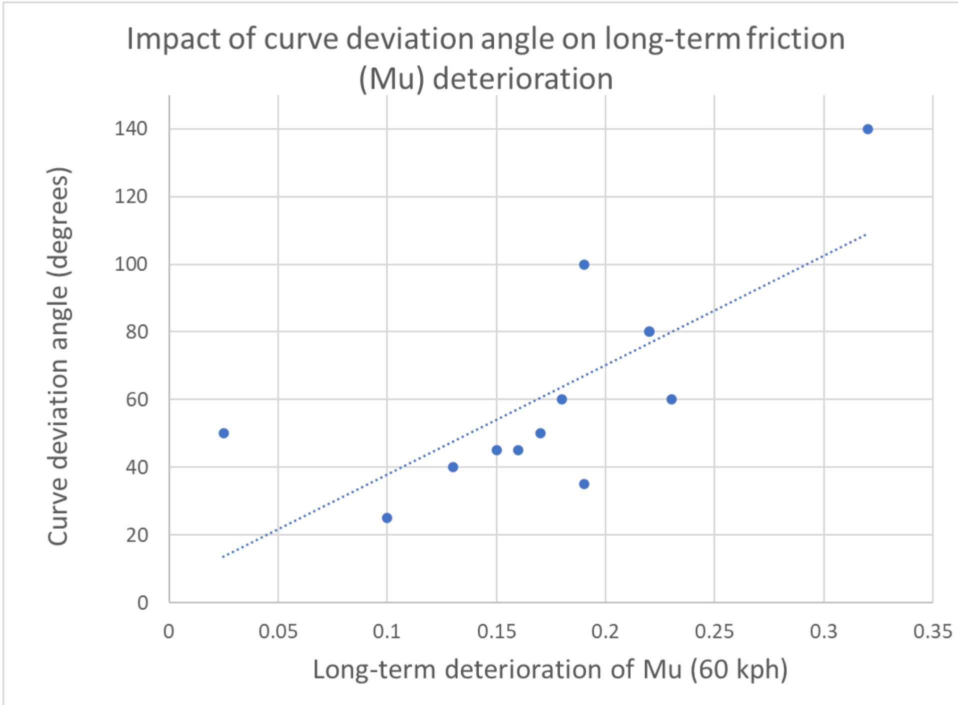


Figure 38 – Graph. Long-term friction deterioration vs. curve deviation angle for calcined bauxite HFST.

Impact of speed difference between posted and advisory speed: Figure 39 presents a scatter plot that compares the LFD to 0, 10, 15, and 20 mph at the calcined bauxite HFST curve sites. Based on Figure 39, it can be seen that the average long-term friction deterioration (the '*' mark in the scatter plot) for a speed difference of 0 mph is almost the same as a speed difference of 10 mph and close to 0.15. However, the long-term friction deterioration at 15 and 20 mph is over 0.20, which, potentially, indicates that higher speed differentials can lead to larger friction deterioration. It is likely that the vehicles brake harder to reduce speeds on higher-speed curves and, therefore, impart more shear stresses on the pavement.

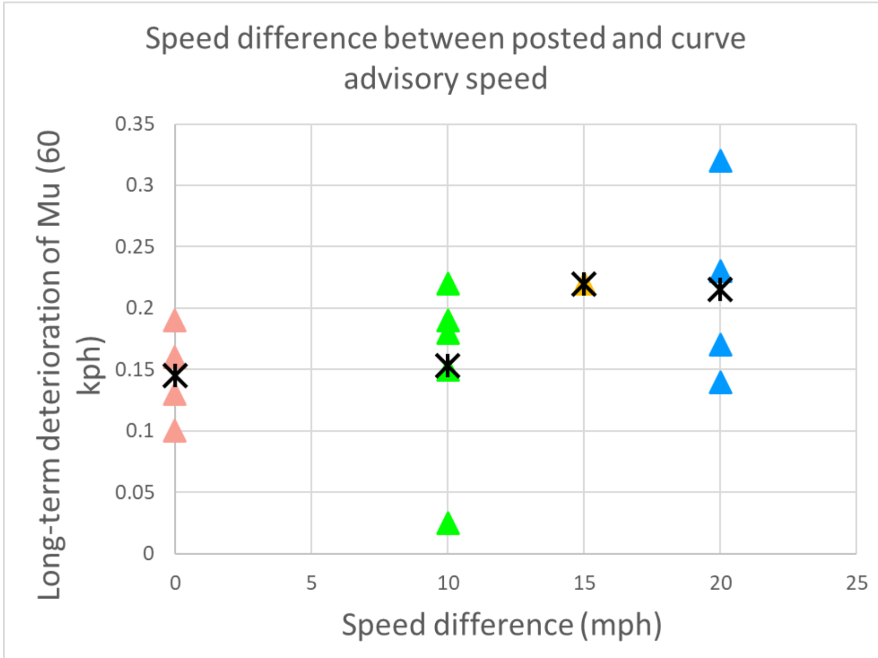


Figure 39 – Graph. Long-term friction deterioration comparison for 0, 10, 15, and 20 mph speed difference at the calcined bauxite HFST curves.

Impact of construction method: Based on discussions with GDOT, it was initially assumed that the construction method would play a significant role in the long-term friction deterioration. Two types of construction methods are used for laying epoxy-based FIST in Georgia: 1) the automated method, which involves automated trucks to dispense epoxy binder and aggregates at a controlled rate; and 2) the manual method, which involves workers spreading epoxy binder and spraying aggregates by hand. The calcined bauxite HFST sites installed in Districts 5 and 6 (2014) involved the manual construction method, while the calcined bauxite HFST installed in Districts 3 and 4 (2017) and the phonolite FIST installed in District 1 (2017) involved the automated method.

Visualization of long-term deterioration between different construction methods.

Among all the test sites, only the calcined bauxite HFST sites constructed in 2014 and 2017 can be compared for the variations in the long-term friction deterioration, as they have different construction methods and use the same materials. It is noted that the initial friction measurements in 4/6 calcined bauxite sites installed with the automated method are not available at this time of analysis. To compute the long-term friction deterioration on these four sites, it was assumed that the initial friction measurement was 0.95 based on similar initial construction friction values measured in the remaining two sites with automated construction. Figure 40 shows the friction measurement over cumulative ESALs between the automated and manual construction methods for calcined bauxite HFST.

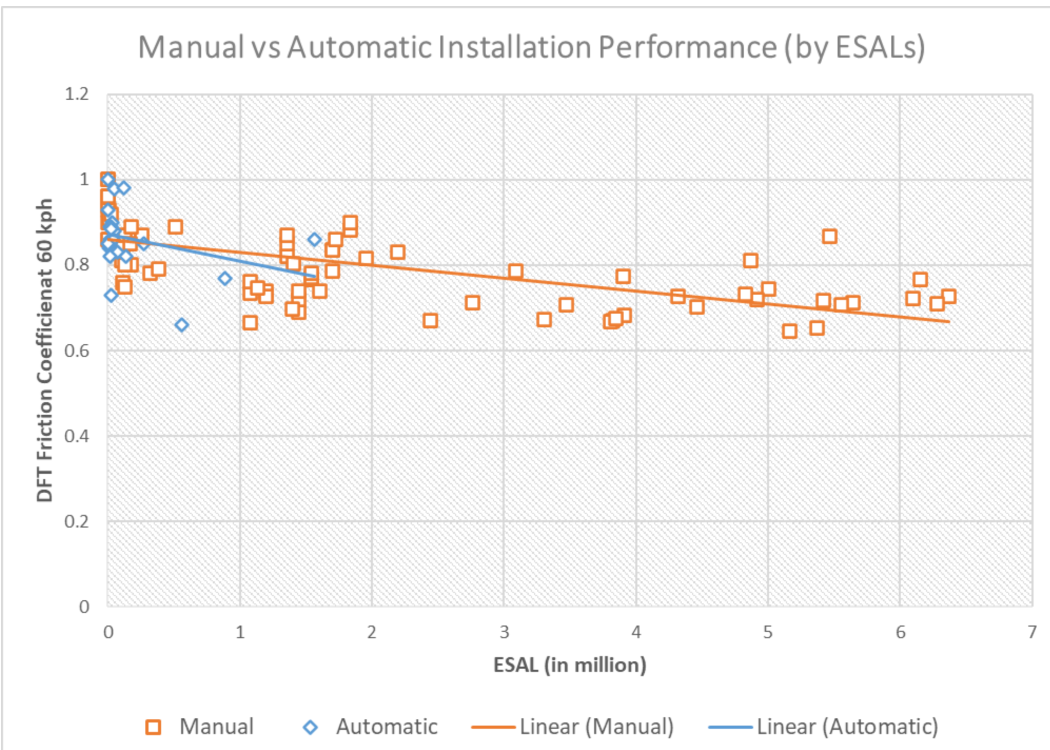


Figure 40 – Graph. Long-term friction deterioration comparison between the automated and manual construction methods for calcined bauxite HFST.

Base on the plot shown in Figure 40, it is worth noting that the manually installed site experienced significantly more traffic loads than the automatically installed sites. This is due to the fact that these sites were installed more recently and exposed to less traffic compared to the manually installed ones. The plot also shows that there is no noticeable performance difference between the different installation methods, since sites share a very similar deterioration trend, even though the automatically installed sites are only in its "early" life cycle compared to the manual sites. However, it should be noted that the analysis shown above is only based on six automatically installed sites with limited exposure to traffic; routine friction monitoring is recommended to confirm the friction deterioration trend follows the trend found on manually installed sites.

Visualization of relationship between long-term deterioration and selected factors on phonolite TPO.

Impact of loading: Figure 41 presents the plot of the LFD vs. ESALs when the LFD is measured for phonolite TPO sites.

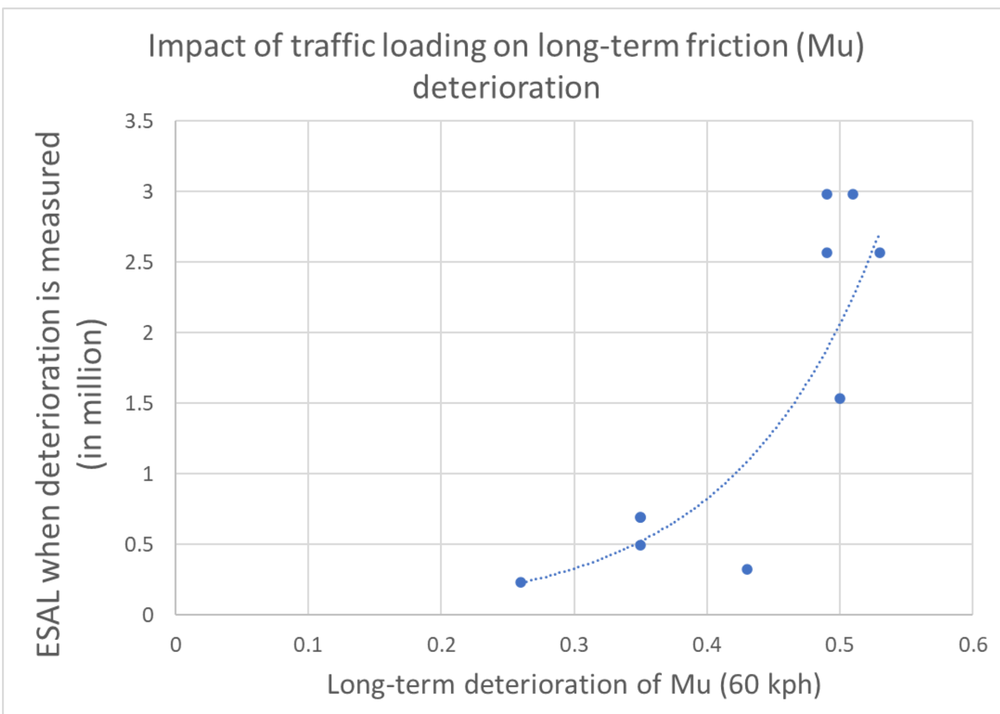


Figure 41 – Graph. Long-term friction deterioration vs. ESALs for phonolite TPO.

Based on Figure 41, the LFD shows correlation with the cumulative traffic loading (ESALs) when an exponential trend is used. It is possible that the phonolite aggregates (with less than 20% alumina content) are softer than the calcined bauxite (the alumina content is more than 87%) and, at higher traffic loading, they are prone to polishing, which, subsequently, results in larger friction deterioration. This observation is based on a limited number of data points, and additional samples are needed to confirm the exponential correlation. Since there is a correlation between LFD and loading, loading becomes a confounding factor in other analyses, and its effect needs to be removed. Therefore, for subsequent factor analysis at the phonolite TPO sites, the LFD is normalized by the ESALs.

Impact of curve speed and radius: Figure 42 presents the plot of LFD/million ESALs vs. the curve radius. The phonolite TPO curve sites are separated into high-speed curves and low-speed curves according to their location, rural or urban. The vehicle speeds and driving conditions on rural and urban curves are different. The posted speed on urban curves is 25 or 35 mph, while the posted speed on rural curves is 45 or 55 mph. Consequently, driver behaviors, vehicle forces, and the curves' friction deterioration performances may not be comparable. After separating the two curve types, LFD/million ESALs shows an inverse relationship with the curve radius. The shorter the curve radius, the higher is the friction deterioration. The relationship can be explained by the higher friction demand (and accompanying higher pavement stresses) on shorter radius curves.

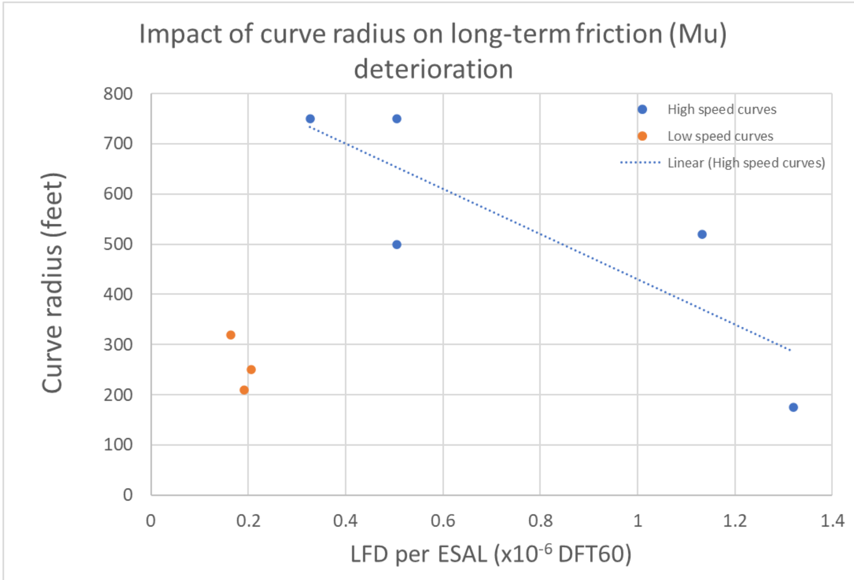


Figure 42 – Graph. Long-term friction deterioration vs. curve radius for phonolite TPO.

Impact of curve deviation angle: Figure 43 presents the plot of LFD/million ESALs vs. the curve deviation angle. As in curve radius analysis, the high-speed and low-speed curves are analyzed separately.

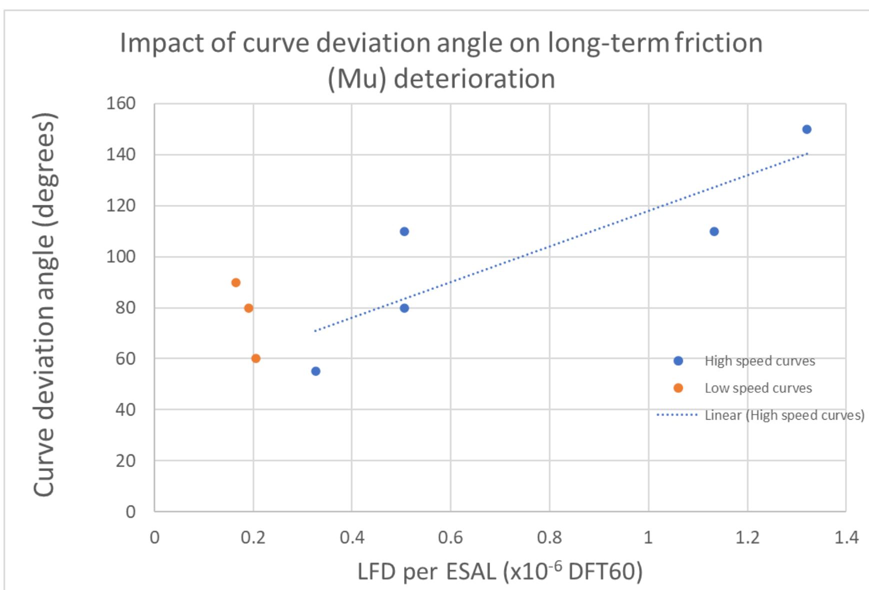


Figure 43 – Graph. Long-term friction deterioration vs. curve deviation angle for phonolite TPO.

Based on Figure 43, LFD/million ESALs shows a positive relationship with the curve deviation angle. The higher the deviation angle, the larger the steering angle change required, and larger lateral stresses are imparted by the vehicle tires on the pavement.

Strength of correlation between the different factors impacting the long-term friction deterioration and the DFT60 LFD.

Table 7 presents the correlation coefficient values between the factors impacting long-term friction deterioration (LFD) and a) calcined bauxite HFST LFD, and b) phonolite TPO LFD/million ESALs. Based on Table 7, there is a low value of correlation coefficient between calcined bauxite HFST LFD and ESALs, which confirms the low impact of cumulative traffic loading on calcined bauxite HFST deterioration. Curve geometry factors, including curve radius, superelevation, and deviation angle, have strong correlation for both calcined bauxite LFD and phonolite TPO LFD/million ESALs, indicating there is a potential impact of high lateral stresses on the friction deterioration, especially on the high-speed FIST curves. There is a no strong correlation between the calcined bauxite HFST LFD and speed difference on the curve, but a positive value indicates it is a potential factor to investigate further.

Table 7 – Correlation coefficients of the factors impacting long-term friction deterioration (LFD) with a) calcined bauxite HFST LFD, and b) phonolite TPO LFD/million ESALs.

Factors impacting LFD	Correlation with calcined bauxite HFST LFD	Correlation with phonolite TPO LFD/million ESALs
ESAL	0.21	No linear correlation
Radius	-0.80	-0.83*
Superelevation	0.90	0.70*
Deviation angle	0.73	0.81*
Speed difference between posted and curve advisory speed	0.43	Not sufficient diversity in the speed difference values to compute correlation coefficient
NOTE: * indicates the correlation coefficient is based on limited data points (only 5)		

It is noted that the correlation coefficients computed for the different factors are based on a limited number of data points, especially for phonolite TPO. Therefore, this study must be extended to additional FIST curve sites with wider ranges of factor values to confirm these preliminary findings.

Spatial DFT friction distribution inside the Georgia FIST curve and the factors impacting the spatial distribution.

The purpose of this analysis is a) to understand the spatial friction distribution inside a FIST curve and determine if there is differential friction, b) to identify the critical sections and wheel path positions with the lowest friction inside the FIST curve, and c) to determine the site characteristics that contribute to the lowest friction section and wheel path positions.

Spatial distribution of DFT friction inside the epoxy-based FIST curves.

Figure 44, Figure 45, and Figure 46 show the box plots of DFT60 for each unique Spot ID (1-16) inside the FIST curve (established in Figure 20) from three intensively tested FIST curve sites. Figure 44 shows the spatial distribution of DFT60 in calcined bauxite HFST at an urban location along State Route 140. Figure 45 shows the spatial distribution of DFT60 in calcined bauxite HFST at a rural location along State Route 140; both are in Cherokee County. Figure 46 shows the spatial distribution of DFT60 in phonolite TPO at an urban location along State Route 2 in Rabun County. As described in Section 4.1.5.2, Spot IDs 1, 2, 13, and 14 are outside of the HFST, and they fall on the underlying asphalt pavement surface. Spot IDs 15 and 16 are on the non-wheel path locations within the HFST surface. Spot IDs 3, 5, 7, 9, and 11 fall on the right wheel path (close to the shoulder), and Spot IDs 4, 6, 8, 10, and 12 fall on the left wheel path (close to the roadway centerline). These box plots represent multiple time stamps of DFT measurements and show a wide range of friction values at each spot.

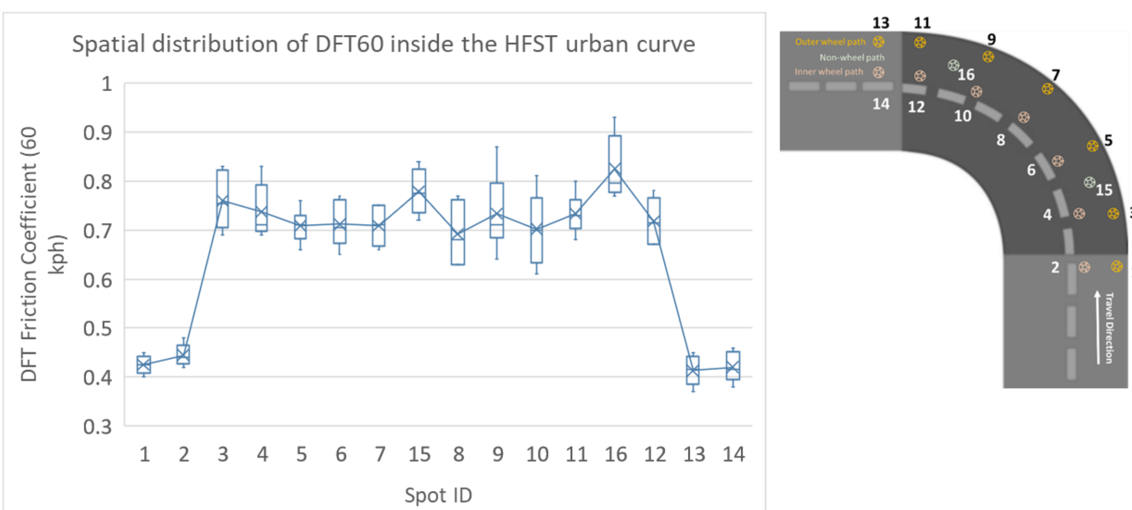


Figure 44 – Graph. Box plots of DFT60 for each unique Spot IDs (1-16) inside calcined bauxite HFST urban curve in State Route 140.

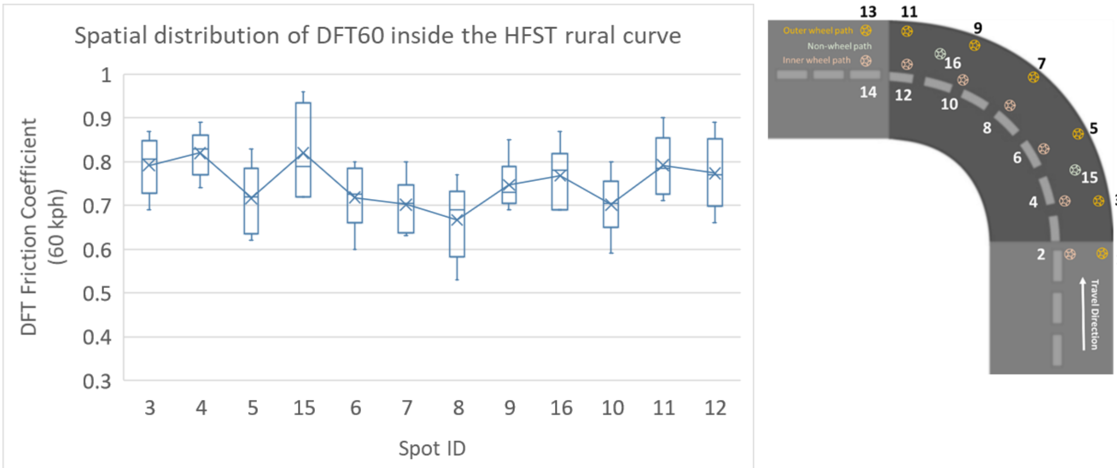


Figure 45 – Graph. Box plots of DFT60 for each unique Spot ID (1-16) inside calcined bauxite HFST rural curves on State Route 140.

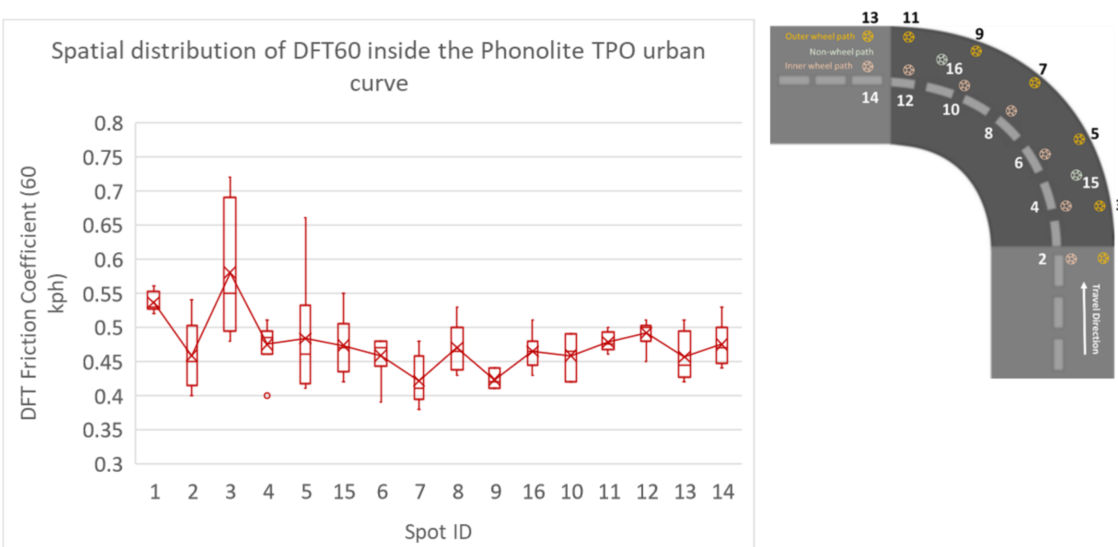


Figure 46 – Graph. Box plots of DFT60 for each unique Spot ID (1-16) inside phonolite TPO urban curve on State Route 2.

From Figure 44, it can be clearly seen that the asphalt pavement (Spot IDs 1, 2, 13, 14) has relatively low mean friction compared to the HFST surface, but it is higher or comparable in the case of phonolite TPO (Figure 46). In Figure 44 and Figure 45, the mean friction in the middle of the HFST curve (Spot IDs 5, 6, 7, 8) is lower than in the beginning (Spot IDs 3, 4) or end (Spot IDs 11, 12) of the curve, and the difference is quite large on rural HFST curves. In a rural HFST curve, the mean friction at the beginning or end of the curve is more than 10% higher than the middle of the curve. In Figure 46, the mean phonolite TPO friction at the middle of the curve and on right wheel path (Spot IDs 7 and 9) is relatively lower than the rest of the site. These observations reveal that there is differential friction inside the epoxy-based FIST curve site and indicate differential friction deterioration. The difference in friction can rapidly increase the trend towards the epoxy-based FIST end of-life once the epoxy becomes brittle and starts losing aggregates, thereby creating a high-risk pavement condition for drivers.

Critical curve section with the lowest friction and site characteristics contributing to its low friction.

Table 8 presents the results for the lowest friction section within each curve site. Based on the results in Table 8, we can observe 24/33 curves (33 instead of 30 because they are bi-directional curve sites) show the lowest friction to occur in the middle of the curve, 5/33 curves have the lowest friction occurring at the end of the curve, and 3/33 curves have the lowest friction occurring at the beginning of the curve. In general, the middle third of the curve typically yields the largest side friction demand, according to FHWA (Milstead et. al., 2011), and, consequently, it experiences high shear stress (due to vehicle’s centrifugal forces acting in the lateral direction).

Table 8 – Table summarizing the lowest friction section in each curve.

Site ID	Lowest Friction Location	Site ID	Lowest Friction Location
1-6-P	End of curve	16-1-PW	Middle of curve
2-6-P	Middle of curve	16-1-PE	Middle of curve
3-6-S	Middle of curve	17-1-P	No clear distinction
4-6-P	No clear distinction	18-1-S	Middle of curve
5-6-P	Middle of curve	19-3-S	Middle of curve
6-6-S	End of curve	20-3-S	Middle of curve
7-6-PI	Middle of curve	21-3-S	Middle of curve
7-6-PW	Middle of curve	22-3-S	Middle of curve
7-6-PE	Middle of curve	23-4-S	Middle of curve
8-6-S	Middle of curve	24-4-S	End of curve
9-6-S	End of curve	25-5-S	Beginning of curve
10-1-P	Middle of curve	26-5-S	End of curve
11-1-P	Middle of curve	27-5-S	Middle of curve
12-1-S*	Beginning of curve	28-5-S	Middle of curve
13-1-S*	Middle of curve	29-2-S	Middle of curve
14-1-S	Middle of curve	30-2-S	Beginning of curve
15-1-P	Middle of curve	* Less than 3 timestamps	

In Figure 47, Figure 48, Figure 49, bar charts are shown to depict the average, median and range of friction values on the front middle and end of a curve. Figures are presented to depict the difference sections of the curve for phonolite urban curves, HFST urban curves, and HFST rural curves respectively.

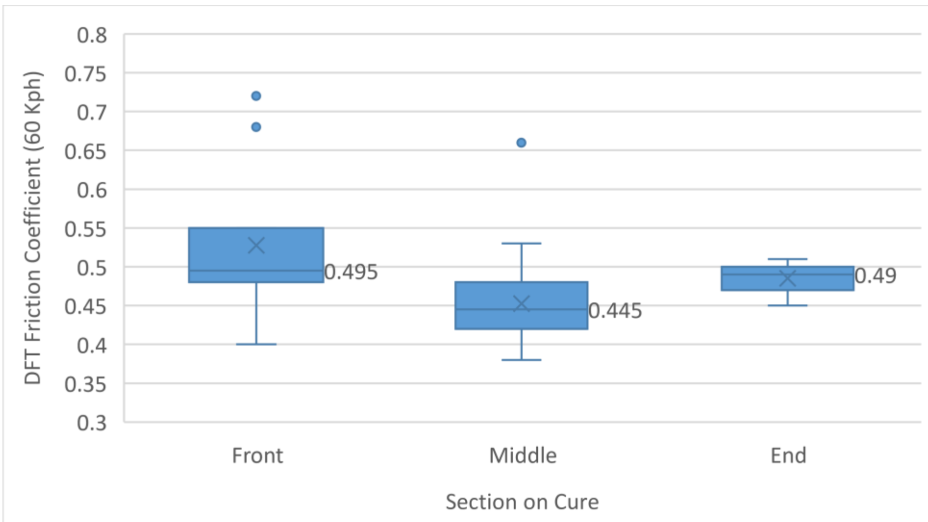


Figure 47 - Illustration. Friction by Section of Phonolite Urban Curve.

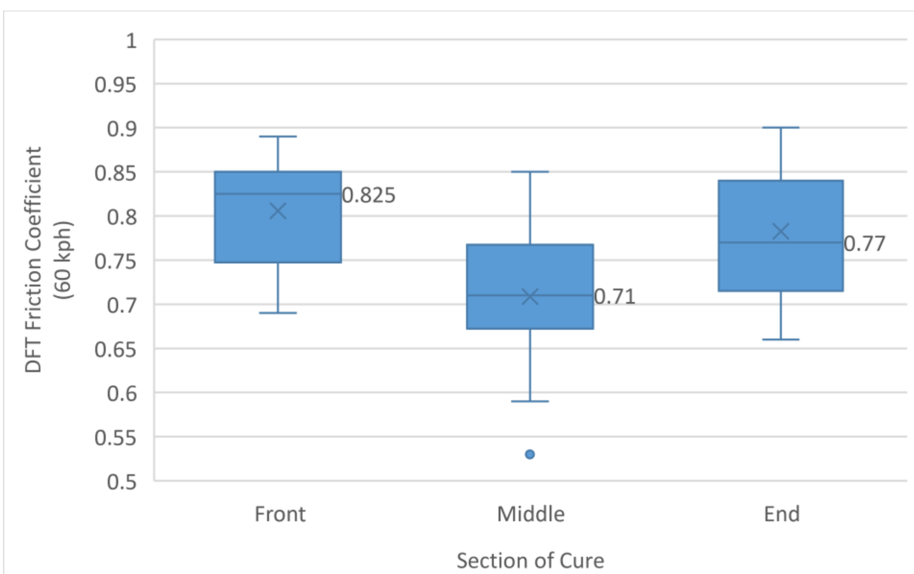


Figure 48 - Illustration. Friction by Section of HFST Rural Curve.

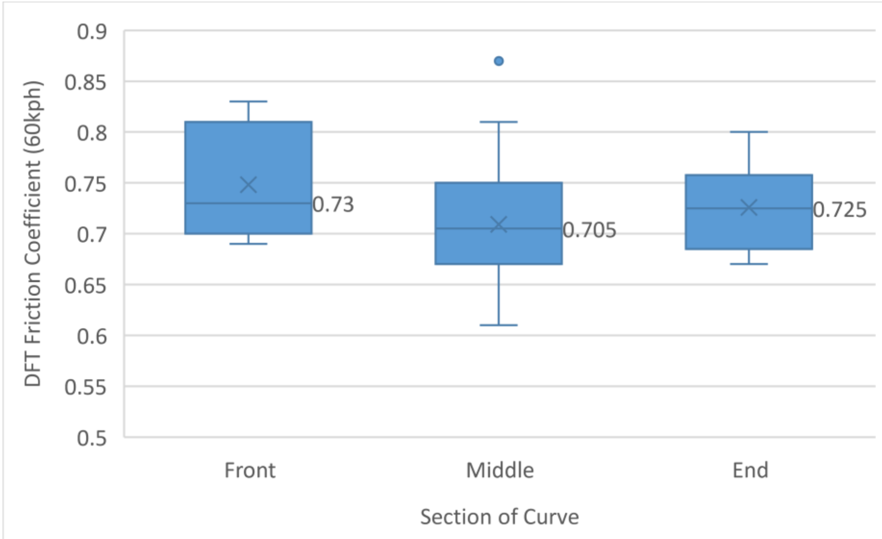


Figure 49 - Illustration. Friction by Section on Urban HFST Curve.

All three figures illustrating friction on the section of curve indicate that the middle of the curve has the lowest friction value. Further analysis of the curves with the lowest friction in the beginning and the end of a curve reveals the following:

1. curves where the lowest friction occurs at the end of a curve usually have traffic lights or intersections at the end of the curve for which the drivers need to brake hard to stop (unlike slowing down while entering a curve) and, consequently, they impart high shear stresses.
2. curves where the lowest friction occurs in the beginning of the curve are observed to have intersections at or before the PC; when vehicles are turning and accelerating, they tend to impart high shear stresses.

Overall, the middle section of the curve is most likely to contain the lowest friction section unless there is strong braking, sharp turning, and strong acceleration requirements, such as STOP signs, traffic lights, intersections, or short sight distances.

This preliminary analysis shows the routinely low friction section in each curve site. In future analyses, the low friction should be analyzed with respect to the normal DFT measurement variation. The normal DFT measurement variation is the difference in friction values between repeated DFT measurements and is typically within 0.03 units based on field measurements. Sites with a friction range more than the normal DFT measurement variation must be analyzed to confirm the findings.

Critical wheel path position with lowest friction and site characteristics contributing to its low friction.

Table 9 presents the results for the lowest friction wheel path position within each curve site. The results for thirteen sites where friction is measured on both wheel paths are shown in Table 9.

The distinct observations from the Table 9 are as follows:

1. Calcined bauxite curves deteriorate faster in the outer radius wheel path than in the inner radius wheel path.
2. Phonolite aggregate curves deteriorate faster in the inner radius than in the outer radius.

Table 9 – Summary of the lowest friction wheel path results.

Site ID	Material	Turn Direction	Low friction wheel path
1-6-P	Calcined bauxite	Left	Outer radius wheel path
2-6-P	Calcined bauxite	Left	Outer radius wheel path
4-6-P	Calcined bauxite	Right	No clear distinction
5-6-P	Calcined bauxite	Right	Outer radius wheel path
7-6-PI	Calcined bauxite	Right	Outer radius wheel path
7-6-PW*	Calcined bauxite	Left	Outer radius wheel path
7-6-PE*	Calcined bauxite	Right	Outer radius wheel path
10-1-P	Phonolite aggregate	Left	Inner radius wheel path
11-1-P	Phonolite aggregate	Left	No clear distinction
15-1-PI	Phonolite aggregate	Right	Inner radius wheel path
16-1-PW*	Phonolite aggregate	Left	Inner radius wheel path
16-1-PE*	Phonolite aggregate	Right	Inner radius wheel path
17-1-P	Phonolite aggregate	Right	No clear distinction

In Figure 50, Figure 51, and Figure 52, bar charts are shown to depict the average, median and range of friction values on both the inner and outer wheel paths. Figures are presented to depict the difference between inner and outer wheel paths for phonolite urban curves, HFST urban curves, and HFST rural curves respectively.

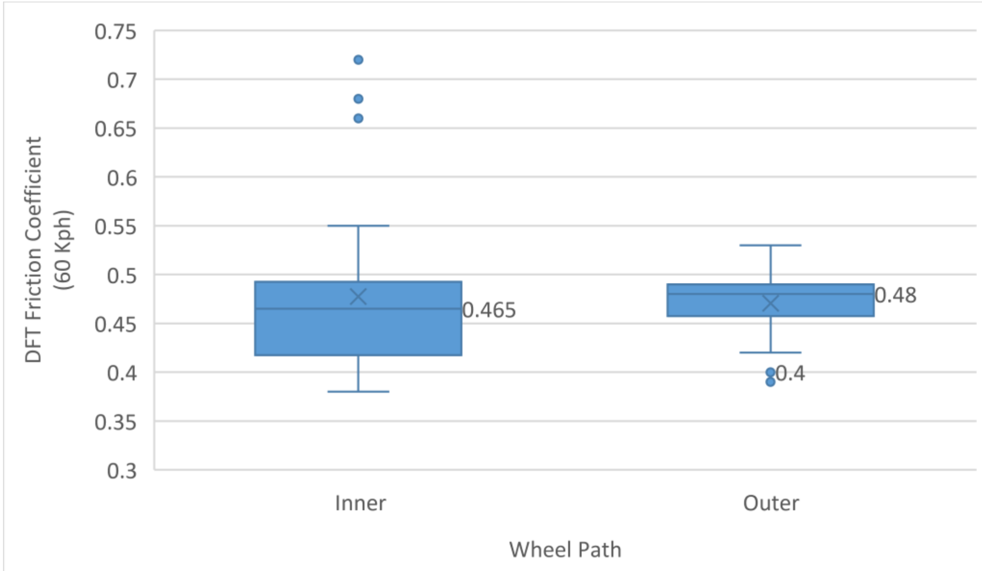


Figure 50 - Illustration. Friction by Inner/Outer Wheel Path on Phonolite Urban Curve.

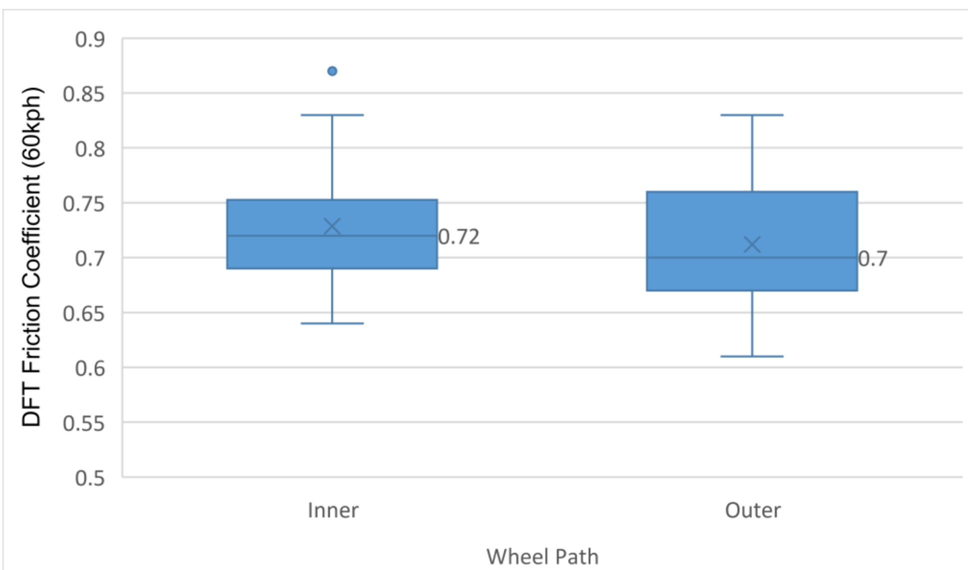


Figure 51 - Illustration. Friction by Inner/Outer Wheel Path on Urban HFST Curve.

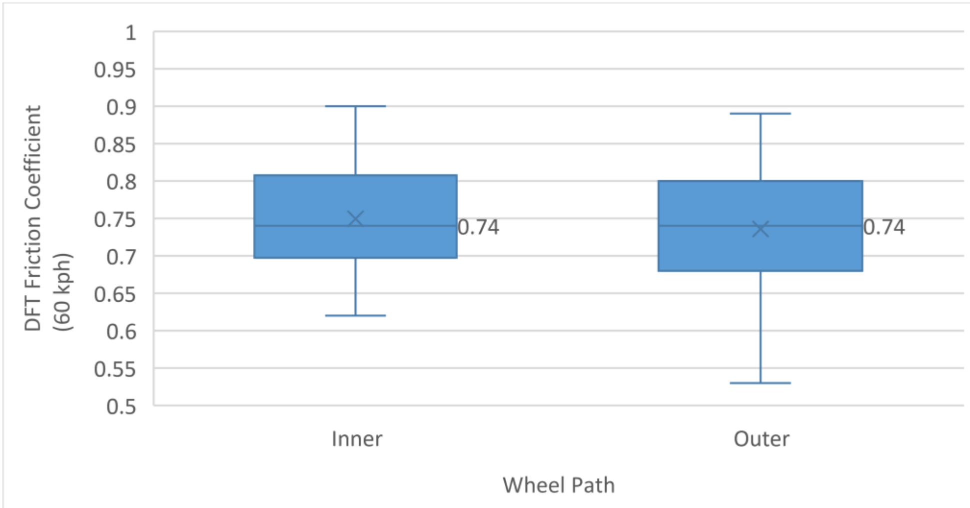


Figure 52 - Illustration. Friction by Inner/Outer Wheel Path on HFST Rural Curve.

Inner wheel path had lower friction values on phonolite cures, while outer wheel path did on HFST curves. Differences in values are minimal. It is hypothesized that higher traffic speeds on HFST sites led to more use of the outside of the curve

Based on vehicle dynamics while negotiating a curve, the highest lateral tire stresses typically are concentrated on the outer radius wheel path under high-speed conditions. This explains why the outer radius wheel path has lower friction in the calcined bauxite sites, all of which have high operating speeds. On the other hand, the stresses are typically concentrated on the inner radius wheel path under low-speed conditions. This can be explained by the shifting of a vehicle's center of gravity towards the lower end of super elevation due to the sloped surface. This explains the inner radius wheel path having lower friction in phonolite TPO sites, especially at the sites (15-1-P, 16-1-PE, and 16-1-PW) located on low-speed urban roadways. A high-speed site with phonolite aggregate (Site ID 10-1-P) also showed lower friction on the inner radius wheel path, but this can be attributed to the distinctly visible aggregate loss in the inner radius wheel path. This preliminary analysis shows the routinely low friction wheel path position in each site. To confirm the critical wheel path with the lowest friction, it is recommended to compare the DFT measurements between the inner and outer wheel paths only if the difference between the DFT measurements on the two-wheel paths is larger than the normal DFT measurement variations.

Spatial variation of DFT friction inside Georgia FIST curve sites and site characteristics impacting the spatial friction variations.

Figure 53 presents the distribution of the friction range (spatial friction variability) for each Georgia FIST site. The average friction range (indicated by ‘x’ in the box pot) is computed from three or more friction ranges calculated at different times at each site. Calcined bauxite sites #1-9 and #25-28 were installed in 2014, and sites #19-24 were installed in 2017. Phonolite sites #11-18 and LWA sites #29-30 were installed in 2017. Based on Figure 53, a few sites stand out (#1, 5, 7, 10, 11, 14, 15, 16, 17, 23, 24, 27, 28); their average friction range is greater than 0.1 DFT units, which means there is non-uniform deterioration within the site. The normal DFT measurement variation is the difference in friction values between repeated DFT measurements and is typically within 0.03 units based on field measurements. The threshold of 0.1 DFT is three times higher than the normal DFT measurement variations observed in the field. Upon detailed investigation of these sites, key site characteristics contributing to non-uniform spatial deterioration are presented in Table 10, along with the site numbers containing these factors.

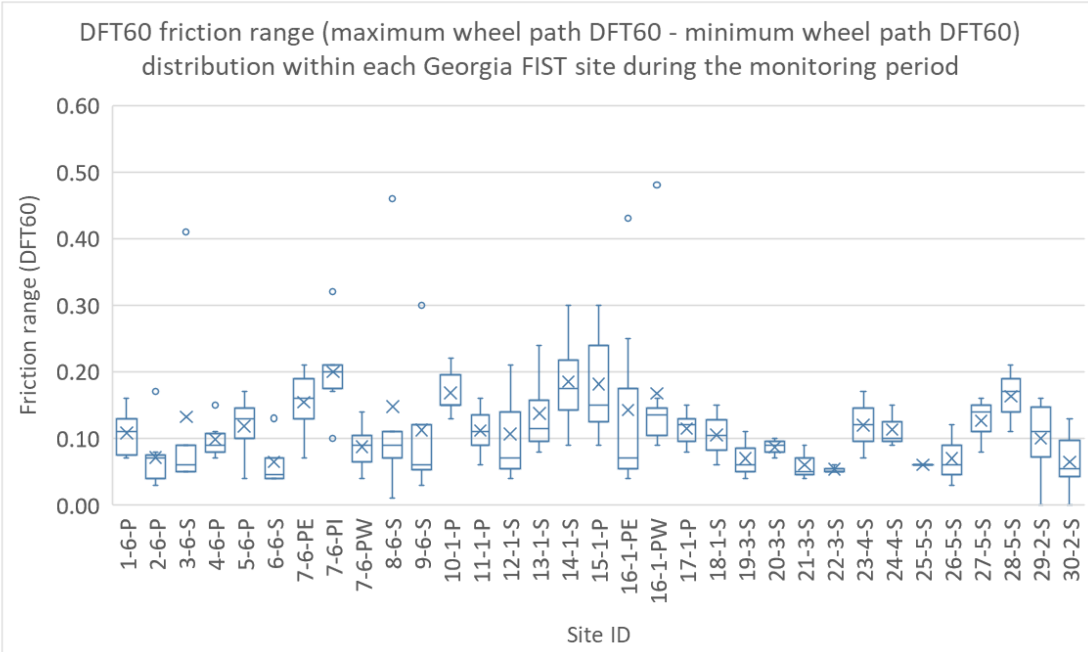


Figure 53 – Graph. Distribution of average friction range for each Georgia FIST site during the monitoring period (2018-2021).

Table 10 – Factors contributing to non-uniform spatial deterioration within the curve site and a list of sites containing these factors.

Non-uniform spatial deterioration contributing factors	Sites #s containing these factors
1) Sharp radius curves (radius < 500 feet.)	5, 7, 10, 14, 15, 16
2) Presence of roadway intersections or driveways	1, 5, 15
3) Site contains reverse or compound curves	7, 10, 14
4) Presence of pavement distresses such as aggregate loss, delamination, aggregate pop-offs, cracking, vegetation in the cracks	10, 11, 27, 28
5) Curve contains inadequate super elevation	23

FIST IN GEORGIA WITH PREMATURE FAILURES AND SITES WITH POTENTIAL CONCERNS

This section presents the friction improvement surface treatment (FIST) sites in Georgia with premature failure and the curve sites with potential concerns. Two premature failure conditions are presented below. The first premature failure condition is asphalt pop-off failure, which is associated with calcined bauxite HFST on SR 119 (Liberty County) and SR 132 (Telfair County) in District 5. The second premature failure condition is aggregate loss associated with the phonolite TPO site in District 1, State Route 2.

Premature failure of calcined bauxite HFST in Georgia

HFST curve sites on SR 119 (Liberty County) and SR 132 (Telfair County), both in District 5, show the asphalt pop-off failure on SR 119 and SR 132, respectively (as seen in Figure 54 and Figure 55).

Figure 54 – Pictures. Asphalt pavement pop-off along with HFST layer in SR 119, Liberty County, GA. (this site has been replaced).

Figure 55 – Pictures. Asphalt pavement pop-off along with HFST layer in SR 132, Telfair County, GA.

The characteristics of asphalt pop-off are that HFST is still bonded to a failed part of the substrate. The curve sites on SR 119 with asphalt pop-off failure have been resurfaced, and the SR 132 sites have not been treated. The asphalt pop-off may have been caused due to application of HFST on old asphalt. According to the field engineer, the asphalt pop-off on SR 119 can be pulled out by hand (Figure 53). The friction measurements at these sites are not available. However, on SR 132 sites with asphalt pop-off failure, the friction value is still high (0.7-0.9) even after 6 years.

Premature failure of phonolite aggregate epoxy in Georgia

The phonolite TPO curves sites on State Route 2 in District 1 show a strong pattern of aggregate loss and low DFT friction values. GDOT needs to monitor them closely and perform additional testing (like measure the texture and friction and record the images). Some of the sites show strong patterns of aggregate loss, which may be caused by lack of bonding between the epoxy and phonolite aggregates or inadequate binder thickness. The low value of friction may be caused by aggregate loss and/or polishing of phonolite aggregate. Figure 56 shows a strong pattern of aggregate loss, and Figure 57 shows a site with aggregate loss on the wheel path, as well as dislodged aggregates on the shoulder. Figure 58 shows an example of aggregate loss on the wheel path on SR 2 without a strong pattern.

Figure 56 – Pictures. Strong patterned aggregate loss in SR 2, Rabun County, GA

Figure 57 – Pictures. Aggregate loss on the wheel path as well as dislodged aggregates on the shoulder.

Figure 58 – Pictures. Wheel path aggregate loss without a strong pattern, SR 2, Rabun County, GA.

SUMMARY OF GEORGIA'S FIST DETERIORATION BEHAVIOR ANALYSIS RESULTS, FINDINGS, AND SUGGESTIONS.

Based on the initial DFT friction data and the data from three years (2018 – 2021) of friction performance monitoring (DFT60 – DFT friction coefficient measured at 60 kph) of 30 sample sites, the following summarizes the findings of the temporal and spatial friction deterioration behavior analysis:

1. **Overall Comparison of FIST Materials**: Calcined bauxite had a high initial friction value with minimal long-term deterioration. Phonolite had a high friction value after installation, but a rapid initial drop within 3 months. After the initial friction drop, phonolite's deterioration stabilized. Light weight aggregate had lower initial friction values at installation and experienced moderate long-term deterioration.

    a. **Calcined Bauxite Friction Condition:** Of the 19 representative calcined bauxite sites out of 342, enhanced initial friction was documented, and minimal long-term deterioration was noticed. Initial friction (right after installation) ranged from .85 to 1 (DFT 60). The initial friction drop was less than 10 % in 3 months, as seen in Figure 29. The overall deterioration, based on 3-6 years of deterioration, is less than 10%, as shown in Figure 28. The current friction condition ranges between .65 and .9 in 2021 (DFT60). Deterioration based on ESAL(s): DFT60 stayed over 0.8 in the early stages of loading (less than 500,000 ESALs). After one million ESALs, most of the calcined bauxite HFST DFT60 measurements dropped below 0.8, and after two million ESALs, friction stabilized at 0.6-0.8.

    b. **Phonolite Friction Condition:** Of the nine representative phonolite sites out of 69, rapid deterioration was noticed. Initial friction (right after installation) ranged between .85 – 1.0, but the initial friction drop was more than 40% in the first 3 months, as seen in Figure 29. After the initial friction drop, phonolite deterioration stabilized, and overall deterioration based on three years of performance monitoring is less than 10%. Current friction on the phonolite sites is between .35 –.55 in 2021 (DFT60). Deterioration based on ESAL(s): DFT60 predominately stayed at 0.5-0,6 in the early stages of loading (less than 500,000 ESALs). After one million ESALs, most of the phonolite TPO friction dropped below 0.5; there is a tangible deterioration trend.

c. **LWA Friction Condition:** Of the two curve sites on the ten-mile installation in 2017, improved friction and moderate deterioration were noticed. Initial friction (right after installation) was about .75 (DFT60). The initial friction drop was less than 10% within three months. The current condition of LWA has friction around .6 (DFT60) in 2021. The overall deterioration, based on three years of performance monitoring, is less than 15%. Deterioration based on ESAL(s): LWA friction performance was stable (0.7 to 0.75) until one million ESALs when friction measurements showed the friction dropping close to 0.6 at 1.2 million ESALs.

2. **Wheel Path vs Non-Wheel Path:** FIST wheel paths deteriorate faster than non-wheel paths (the wheel path is constantly exposed to traffic load). The friction values of the wheel path and non-wheel path are similar in the early stages to the FIST life. However, the wheel path measured lower friction than did the non-wheel path on most sites during the monitoring period.

3. **Critical Section on Curve**: Predominately, the middle section of a curve contains the lowest friction. The average friction range (maximum DFT60 – minimum DFT60) in the 30 FIST sites varies from 0.05-0.20 DFT60. The beginning of a curve contains the lowest friction when vehicles are braking hard to slow down for entering the curve, especially under large speed differential (the difference between the posted speed and the advisory speed) conditions (e.g., greater than 15 mph). An end-of-curve section contains the lowest friction when the curve is followed by intersections, stop signs, or traffic lights. Here, the drivers are braking to respond to the intersection/stopping

condition while simultaneously correcting their steering to come out of the curve, leading to larger stress on the pavement. Outer wheel path positions with longer radii (the higher side of superelevation) contain the lowest friction under high-speed conditions. Inner wheel path positions with shorter radii (the lower side of superelevation) contain the lowest friction under low-speed conditions.

4. **Factors for Deterioration**: Based on the analysis of spatial variability, the following five site characteristics are identified as contributing to non-uniform friction deterioration within the FIST curve sites: 1) sharp radius curves (radius < 500 feet); 2) presence of roadway intersections or driveways; 3) site contains reverse or compound curves; 4) presence of pavement distresses, such as aggregate loss, delamination, aggregate pop-offs, cracking, and vegetation in the cracks; and 5) curve contains inadequate superelevation. Based on the literature review and on interviews with experts, construction quality is also a major factor impacting the friction deterioration. However, construction quality data was not available to analyze its impact on long-term friction deterioration.
5. **Automatic vs Manual Construction:** The HFST construction method (manually installed vs. automatic installation using trucks) did not have substantial differences in their long-term friction deterioration. Manually installed HFST sites in 2014 are still showing high friction after six years.
6. **Recommendations:**
   a. Recommend not using phonolite materials in the future because phonolite materials on State Route 2 have performed poorly. In addition, it is recommended to pay

attention need to phonolite material on State Route 2 because of low friction conditions (.35 –.55 in 2021).

b. Perform an additional assessment monitoring of HFST and LWA to study end-of-life characteristics or early warning signs for fast friction drop rates. The need to assess LWA is not as urgent as HFST. HFST is an epoxy-based material, and its end of life may be associated with a smooth, glossy epoxy surface.

c. Implement FIST on sites with low traffic volumes and high crash rates due to the higher return on investment, since FIST has high performance on sites with low traffic volume.

d. Fill potholes created by asphalt pavement pop-off to improve ride quality.

e. Continue to collect friction data every three months to monitor the safety risks at these sites.

f. Implement and study the deterioration of LWA on more sites, especially at the sites with high friction demands to observe their deterioration behavior. Only two sites with low friction demand were inspected, while 19 calcined bauxite sites were inspected.

g. Assess the crash reduction of LWA and HFST with more LWA sites. Since LWA is at least one-fifth the cost of HFST but had slightly worse friction performance, it is necessary to determine which material is more cost-effective for reducing crashes.

h. Insignificant performance difference between manual and automatic construction methods was observed. Therefore, it is still feasible to apply manual HFST construction for localized, small areas as long as the construction quality is good.

CHAPTER 5. TECHNICAL AND MANAGERIAL INTEGRATED EPOXY-BASED FIST SAFETY MANAGEMENT FRAMEWORK

HFST treatments are increasingly being applied to prevent fatalities at critical locations (such as horizontal curves) that have high friction demand and HFST friction reductions, which are a serious safety concern. Significant HFST friction deteriorations can occur because of the exposure of the smooth epoxy layer as a result of aggregate loss (due to aging related to a reduction in the epoxy's binding capacity and/or the impact of vehicles' tires shear forces acting on the HFST surface), especially towards the end of the HFST service life even with good long-term performance. This creates a hazardous pavement surface for drivers. There are no standard guidelines for when to apply maintenance/replacement treatments (the right time) or when the appropriate treatment (the right treatment type) should be applied to address HFST deterioration. Therefore, needs for enhancing current HFST maintenance and replacement practices include 1) trigger criteria for replacing HFST based on risk and HFST condition, 2) an inventory of maintenance and replacement treatments that address HFST failures, and 3) a treatment and action decision tree based on an overall rating of pavement condition, deterioration, traffic volume, etc. to determine the proper treatment timing and method.

Based on a literature review, a National Survey, field observations, and discussion with experts in NCAT, FHWA, and state DOTs, the current HFST safety management challenges and needs were identified (in Chapter 2). The core contents of the identified needs were extracted into nine technical modules and logically organized into an integrated framework comprising both technical and managerial aspects.

This framework is not only applicable to calcined bauxite HFST but can be scaled up to optimally manage different types of friction improvement surfaces, including all epoxy-based FIST treatments (or thin polymer overlays). Figure 59 shows the proposed framework, which consists of nine modules grouped under the four HFST lifecycle activities; the core objectives of each module are also shown. The core objectives serve as a guide and checklist for transportation agencies to systematically implement network-level HFST safety management cost-effectively. The following section elaborates the technical content in each module and describes the critical actions that serve as a roadmap for researchers and transportation agencies to operationalize the proposed modules. These critical actions are categorized under research, development, and deployment. The nine technical modules are listed below:

1. Site selection and optimal HFST installation limits,
2. HFST binder specification, quality control assessment, and recording of construction data,
3. HFST performance measures,
4. Performance measurement technologies and procedures,
5. Sampling representative sites and testing locations,
6. Performance monitoring frequency,
7. Network-level HFST performance monitoring and rating system,
8. Performance forecasting, and
9. HFST maintenance and replacement (M&R).

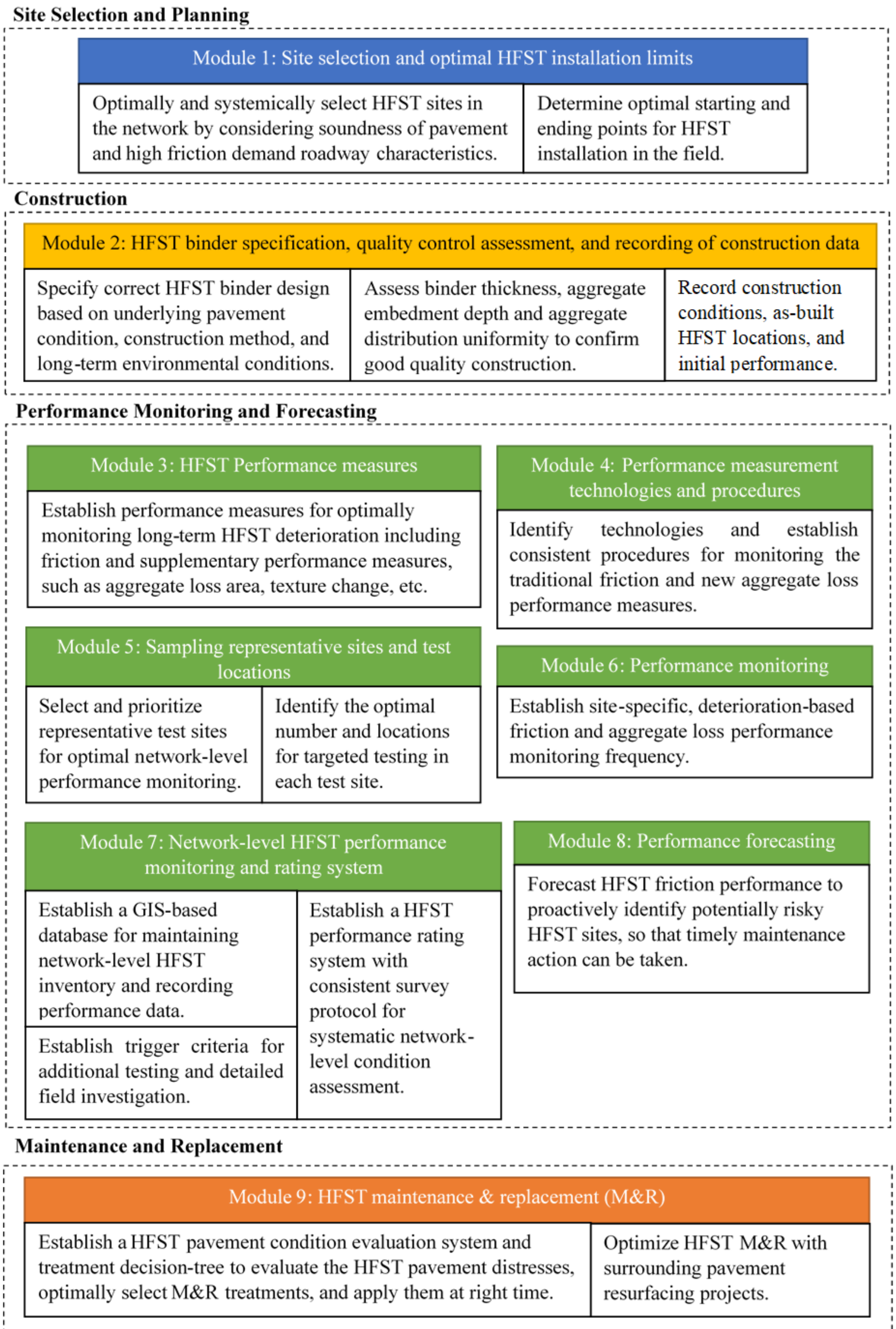


Figure 59 – Diagram. Proposed epoxy-based FIST safety management framework consisting of nine modules and core contents in each module.

MODULE 1: SITE SELECTION AND OPTIMAL HFST INSTALLATION LIMITS

This module primarily covers the HFST-specific activities involved in site selection and planning of HFST installation limits (beginning and ending locations) in the field. The core objectives associated with this module are as follows: 1) to optimally and systemically select sites in the network for HFST treatment that considers soundness of underlying pavements and high friction demand so that longer pavement life can be achieved, and crash reduction benefits can be maximized in the network, and 2) to determine the optimal starting and ending points for HFST installation of the site. The following are the critical actions under the research, development, and deployment categories to operationalize this module:

Research:

Identify and rank the roadway characteristics (including curve geometry, friction, sight distance, driving speed, etc.) associated with high friction demand by performing correlation analysis between run-off road (ROR) and/or wet weather crashes and the roadway characteristics.

Development:

1. Develop a systematic procedure for selecting sites for installing HFST at the network-level by considering ROR/wet weather crashes and high friction roadway characteristics that can be obtained using a ball bank indicator value (a combined indicator to measure the lateral forces experienced by a driver, including side friction, curvature, superelevation, and driving speed) or from curve geometry (including curve radius, and super-elevation).

2. Develop a method to cost-effectively identify the suitable beginning and ending points of HFST installation based on roadway geometry, vehicle dynamics, and existing friction and texture conditions. This can be achieved by analyzing a) low friction locations along the curve site's curve using continuous friction measurement devices, like a Side-force Coefficient Routine Investigation Machine (SCRIM), and b) vehicle dynamics (high lateral forces, vehicle run-off road position, etc.) using vehicle simulation (like CarSIM). Texture can be measured continuously using high-resolution profilometers on the wheel path or 3D line laser scanning.

Deployment:

Develop standard procedures and training materials for transportation agencies to a) select the pavement with good underlying conditions for HFST installation, and b) recommend remedial treatments (like shot blasting) for HFST installation on pavements that have unsound conditions to make them suitable for HFST installation. Recently, several guideline documents for assessing the suitable pavement conditions for HFST have been published by FHWA, FDOT, and NJDOT (FHWA, n.d) (FDOT, 2019) (NJDOT, 2020).

MODULE 2: HFST BINDER SPECIFICATION, QUALITY CONTROL ASSESSMENT, AND RECORDING OF CONSTRUCTION DATA

The core objectives that need to be considered during the construction of HFST in the field are presented in this module; they are as follows:

1. Specify correct binder components (polymer + hardener) and their mix proportions best suited for the underlying pavement and environmental conditions (during construction

and long-term) to achieve good bonding with the underlying pavement and promote HFST longevity. Ensure proper proportioning of binder components and mixing of the binder during the construction process.

2. Assess binder thickness (50-60 mils, depending on the surface), aggregate embedment depth (50-65% inside the epoxy), and aggregate distribution uniformity to ensure good quality construction.
3. Record construction conditions (including installation method, site preparation, temperature, moisture content, binder composition, binder thickness, etc.), as-built HFST limits (beginning and ending HFST mile log or GPS), and initial performance (friction, texture, etc.).

Construction data recorded and highlighted in the third objective is useful for determining the critical sites to monitor and the optimal monitoring frequency for the representative HFST sites. Initial friction and texture data can be used as a baseline to analyze deterioration by comparing these values later in the HFST lifecycle to monitor deterioration.

Development:

Develop automatic and area-based aggregate embedment and uniformity measurement methods using 3D sensing technology. 3D pavement scanning technology can be used to scan the surface of finished HFST surface areas and measure the aggregate height automatically. Nominal/typical aggregate size and average aggregate height from the finished surface can be subtracted to estimate the aggregate embedment depth.

Deployment:

Document the best practices and lessons learned regarding HFST binder design, surface preparation, construction operation, and construction quality assessment to enable HFST to perform well throughout its service life without premature failures.

MODULE 3: PERFORMANCE MEASUREMENT

The core objective of this module is to establish performance measures for optimally monitoring long-term HFST deterioration, including friction and supplementary performance measures, such as the aggregate loss area, texture changes, etc.

HFST aggregate loss has been identified as one of the important factors contributing to reduced friction (Pranav, C. et al, 2021) The authors have performed studies at the NCAT Test Track to study the characteristics of HFST aggregate loss and its relationship with friction. The authors a) identified HFST aggregate loss characteristics (based on appearance and surface texture), including the color contrast between HFST surfaces and their background pavement colors and changes in 3D macrotexture (Pranav, C. et al, 2021), b) characterized HFST aggregate loss using quantitative parameters, such as aggregate loss areas derived from color contrast and 3D surface macrotexture parameters derived from topographical properties (such as aggregate height, shape, and density (Pranav, C. et al, 2021) and c) revealed a strong correlation between DFT friction and aggregate loss areas, and, also, a strong correlation between friction (DFT60) and 3D macrotexture parameters. The authors' study provides sufficient evidence to conclude that HFST friction deterioration is largely controlled by HFST aggregate loss and change in macrotexture.

This is an important finding because DOTs can now view aggregate loss as an alternate performance measure (a supplement to friction measurement) to study HFST friction deterioration. Moreover, HFST aggregate loss parameters (derived from visual inspection or using 2D images or 3D surface data) can supplement current friction measurement practices that use DFTs and are labor-intensive, traffic-disrupting, time-consuming, and sometime dangerous, even with traffic control, to periodically monitor the friction at HFST sites. For example, state DOTs can monitor HFST aggregate loss parameters; if they detect low friction based on a predefined HFST aggregate loss threshold at particular sites, DOTs can perform targeted DFT measurements. Further, HFST aggregate loss performance can be used to determine the suitable timing for taking proactive maintenance actions on HFST sites before the friction loss occurs.

The following are the critical actions under the research, development, and deployment categories to operationalize this module:

Research:

1. Confirm the correlation between aggregate loss parameters and friction by performing additional testing with larger and more diverse data sets (preferably in real-world roadway conditions).

2. Analyze the spatial relationship between the overall site's wheel path aggregate loss area and friction (using locked-wheel skid testers and continuous friction measurement devices); confirm if the strong correlation between aggregate loss percentage area and friction still holds good on a large scale.

Development:

Develop a model and methodology to predict friction using aggregate loss performance measures, such as aggregate loss area and HFST surface macrotexture parameters.

Deployment:

Develop a standard list of performance measures to monitor HFST deterioration (including friction, aggregate loss area, conventional texture parameters like MPD, new texture parameters related to HFST shape, size, and density, etc.) so DOTs can choose the performance measures that fit their agency's needs and resources.

MODULE 4: PERFORMANCE MEASUREMENT TECHNOLOGIES AND PROCEDURES

The core objective of this module is to identify technologies that can be used to establish consistent procedures for monitoring traditional friction and new aggregate loss performance measures. Two potential performance measurement technologies to monitor the HFST friction deterioration are discussed in this section.

First, continuous friction measurement devices (CFMD), like SCRIM devices and Grip Tester devices, have several advantages over traditional friction measurement devices (like the locked-wheel skid tester and the Dynamic Friction Tester). The CFMD has been proven to provide friction measurements that correlates to the traditional measurements (Kouchaki et al., 2018), and can collect friction data at highway speeds, collect friction at multiple spots along the curve (potentially identifying the weakest friction spot), and do not require traffic stoppage. Although promising, the continuous friction measurement devices (such as SCRIM devices) are expensive and may not be cost-effective for periodically monitoring isolated epoxy-based FIST sections scattered throughout a state. However, transportation agencies could rent a SCRIM device for assessing their network-level friction and collect friction data on the epoxy-based FIST sites.

Second, visual inspection, 2D images, and 3D range pavement surface images from cameras and 3D pavement scanning technologies can potentially capture HFST aggregate loss and other distresses (like delamination and asphalt substrate pop-off) in the field, and they can be used to monitor the HFST deterioration. Visual inspection is a practical and cost-effective method to assess the aggregate loss performance based on visual characteristics, such as a) epoxy-based FIST pavement color change, and b) presence of loose aggregates on the shoulder. Local area DOT inspectors can do a windshield survey or an on-field walking survey using these identified characteristics to detect aggregate loss. However, the walk-up surveys are potentially time-consuming and laborious. Therefore, DOTs can leverage their previously collected 2D pavement images (primarily used for pavement condition assessment) or collect the pavement images using low-cost smartphones or dashboard cameras fitted to routine maintenance vehicles to perform aggregate loss assessment. A dedicated engineer at the main office can perform the aggregate loss assessment at epoxy-based FIST sites using these collected images. The engineer can visually review the 2D images of epoxy-based FIST sites and assess the epoxy-based FIST sites' aggregate loss performance. One of the key challenges with manual or 2D image-based visual inspections is that they are subjective and can vary with different inspectors, lighting conditions, how fast the inspector is driving, and the camera resolution and configuration. The subjectivity challenge can be addressed using 3D pavement scanning technologies that can be used objectively to assess aggregate loss and other distresses based on texture characteristics. The observed relationship between highlighted texture parameters and DFT friction shows that texture parameters (including traditional mean profile depth, ridge to valley depth, and HFST topography-based parameters such as average height, angularity, and density) are promising for detecting poor (low) HFST friction performance and can potentially predict low friction at HFST sites [3.11]. Thus, state transportation agencies can leverage their 3D pavement scanning technologies (that state DOTs have already used to collect 3D pavement data) to cost-effectively and regularly monitor HFST friction deterioration.

Based on the above discussion, the following are the critical actions under the research, development, and deployment categories to operationalize this module:

Research:

1. For continuous friction measurement devices, do the following:
    a. Assess accuracy and reliability of CFMDs to measure continuous friction on HFST roadway curves in diverse conditions (including sharp curves, high and low speeds, high and low temperatures, uphill/downhill inclines, etc.), and determine the stable operating conditions for CFMDs to measure HFST friction on the curves.
    b. Comprehensively identify the outlier-causing factors (sudden jerking of the test vehicle's steering wheel, wavering of the test wheel from the wheel path, etc.) and consistency-impacting factors (e.g., seasonal variation, temperature changes, fatigue in the mechanical parts, etc.).
    c. Determine a suitable spatial friction aggregation unit (10m, 100m, 0.1mile, etc.) to aggregate the continuously measured friction values into a single value to represent the overall friction of the epoxy-based FIST site.

2. For aggregate loss performance measurement devices, do the following:
    a. Evaluate the accuracy and feasibility of detecting aggregate loss areas using low-cost camera images (e.g., from a smartphone), which can be collected by DOT maintenance crews during their routine surveys by attaching cameras to their vehicles. The collected images can be reviewed later to assess the aggregate loss based on a standard evaluation protocol.
    b. Evaluate the accuracy and feasibility of leveraging DOTs' previously and currently collected 2D pavement images (primarily used for pavement condition assessment) to visually assess the aggregate loss and establish the aggregate loss deterioration trend.
    c. Evaluate the accuracy and feasibility of using continuous, highway-speed, and, preferably, full-lane 3D pavement sensing technology (such as LCMS, which is already commonly used by state DOTs for pavement condition evaluation) to measure aggregate loss texture parameters.
    d. Determine the spatial data (HFST aggregate loss parameters) aggregation method and units (linear or area based, 100 mm or 1 m or larger dimensions) that truly reflect the vehicle tire and pavement interaction areas so that the relationship between a site's overall friction and the HFST aggregate loss parameters can be analyzed. For example, analyze the sensitivity of texture parameters, especially their computation length and area, their statistical distribution and aggregation (such as mean, median, model, etc.) and their corresponding impact on friction.

Development:

1. For continuous friction measurement devices, do the following:
    a. Develop suitable methods to remove outliers and to correct the variations in the CFMD-measured friction values at different time stamps.
2. For aggregate loss performance measurement devices, do the following:
    a. Develop methods to automatically assess HFST aggregate loss using 2D sensors (including smartphone cameras, Go Pro cameras, etc.). Images captured with the 2D sensors can reduce the dependency of on-field manual surveys to measure aggregate loss.
    b. Develop methodologies to accurately measure pavement texture quickly and continuously on the entire site using laser profilers and 3D scanning technologies.

Deployment:

1. Develop standard operating procedures (SOPs) for DFT, locked-wheel skid testing, CFMD, 2D imaging, and 3D scanning technologies to measure friction and aggregate loss on HFST sites.
2. Establish an aggregate loss baseline using devices like smartphones, GoPro cameras, and aggregate loss performance measures (aggregate loss areas) to compare the loss of aggregate over different time stamps. This is to allow change in friction to be correlated with changes in aggregate loss.

MODULE 5: SAMPLING REPRESENTATIVE SITES AND TESTING LOCATIONS

The core objectives of this module include 1) selection and prioritization of representative test sites for optimal network-level performance monitoring and 2) identification of the optimal number and locations for targeted testing in each test site.

To prioritize representative sites, first the HFST sites (limited numbers) in the network that are representative of the rest of the sites need to be identified and grouped; they should have similar characteristics (such as materials used, ages, construction types, traffic volumes, etc.) and exhibit similar deterioration behaviors. After grouping, representative HFST sites must be selected and prioritized for monitoring in each group. HFST sites that have extreme deterioration conditions (such as a high truck volume, high friction demand, etc.) in the group can be selected and prioritized for monitoring because such sites alert transportation agencies to the potential deterioration of other sites in the group.

Within each representative site (which are several hundred feet long), the optimal number of targeted locations need to be identified to monitor friction performance. A minimum requirement is to measure friction in the wheel path locations on the curve where there is a high potential for aggregate loss due to high shear stresses caused by vehicle acceleration, braking, and turning actions (such as at the beginning of a curve, at the middle of a curve, at the end of a curve, at the intersection point on a curve, etc.). In addition, the non-wheel path location can be collected to infer the friction deterioration value by comparing the friction difference between the wheel path and the non-wheel path.

The following are the critical actions under the research and development categories to operationalize this module:

Research:

1. Determine and rank the factors (binder composition, aggregate material used, construction quality, construction method, age, environmental conditions, roadway geometry, etc.) that significantly impact HFST deterioration performance by analyzing a diverse range of these factors.
2. Identify critical curve sections and wheel path positions inside each site by using continuous friction measurement devices (such as SCRIM devices) and using vehicle simulation (such as CarSIM). CarSIM's vehicle simulation can be used to explain the locations of low friction in a curve site based on vehicle dynamics (e.g., high acceleration and deceleration spots, lateral forces, etc.).

Development:

1. Develop a systematic procedure to group HFST sites and select representative sites from the group for optimal network-level performance monitoring. The expected steps are a) to collect the HFST site information, b) to rank the significant factors from the site information, c) to group HFST sites based on the ranking of these factors, d) to set constraints, such as the number of groups and representative sites in each group, and e) to remove premature failure sites from the grouping.
2. Develop low-cost automatic network-level screening methods using 2D images or 3D technologies to determine targeted sites for testing.

MODULE 6: PERFORMANCE MONITORING FREQUENCY

The core objective of this module is to establish the site-specific HFST friction and aggregate loss monitoring frequency for different scenarios (including high deterioration vs. low deterioration, high traffic vs. low traffic, etc.).

Based on the National Survey and interviews with experts, the service life of HFST depends on the construction quality and the underlying pavement condition. Poor quality construction and unsound pavement conditions can lead to premature failures of the HFST sites. Such sites need to be monitored frequently. Well-constructed HFST sites show good performance for several years before deteriorating. For HFST sites that are performing well, it is optimal to monitor them at a low frequency (e.g., once in 2-3 years) during their early life. However, once HFST sites start showing signs of deterioration, it is optimal to monitor them at a higher frequency (e.g., once in 0.5-1 year) to proactively identify safety concerns and address them.

The monitoring frequency for each site would depend on performance deterioration behavior. Slowly deteriorating sites can be monitored less frequently than quickly deteriorating sites. Deterioration is impacted by different site characteristics, including age, materials, construction quality, traffic and truck volume, loading on the site, environmental conditions, roadway characteristics (such as curve radius, etc.), severity of aggregate loss, and other distresses (cracking, potholes, delamination, etc.). For example, sites that are older than eight years and have high truck volumes need to be monitored more frequently (every six months) than sites with low truck volume (once a year). However, additional studies are required to establish the exact monitoring frequency for sites with different site characteristics.

The following are the critical actions under the research and deployment categories to operationalize this module:

Research:

Determine the site-specific HFST friction and aggregate loss monitoring frequency by analyzing the friction and aggregate loss deterioration (rate of change) at the HFST sites with different site characteristics (material used, construction quality, age, traffic volume, environmental conditions, etc.).

Deployment:

Develop training materials recommending the performance monitoring frequencies for different site characteristics, deterioration, and severity level of deterioration.

MODULE 7: NETWORK-LEVEL HFST PERFORMANCE MONITORING AND RATING SYSTEM

A cost-effective HFST performance monitoring and rating system at the network level is urgently needed to support systematic performance monitoring and safety management. The main objective of this module is to establish 1) a GIS-based database for maintaining network-level HFST inventory and recording performance data, 2) an HFST performance rating system with consistent survey protocols for systematic network-level condition assessment, and 3) the trigger criteria for additional testing and detailed field investigation.

The GIS-based database system for managing HFST inventory and performance data is needed to store the key information of the HFST sites (including as-built location, materials, installation date, age, performance measure values, etc.) and present it in a GIS map. DOTs can identify the sites with different performance levels in the network using a color-coded representation (such as green for good, yellow for fair, and red for critical), as illustrated in Figure 60. This information is useful for assessing the overall condition of the HFST sites in the network and prioritizing monitoring activities (adjusting the monitoring frequency or performing a detailed investigation).

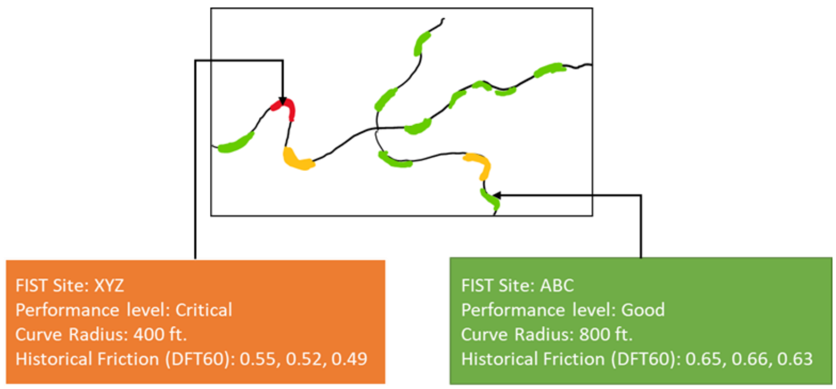


Figure 60 – Diagram. An illustration of color-coded visualization of FIST performance levels in the network and the site characteristics.

The HFST performance rating system with a consistent survey protocol is needed to evaluate one or more performance measures (such as friction, the aggregate loss area, and texture parameters) and to assign a performance level/rating to represent the condition of the HFST site. The performance measure parameters, such as friction coefficients, aggregate loss percent areas, and the deterioration (percentage change in two previous time stamp measurements) can be used to compute a composite performance level (like good, fair, critical) or a 0-100 rating for each site. The key components of the survey protocol must address the following:

1. What to assess? This includes performance measure and extent, such as friction or loss of aggregates (based on color contrasts or texture parameters and measured by area, by linear foot, or by percentage).
2. Where to assess? The examples include travel lane wheel paths, roadside shoulders, middle sections of curves, cross slope transition sections, etc.
3. How to assess performance measure? The examples include friction measurement devices, visual inspection, and 2D and 3D technologies to assess aggregate loss, etc.

Finally, performance-based trigger criteria are needed to provide guidance on when to increase the testing frequency or perform a detailed investigation of the HFST sites based on the friction and/or aggregate loss deterioration attributes and/or the performance level/rating. The trigger criteria can be implemented in the form of a performance monitoring decision matrix. Four recommended elements of this decision matrix include the performance measure (friction, aggregate loss), deterioration attributes (performance measure value and rate), trigger criteria (threshold values of the performance measure and deterioration attribute), and action steps. An example of a decision matrix (based on the DFT coefficient and aggregate loss percentage area) with the trigger criteria and action steps is shown in Table 11.

Table 11 – Example decision matrix to provide guidance on performance monitoring frequency.

Performance measure	(DFT coefficient, Mu), (aggregate loss percentage, ALP), others*	
Deterioration attribute	Trigger Criteria	
Value	(Mu > 0.50), ALP < 30% of wheel path	(Mu < 0.50), ALP > 30% of wheel path
Rate		Annual Mu drop or ALP increase > 10%.
	Action steps	
	Continue low frequency monitoring frequency.	Switch to intensive high frequency monitoring – 3 months.
*Others include texture-based indicators (like MPD), performance rating, etc.		

The following are the critical actions under the research, development, and deployment categories to operationalize this module:

Research:

Identify early warning signs and develop maintenance trigger criteria by analyzing the friction and aggregate loss deterioration attributes characterizing “end-of-life” HFST performance, such as 1) dropped performance value (severity), 2) performance drop percentage (difference between two consecutive measurements), and 3) performance drop rate (during multiple measurements).

Development:

1. Develop a network-level, cost-effective HFST performance monitoring and rating system (including visual inspection and 2D imaging using smartphones to proactively identify potentially unsafe sites) and support a risk-based, targeted, and optimal sampling and monitoring strategy.
2. Build a GIS-based data storage and management system to store, track, process, and analyze site performance data for successful implementation of the recommended HFST condition monitoring and rating system.

Deployment:

1. Develop training materials for DOT engineers to implement the cost-effective HFST performance monitoring and rating system.
2. Develop training materials for DOT engineers to apply the performance monitoring decision tree, perform additional testing, and proactively identify potentially unsafe sites for performing detailed field investigations.

MODULE 8: PERFORMANCE FORECASTING

The core objective of this module is to forecast HFST friction performance to proactively identify potentially risky HFST sites so that timely maintenance action can be taken. The critical action required to operationalize this module is to develop an accurate and reliable HFST friction forecasting model using friction (based on a skid number determined by a locked wheel skid tester), supplementary measurements (such as aggregate loss, texture depth, aggregate loss area covered, etc.), and advanced techniques (such as machine learning).

MODULE 9: HFST MAINTENANCE & REPLACEMENT (M&R)

The core objectives of this module include 1) establishing an HFST pavement condition evaluation system and a treatment decision tree to evaluate the HFST pavement distresses, optimally select M&R treatments, and apply them at the right time and 2) optimizing HFST M&R with surrounding pavement resurfacing projects. The following are the critical actions under the research, development, and deployment categories to operationalize this module:

Research:

Identify suitable HFST maintenance and replacement treatment alternatives. One of the approaches is applying existing asphalt pavement maintenance treatments on deteriorated HFST sites and synthesizing their successes and failures.

Development:

1. Develop an inventory of deployable HFST maintenance treatments to address the failures on the HFST sites.
2. Develop an HFST pavement condition evaluation system to evaluate the pavement distresses (including aggregate loss, cracking, delamination, etc.) based on their extent and severity.
3. Develop a treatment decision tree based on 1) overall rating, 2) the friction coefficient and aggregate loss measures and their deterioration (e.g., friction dropped value, aggregate loss rate, etc.), 3) pavement and site conditions (such as age of underlying pavement, cracking, rutting, and other distresses, etc.), and 4) traffic conditions.

Deployment:

1. Document best practices and lessons learned for treating the failed HFST sites.
2. Develop training materials for DOT engineers to perform HFST pavement condition evaluation.
3. Develop strategies and plans for optimizing the HFST M&R treatment by coordinating with surrounding resurfacing projects' schedules.

SUMMARY AND REFINEMENT

HFST friction deterioration is a serious safety concern, especially since HFST is typically applied on critical locations with high friction demand, such as horizontal curves. Therefore, HFST needs to be installed, operated, and managed safely and cost-effectively to ensure the HFST sites are safe throughout their lifecycle activities. However, HFST application and safety management involves different life cycle activities (such as site selection and planning, construction, performance monitoring, and maintenance and replacement) and complex and challenging technical components (including site selection criteria, construction quality control, performance measures, maintenance trigger criteria, etc.). The contributions of this chapter are as follows:

- Provided insight and understanding of the technical and managerial challenges and identified the needs involved in each of the complicated HFST life cycle activities, including site selection and planning, construction, performance monitoring, and maintenance and replacement.
- Developed a comprehensive technical and managerial integrated framework with 9 modules covering the HFST lifecycle activities; researchers and DOTs can now holistically see the different components of HFST life cycle activities and systematically and cost-effectively manage HFST safety issues. This framework can also be used as a checklist of items for agencies to ensure good quality HFST installation and effective management.
- Outlined a roadmap of the needs for research, development, and deployment of improvements to current HFST practices.

We make the following recommendation to further refine the proposed framework/roadmap, and enhance current HFST practices:

- Develop HFST safety management implementation guidelines (including site selection, construction quality control specifications, performance measures, measurement technologies and methods, selection of testing locations and positions, determination of performance testing frequencies, and determination of performance evaluation and trigger criteria thresholds for maintenance activities).
- Conduct a national level workshop, organized by FHWA, to share the proposed framework and receive feedback to further refine the proposed framework and incorporate HFST best practices and lessons learned from other transportation agencies.
- Form a committee at the national level to further refine the proposed roadmap and prioritize the key actions for enhancing HFST safety management practices.

CHAPTER 6. GUIDE FOR GEORGIA'S FIST PERFORMANCE MONITORING AND MAINTENANCE PROGRAM

As discussed in Chapter 3, GDOT has installed 421 FIST curve sites (342 calcined bauxite HFST, 69 phonolite TPO, and 10 lightweight aggregate chip seal). There is an urgent need to proactively identify HFST sites that show signs of critical deterioration (including low friction, rapid friction deterioration, extensive aggregate loss, etc.) and apply suitable treatments at the right time before the site becomes hazardous for roadway users, especially because there are 411 aging epoxy-based FIST sites (all with calcined bauxite HFST or phonolite TPO). Since the primary goal for transportation agencies like GDOT is to cost-effectively minimize the safety risk for roadway users, there is a need to establish a long-term performance monitoring and maintenance program to safely and cost-effectively manage these epoxy-based FIST sites. The primary objective of this network-level long-term performance monitoring program is to maximize GDOT's understanding of network-level FIST friction and safety deterioration (at sites that have reached their end of life or that show signs of failure) at minimal cost. This chapter utilizes the modules associated with the performance monitoring and condition evaluation life cycle activities of the integrated framework (discussed in Chapter 5) to devise an optimized strategy and develop implementation steps for Georgia's FIST long-term performance monitoring.

This chapter recommends an optimized strategy in Section 6.1 for GDOT's HFST (and FIST) long-term performance monitoring; it recommends monitoring representative FIST curve sites using the Dynamic Friction Tester (DFT) and, also, monitoring the remaining sites in the network using cost-effective supplementary measurements (such as the loss of aggregates discussed in the integrated framework). Section 6.2 presents the recommended guidance for Georgia's network-level HFST (and FIST) long-term performance monitoring and maintenance program, which is based on the integrated framework. The recommended guidance consists of eight steps and discusses a systematic approach for monitoring representative FIST curve sites (using the DFT) and the remaining sites in the network (using cost-effective supplementary measurements, like loss of aggregates).

OPTIMIZED STRATEGY FOR GDOT'S NETWORK-LEVEL FIST LONG-TERM PERFORMANCE MONITORING

This section recommends an optimized strategy for GDOT's network-level FIST long-term performance monitoring by evaluating five performance measurement alternatives (including friction and aggregate loss measurement) based on their potential for network level performance assessment and immediate implementation potential. Currently, DFT is the only technology used by GDOT to measure friction on FIST sites. Continuous friction measurement devices (CFMD) and potential aggregate loss measurement methods (including visual inspection, 2D imaging, and 3D pavement scanning for macrotexture) are proposed in the integrated framework for long-term FIST performance monitoring. A combination of the performance measures (friction and aggregate loss), and measurement technologies yields the following five performance measurement alternatives to monitor the FIST sites:

1) Friction measurements with DFT
2) Friction measurement with CFMD
3) Aggregate loss measurements with visual inspection

4) Aggregate loss measurements with 2D imaging
5) Aggregate loss measurements with 3D pavement scanning for 3D macrotexture (using 3D pavement data already collected by GDOT for inventorying pavement distresses)

Friction measurement using DFT: Friction measurement with DFT is already being used by GDOT for monitoring selected FIST sites to critically assess their long-term performance. However, DFT measurements have several limitations, including expensive traffic control measures, time-consuming measurements, labor intensive actions, and traffic congestion due to lane closures. In addition, there are a limited number of DFT devices and operators to measure friction on all the FIST sites. On the bright side, several FIST sites were installed under six different FIST construction projects and likely have similar ages, materials, construction characteristics, environmental conditions, and long-term deterioration behaviors. Therefore, representative sites in each group can be selected for monitoring deterioration in each group. It is assumed the remaining sites in each group have similar deterioration behaviors and would reach the end of their lives at approximately the same time. Such a strategy would help GDOT optimally monitor only a limited number of representative sites in the network using DFT. When the friction drops critically, all the other sites in the group can be tested.

Friction measurement using CFMD: Although continuous friction measurement devices (CFMD), like a SCRIM device and a Grip Tester, are not currently used by GDOT, they have several advantages over DFT spot measuring: they can collect friction data at highway speeds, collect friction data at multiple spots along the curve (potentially identifying the weakest friction spot), and do not require traffic stoppage. Although promising, the continuous friction measurement devices (such as a SCRIM device) are expensive; they may not be cost-effective for monitoring isolated epoxy-based FIST sections scattered throughout the state. However, if the CFMDs are utilized for statewide routine friction data collection, they could eventually cover the FIST sites. The CFMDs' accuracy and consistency in measuring FIST friction on the curve sites need to be evaluated prior to deploying them.

Aggregate loss measurement: On the other hand, all performance measurement alternatives based on aggregate loss measurement can be used to assess the FIST sites in the network. Although aggregate loss is not a direct safety risk indicator like friction, it can be used to screen candidate sites for conducting targeted friction testing based on the aggregate loss percentage and its observed deterioration. Aggregate loss measurement with visual inspection is implementable immediately. Meanwhile, the aggregate loss measurement with 2D imaging and 3D pavement scanning for macrotexture still needs technological development and validation. Unlike friction measurement with a DFT, which cannot be operated throughout the state due to the limited number of devices and operators, visual inspection can be performed statewide by local District or Area engineers if consistent FIST performance assessment protocols and training are provided. Based on their assessment of aggregate loss, a limited number of sites can be identified for targeted friction testing using the DFT.

Based on the evaluation of the performance measurement alternatives, the following optimized strategy is recommended to GDOT for long-term FIST performance monitoring:

1) Monitor representative FIST sites (e.g., the 30 test sites) using friction performance measurements that are already being used (e.g., DFT). Representative FIST sites include sites with high risks, such as sharp curves, sites with low friction, and test sites to observe the insight of deterioration behavior and symptoms before fast deterioration.
2) Monitor the remaining FIST sites (e.g., 391 sites) with aggregate loss performance measures using visual assessment (or 2D imaging and 3D laser technologies).

IMPLEMENTATION GUIDE FOR GEORGIA'S NETWORK-LEVEL FIST LONG-TERM PERFORMANCE MONITORING PROGRAM

This guide is recommended based on a) the technical and managerial integrated framework discussed in Chapter 5, b) three years of DFT measurements and field performance observations that have been performed on Georgia's test sites, c) HFST National Survey outcomes, d) HFST long-term performance monitoring on the NCAT test track, and e) a literature review and interviews with DOT and FHWA engineers. This guide provides recommendations on performance measures, testing locations and positions, frequencies, and performance evaluation and trigger criteria thresholds in support of the optimized FIST long-term performance monitoring system, which uses DFT and aggregate loss performance measures. Thus, GDOT can better establish its FIST long-term performance monitoring and maintenance program using internal resources and/or external contactors.

This guide presents a systematic approach with the following eight steps based on the performance monitoring and condition evaluation technical modules discussed in the integrated framework:

- Step 1: Select the performance measures and the measurement method.
- Step 2: Group curve sites with similar materials, ages, construction methods, and site characteristics in networks that have similar performance and deterioration behaviors.
- Step 3: Select the representative sites within each group to perform targeted testing.
- Step 4: Select critical section and critical wheel path positions within curve sites to measure performance.
- Step 5: Determine the number and locations of the friction measurements within critical sections and critical positions.
- Step 6: Determine the testing frequency for routine monitoring and intensive monitoring.
- Step 7: Establish the trigger criteria for intensive monitoring and detailed field investigations based on observed friction/aggregate loss deterioration attributes.
- Step 8: Determine follow-up actions based on the detailed field investigation.

Steps 2-5 are recommended especially for monitoring representative sites using DFT. Steps 1 and 6-8 apply to monitoring representative sites using DFT and monitoring the remaining sites based on aggregate loss. The following are the detailed descriptions of each of the eight steps and recommendations for immediate implementation and future work.

Step 1: Select performance measure and measurement method.

For monitoring representative sites (the 30 test sites previously identified), it is recommended to use a friction coefficient as a performance measure and DFT as the measurement method. GDOT currently specifies the DFT friction coefficient as the performance measure for pre-installation testing and post-installation quality acceptance testing (GDOT Special Provision Section 419 -- High Friction Surface Treatment). To be consistent with the GDOT specifications for friction testing, continuing to use the DFT is suggested for the long-term FIST friction performance monitoring of the 30 representative sites. Besides being consistent with GDOT's specifications, the DFT is essential for continuing the existing study (performed in this research for 3 years) of 1) the real-world FIST friction performance and its deterioration behavior, 2) feasibility analysis of using lightweight aggregate (LWA) chip seal as the FIST alternative in Georgia, and 3) development of a performance forecasting model for the epoxy based HFST and phonolite TPO and for the LWA.

For monitoring the remaining epoxy-based FIST sites in the network (411-30 = 381 sites), it is recommended that cost-effective supplementary performance measurements, like loss of aggregates, be used. Assessing the FIST aggregate loss based on visual inspection with the help of local engineers is recommended. Local engineers would assess 1) the aggregate loss area on the wheel paths (based on color contrast and smoothness difference between FIST aggregates and background pavement surfaces), and 2) the presence of loose aggregates on shoulders/rumble strips. To support immediate implementation of aggregate loss assessment using visual inspection, it is recommended that a standard survey protocol for assessing epoxy-based FIST aggregate loss be developed to include the following:

1) What to measure (e.g., the loss of aggregates or color contrast measured by area, by linear foot, or by percentage),
2) Where to measure (e.g., travel lane wheel path and roadside shoulder, PC, PT, or middle of curve),
3) How to measure cost-effectively and sustainably (e.g., conduct visual inspection by local area engineers and take photos using low-cost smartphones and consistent procedures so the images taken at different times can be compared to determine the loss of aggregate propagation).

For future cost-effective and automatic implementation of aggregate loss assessment, it is recommended that a network-level cost-effective epoxy-based FIST performance monitoring and rating system (including visual inspection and 2D imaging using smartphones and 3D sensing technologies) be developed to proactively identify potentially unsafe sites, to perform detailed field investigations, and to select epoxy-based FIST sites for treatment. This epoxy-based FIST performance monitoring and rating system is to be similar to GDOT's COPACES rating system for network level pavement condition evaluation. For implementing the recommended system, low-cost smartphones, 2D imaging (based on contrasting color appearance), and 3D laser technologies with automatic extraction of loss of aggregates and 3D texture (e.g., mean profile depth, etc.) need to be explored and developed. In addition, continuous friction measurement devices (like a SCRIM device) also need to be explored to develop a network level friction measurement and standard operating conditions; a friction assessment procedure needs to be established to measure epoxy-based FIST friction, especially on curved roadways.

Step 2: Group curve sites with similar materials, ages, construction methods, and site characteristics into networks that have similar performance and deterioration behavior.

Based on the current data collection design (for selecting 30 representative curve sites, as discussed in Chapter 3), the following seven factors are recommended for grouping FIST sites:

1. FIST material used (calcined bauxite HFST; phonolite TPO; LWA),
2. Age of existing FIST,
3. Construction method (automatic or manual),
4. Geographical regions (urban and rural, mountain area and plains;),
5. Environmental conditions (hot and wet climate, cold and dry climate, temperature going below the freeze point, etc.),
6. Traffic volume (e.g., AADT < 1000; 1000 <=AADT< 5000; AADT >= 5000, etc.); and
7. Curve geometry, including radius (e.g., < 500 ft., > = 500 ft.), and deviation angle (e.g., < 50 degrees or > 50 degrees).

To implement the grouping, taking a stage-wise approach in which larger groups of FIST curve sites are identified first and then split into subgroups is recommended. An example is presented for grouping calcined bauxite HFST sites in GDOT District 6 using three stages of grouping as follows:

- Stage 1 grouping: HFST curve sites are grouped broadly in this stage based on materials used, ages, environmental conditions, in the same order, which, respectively, covers larger groups of sites. For example, in District 6, the material used is calcined bauxite epoxy only, so all the sites form one group. The group is further divided based on the age (i.e., sites installed in 2014 and sites installed in 2016), resulting in two distinct groups. Since GDOT's HFST contracting projects involve installation of multiple HFST sites in the same region, both groups contain sites with similar environmental conditions. This constitutes the first stage of grouping.
- Stage 2 grouping: Due to the large spatial distribution of each group, the traffic volumes (and truck volume) are not similar. Sites with high traffic volume deteriorate faster, especially in their early life and as they advance toward their terminal life. So, the two groups are further divided into fast deterioration and slow deterioration sites based on traffic volume (AADT < 5000, AADT > = 5000). Thus, the two groups in Stage 1 are divided into four groups based on similar characteristics.
- Stage 3 grouping: Sharp and short curves typically experience larger amounts of stress on the pavement during turning and, therefore, deteriorate faster than long and flat curves. Therefore, within each group from Stage 2, sites with sharp, short curves (curve radius less than 1000 feet, deviation angles greater than 20 degrees, curve lengths less than 1000 feet) are grouped together, and flat, long curves are grouped together. Thus, eight groups of FIST sites with similar deterioration behaviors are created in District 1.

For enhancing the grouping of FIST sites,

1) It is recommended that the sites be grouped based on 1) truck volume and 2) geometrical side friction demand in Stages 2 and 3. In the preliminary findings of factors impacting long-term friction deterioration, it was noted that truck volume and geometrical side friction demand (based on speed limit, curve radius, and deviation angle) have high correlation with friction deterioration.
2) It is recommended that the sites associated with premature failure causal factors be separated from the long-term monitoring sites, as they can bias the deterioration performance of the group. The prior pavement condition (such as age, cracking extent, macro texture, surface, and subsurface drainage, etc.) and construction quality (such as aggregate embedment depth, epoxy thickness, pavement moisture prior to installation, etc.) have significant impact on deterioration and cause premature failures, such as asphalt pavement pop-off, epoxy layer delamination, aggregate loss, and cracking.

Step 3: Select the representative sites within each group to perform targeted testing.

After grouping the sites, it is recommended that sites that have extreme deterioration conditions (including highest truck volume, highest friction demand, steep vertical grades, etc.) be selected as representative sites for long-term monitoring because these representative sites deteriorate faster and have a relatively high safety risk. Deterioration observed from these sites can alert GDOT to the potential deterioration of other sites in the group. GDOT can then prioritize and evaluate the condition of other sites within the group, although they will, at that point, have relatively less extreme deterioration conditions. Currently, the 30 test sites among the 411 FIST curves are selected as representative sites for long-term performance monitoring (using DFT). Continued monitoring of these sites is recommended. Within the selected representative sites, if the FIST is applied in both travel directions of the curves, monitoring performance in the direction that contains the upward grade will be monitored. In addition, selecting the travel direction in which the trucks are fully loaded is recommended for monitoring the performance.

Based on the field observations, few phonolite FIST sites on SR 2 are showing signs of increasing aggregate loss. Only State Route 2 sites are being monitored in the current plan; however, there are additional phonolite FIST sites on State Routes 51, 77, and 172 that have not been monitored previously. Therefore, it is essential to monitor DFT friction in at least three other phonolite FIST sites on state routes. Based on this step, select one representative site with high truck volume and friction demand on State Routes 51, 77 and 172.

Step 4: Select critical section and position within the curve site to measure performance.

DFT tests require stopping traffic to conduct the tests, which causes congestion on the roadways. Moreover, it is time-consuming and labor-intensive to measure DFT friction at multiple spots on an entire curve (usually 500 feet or more). Therefore, it is necessary to reduce the number of tests and the time spent on each site for performing DFT tests so that a roadway can be opened to traffic quickly. Therefore, it is required to 1) identify critical sections within a curve to narrow the length of the curve assessed with DFT, and 2) identify critical positions within the critical section to perform DFT tests.

This research identified the critical sections and critical wheel path positions based on the analysis of limited DFT tests on the representative sites. The preliminary findings are presented in Chapter 4. It is recommended to continue collecting DFT measurements along the entire curve and both wheel paths to confirm the findings and study the future deterioration behavior. In addition, the critical section and position in the curves need to be further identified and confirmed by analyzing the lowest friction locations within the curves using continuous friction measurement devices like a SCRIM. Also, it is recommended to study the phonolite TPO aggregate loss area and analyze the changes over time (using 2D images and 3D scanning data) to determine the critical spots where aggregate loss is occurring.

The beginning of the curve section yields high friction demand when there is inadequate spiral transition and super elevation. For future research, it is recommended that the locations that yield high friction demand in a curve be determined by studying continuous geometrical characteristics, including a) spiral transition and b) superelevation change along the curve so such characteristics can be used in the future to determine critical sections of the curve. GDOT can process the Curve Advisory Reporting Service (CARS) data to obtain the super elevation and curve geometry to perform this analysis.

Step 5: Determine the number and location of friction measurements within the critical section and critical position.

Based on the current operations and outcomes of this research, it is recommended that six friction measurements be collected for each of the representative test sites – three measurements on the critical position wheel path at the point of curve, point of tangent, and middle of curve spots, one measurement on the other wheel path at the middle of the curve, one measurement on the non-wheel path, and one measurement on the asphalt pavement critical position wheel path. This is a comprehensive friction measurement approach, and it covers at least one spot in each of the three potential critical sections of the curve (beginning, middle, and end) when the critical section of the curve is not identified. A baseline friction measurement on the non-wheel path (would serve as a reference to compare wheel path deterioration) and a control friction measurement at the asphalt spot should be also collected. Figure 61a illustrates the recommended locations of the six friction measurement spots based on the comprehensive measurement approach. Although it covers all the potential critical sections, the limitation of this approach is that it is time- and effort-consuming to move to different spots along the curve to take the friction readings. Moreover, the aggregate loss and friction deterioration can start anywhere within the critical section, and this approach of using fixed spots may not capture the friction deterioration until the aggregate loss spreads to the testing spot.

There is a need to develop an optimized friction measurement approach that a) minimizes the DFT data collection time, 2) efficiently collects the friction data, and 3) includes random sampling to capture aggregate loss and friction deterioration. Therefore, it is recommended to first identify the critical sections in each FIST site and collect three DFT measurements at random spots along the critical section (roughly at about 25%, 50%, 75% of the length of the critical section) on the critical position wheel path. In addition, it is recommended to collect one DFT measurement at the asphalt pavement wheel path position to serve as a control friction measurement; also, collect one measurement from the non-wheel path position as a reference to compare the wheel path deterioration. Figure 61b illustrates the locations of friction measurement spots using the optimized friction measurement approach. Finally, it is recommended to take the minimum of the three DFT friction coefficient readings at the three tested critical wheel path spots as the site's overall friction value.

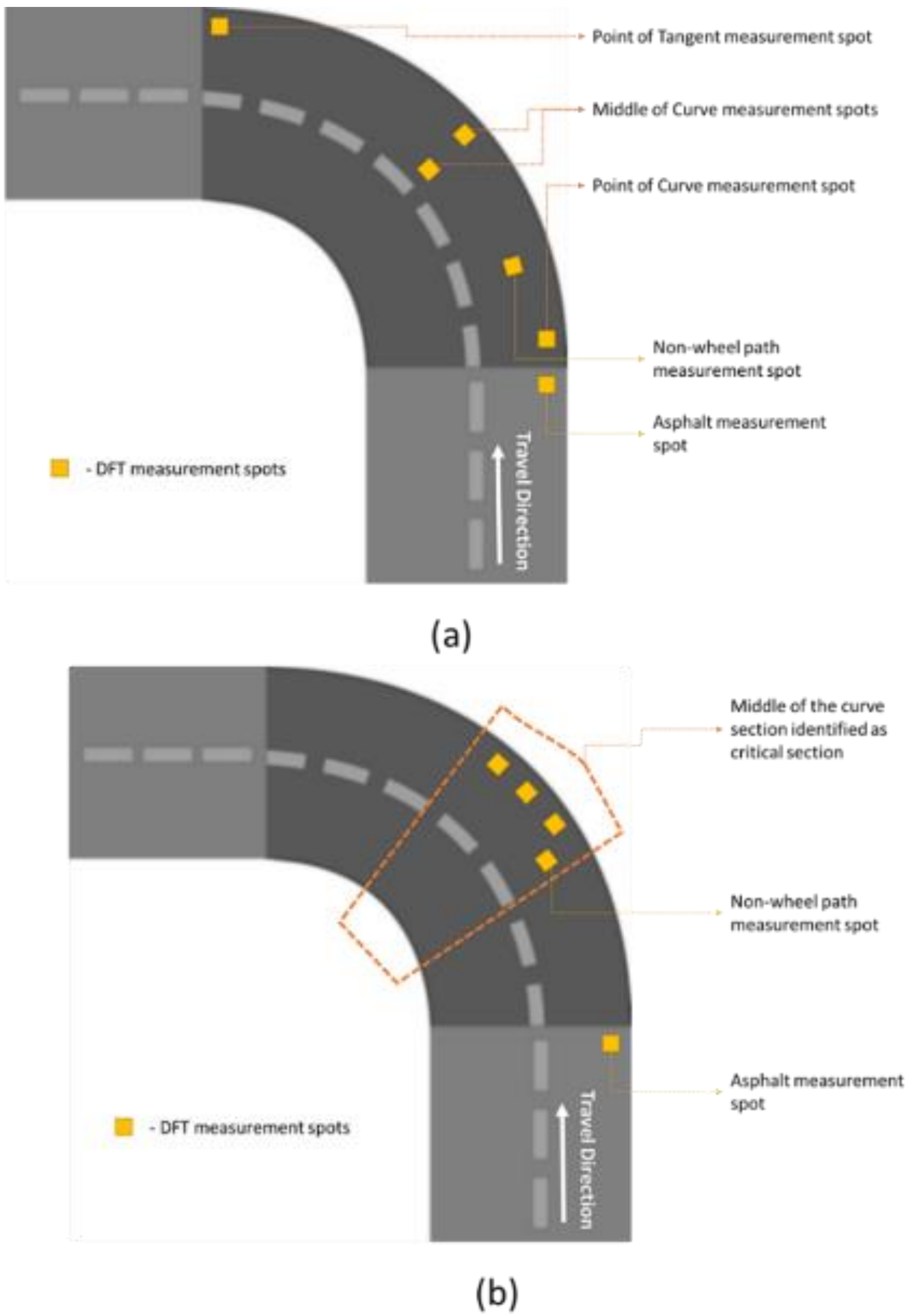


Figure 61 – Illustration. Illustrations of locations of DFT measurements: (a) Comprehensive friction measurement approach, and (b) Optimized friction measurement approach.

Step 6: Determine the testing frequency for routine monitoring and intensive monitoring.

Based on observations at the NCAT test track HFST section, the friction on a well-constructed site is high, remains stable for a long period of time (over eight years), and indicates good long-term performance. However, even with good long-term performance, the friction drops suddenly and rapidly towards the HFST's end of life, creating a safety risk for drivers. Therefore, sites with potential risk need to be monitored more frequently than do sites with good performance. Meanwhile, the DFT resources are limited and require expensive traffic control at each site. Therefore, GDOT needs to optimally use the DFT resources and focus more on the potentially risky sites. Thus, two categories of monitoring frequencies are recommended: 1) routine monitoring frequency for sites that are performing well, and 2) intensive monitoring frequency for sites that are not performing well and are, therefore, risky. Routine monitoring frequency is approximately one year, and intensive monitoring frequency is approximately three months. Routine monitoring frequency for a site is changed to intensive monitoring once the FIST site shows signs of significant deterioration (such as a drop in friction coefficient > 15% or the friction coefficient drops below 0.55, or both); the trigger criteria for intensive monitoring is discussed in Step 7.

For routine monitoring and intensive monitoring of representative sites using DFT measurements, the following recommendations are based on the three-year field data analysis:

For routine monitoring,

- Annual monitoring on calcined bauxite HFST (HFST sites performing well so far).
- Semi-annual monitoring on lightweight aggregates sites (these sites currently have mild aggregate loss and flushing).

For intensive monitoring,

- Quarterly monitoring for phonolite TPO (these sites show aggregate loss and low friction and are already being monitored at the intensive frequency).
- Semi-annual monitoring for low-traffic HFST sites; and
- Quarterly monitoring for high-traffic HFST and lightweight aggregate sites.

For monitoring the remaining sites in the network, the following recommendations are made:

- Perform annual visual inspection on calcined bauxite HFST sites.
- Perform semi-annual visual inspection on lightweight aggregate sites; and
- Perform quarterly visual inspection on phonolite TPO sites.

It is noted that the above recommended monitoring frequencies are preliminary and need to be fine-tuned with data collected for an additional two to three years using DFT testing and the new performance measures (loss of aggregates). This would help road agencies and engineers understand the deterioration behavior and end-of-life friction and aggregate loss characteristics; it would also help fine-tuning of the monitoring frequencies.

Step 7: Establish the trigger criteria for intensive monitoring and detailed field investigations based on observed fiction/aggregate loss deterioration attributes.

Once the testing commences with routine monitoring on the representative sites using DFT, it is important to establish the criteria to trigger intensive monitoring and to perform detailed field investigation; however, such trigger criteria is currently lacking. Trigger criteria can be developed based on FIST performance deterioration attributes, such as a) value (e.g., what is the current condition of the friction, how much aggregate loss area, etc.) and b) rate (e.g., friction change in a single time stamp or over multiple time stamps). Thresholds set on these deterioration attributes (e.g., friction value < 0.6 or aggregate loss area > 10%, percent change in friction > 10% in single time stamp, etc.) constitute trigger criteria.

To establish the friction trigger criteria, it is useful to analyze the long-term friction deterioration of HFST test section at NCAT (shown in Figure 62). The rapid drop in skid number was observed after the skid number dropped more than 15%; it dropped below SN = 50 and did not bounce back in consecutive measurements. The analysis of the skid number deterioration at NCAT, shown in Table 12, presents an example of the recommended friction trigger criteria for intensive monitoring and detailed field investigations. It must be noted that the NCAT HFST test section's long-term friction analysis involved accelerated deterioration of pavement using heavy truck loading. However, the Mu threshold values (e.g., 0.50) may be conservative for regular traffic conditions in Georgia and need to be refined further by analyzing additional Georgia-specific long-term FIST performance data.

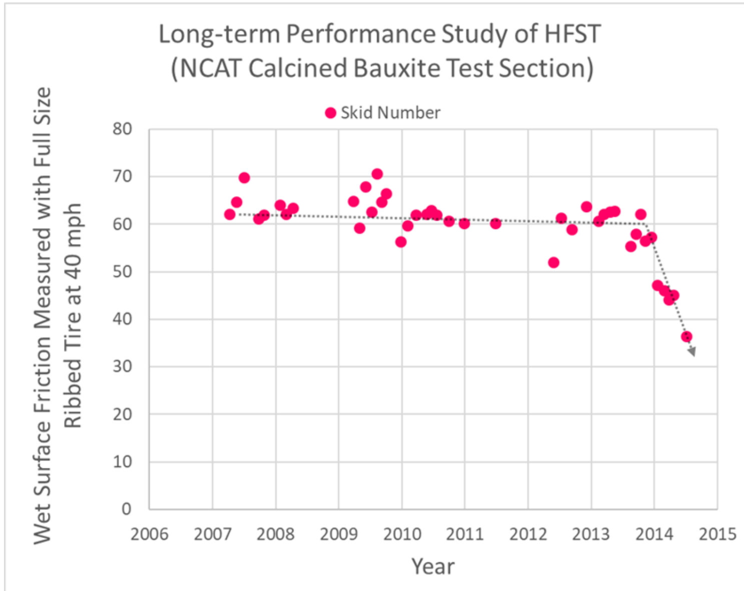


Figure 62 – Graph. Friction (measured using locked wheel skid trailer) drops suddenly at the end of HFST life. Data courtesy of NCAT.

Table 12 – Example of recommended trigger criteria for intensive monitoring and detailed field investigations based on NCAT HFST friction deterioration behavior.

Performance measure	DFT coefficient, Mu measured at 60 kph		
Deterioration attribute	**Trigger Criteria**		
Value	***(Mu > 0.50)***	***(Mu < 0.50)***	***(Mu < 0.50)***
Rate		***Mu drops greater than 10% annually.***	***Mu did not recover above the initial dropped value for 3 consecutive intensive monitoring periods***
	Action steps		
	Continue routine monitoring frequency.	Switch to intensive monitoring frequency – 3 months.	Perform detailed investigation in the test site to evaluate the pavement and site condition to determine maintenance treatments and timing.

Alternatively, the Mu thresholds (e.g., 0.50 in Table 12) can be established based on correlating relative safety risks to the friction values, as done by the New Zealand Transportation Agency (NZTA, 2013), rather than using friction deterioration behaviors. Table 13 shows the decision-making criteria set up by NZTA. NZTA has set different skid resistance thresholds (called Investigatory Level, IL) for different site categories and site characteristics based on an Equivalent SCRIM Coefficient (ESC) to perform field investigations, which is a good way to manage friction. NZTA performs annual skid resistance on their entire network using a SCRIM, a continuous friction measurement device that measures friction as a side-force coefficient (also called SCRIM coefficient). The IL is established based on historical crashes analysis, friction demand, and site investigation. An appropriate default value for the IL is given to each site category to reflect the relative risk of a wet road or skidding crash at each of site category. In addition, NZTA has established threshold levels (a threshold friction value to perform and program maintenance or treatment at the site) that are based on a skid resistance value of 0.1 units below the Investigatory Level or 0.30, whichever is higher, based on the risk-based approach used by NZTA,

Table 14 presents the example of recommended friction trigger criteria for intensive monitoring and detailed field investigations based on risk levels at different site categories.

Table 13 – NZTA skid resistance investigatory levels based on Equivalent SCRIM Coefficient (ESC) for different site categories.

Site category	Skid site description	Investigatory level (IL), units ESC					
		0.35	0.40	0.45	0.50	0.55	0.60
1	Approaches to: a) Railway level crossings b) Traffic signals c) Pedestrian crossings d) Stop and Give Way controlled intersections (where state highway traffic is required to stop or give way) e) Roundabouts. One lane bridges: a) Approaches and bridge deck.						
2	a) Urban curves <250m radius						
	b) Rural curves <250m radius			L	M	H	
	c) Rural curves 250-400m radius		L	L	M	H	
	a) Down gradients >10%. b) On ramps with ramp metering.						
3	a) State highway approach to a local road junction. b) Down gradients 5-10% c) Motorway junction area including on/off Ramps d) Roundabouts, circular section only.						
4	Undivided carriageways (event-free).						
5	Divided carriageways (event-free).						

Note 1: The SCRIM coefficient can vary based on temperature, seasonal effects, and other testing conditions, like speed. The Equivalent SCRIM coefficient is the SCRIM coefficient corrected for the temperature, seasonal effects, and other variations in the testing conditions.

Note 2: The default ILs are the black areas for all site categories except for the rural curves shown in Site Categories 2b and 2c. The greyed boxes on either side of the black area indicate alternative ILs that may be considered. For Site Categories 2b and 2c, the ILs have white letters (L, M, and H) inside the greyed areas, which represent the IL for low, medium, and high-risk sites.

Table 14 – Example of recommended trigger criteria for intensive monitoring and detailed field investigations based on risk level at different site categories.

Performance measure		DFT coefficient, Mu measured at 60 kph		
Deterioration attribute	**Site Category**	**Trigger Criteria**		
Value	***Low speed curves, < 500 feet radius***	***(Mu > 0.50)***	***(Mu < 0.50)***	***(Mu < 0.45)***
	High speed curves, > 500 feet radius	***(Mu > 0.55)***	***(Mu < 0.55)***	***(Mu < 0.50)***
	High speed curves, < 500 feet radius	***(Mu > 0.60)***	***(Mu < 0.60)***	***(Mu < 0.55)***
		Action steps		
		Continue routine monitoring frequency.	Switch to intensive monitoring frequency – 3 months.	Perform detailed investigation in the test site to evaluate the pavement and site condition to determine maintenance treatments and timing.

Next steps: It is recommended to continue monitoring and collecting DFT friction performance data at Georgia's phonolite TPO sites for development of friction performance deterioration curves to analyze and establish friction-based trigger criteria for phonolite TPO. Unlike calcined bauxite HFST at the NCAT test section, for which the end-of-life friction deterioration behaviors have been documented, there is no documented deterioration behavior for phonolite TPO for developing trigger criteria.

To use the visual inspection method to monitor the remaining 381 FIST curve sites in the network, aggregate loss-based trigger criteria for performing detailed field investigation and friction testing need to be developed. Table 15 shows an example of aggregate loss-based trigger criteria for performing increased monitoring and detailed field investigation.

Table 15 – An example of aggregate loss-based trigger criteria for increased monitoring and performing detailed field investigation.

Performance measure	*Loss of aggregate by area*		
Deterioration attribute	**Trigger Criteria**		
Value	Aggregate loss area < 10 % of wheel path	Aggregate loss area > 10% and < 30 % of wheel path	Aggregate loss area > 30 % of wheel path
Deterioration		Aggregate loss area increased by 10% of total wheel path area	Aggregate loss area increased by 5% of total wheel path area for three consecutive intensive measurements
	Action steps		
	Continue routine monitoring frequency.	Monitor the site intensively, every 3 months	Perform detailed investigation in the test site and measure friction.

The performance measure used in this example is the aggregate loss area, which is determined based on visibility of the epoxy and the background pavement. However, the thresholds of the aggregate loss percentages need to be adjusted based on actual deterioration. For future research, it is recommended to further analyze the aggregate loss deterioration attributes (area of aggregate loss and rate of increase) to develop the trigger criteria.

Step 8: Determine follow-up actions based on the detailed field investigation.

The final step in the recommended guidance for the Georgia's FIST long-term performance monitoring and maintenance program is to determine follow-up actions to take based on a detailed field investigation. The recommended follow-up actions include the following:

1. Evaluate the condition of the FIST surface based on aggregate loss and other distresses, such as delamination, potholes caused by asphalt pavement pop-offs, cracking, etc., to determine the timing and suitable maintenance treatments or roadway replacement.
    1) Potential maintenance treatments include a) micro mill and apply new FIST treatment, or b) spot treatment, such as cut, fill, and overlay on potholes, etc.
    2) Develop strategies and plans for optimizing the FIST replacement with coordination of surrounding resurfacing projects' schedules.
2. Install safety warnings, such as reduced advisory speed signs, to alert drivers when the FIST site requires maintenance treatments.
3. Investigate other sites besides the representative sites in the group and test friction coefficients on other sites to determine if additional monitoring is required.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

The Georgia Department of Transportation (GDOT) has an active HFST program that applies HFST on specific curves. Georgia has the highest number of miles (more than 90 accumulated centerline roadway miles) and curve sites (more than 411) in the US (as of December 2020); these sites use epoxy-based friction improvement surface treatments (FIST) sites, including calcined bauxite HFST and phonolite TPO (phonolite, or "Wyoming bauxite," aggregate). GDOT has also been exploring the use of lightweight aggregates (LWA) without epoxy as an alternate friction improvement treatment. These sites are summarized below:

a) Calcined bauxite HFST (342: 42 sites installed in 2014 in Districts 5 and 6; 300 sites mostly installed in 2017 in Districts 3, 4, 5 and 6).
b) Phonolite, or "Wyoming bauxite," (69 sites installed in 2017 in District 1).
c) Light Weight aggregates (continuous chip seal application covering 10 sites installed in 2017 on State Route 16 in District 2).

Based on our literature review, national HFST survey, and interviews with experts in FHWA, NCAT, and state DOTs, the following is the summary of our findings:

1. Based on the national survey and NCAT observations, HFST life varies from 2-10 years depending on various factors, including underlying pavement condition, construction quality, material used, age, environmental conditions, truck volume, and geometric characteristics. Well-constructed HFST on a good underlying pavement can maintain high and stable friction for a long

time (7-12 years), which is considered good long-term performance (FHWA, 2019).

2. Even with good long-term performance, observation from the long-term performance monitoring of HFST sections at the National Center for Asphalt Technology (NCAT) Test Track has shown that friction (measured as a skid number using a locked wheel skid-trailer) drops significantly and rapidly at HFST's end-of-service life, even when there is no clear friction deterioration trend based on skid number readings. The rapid friction deterioration at the end of the HFST service life is due to smooth glossy surfaces created by loss of HFST aggregates from the HFST surface. The aggregate loss is caused by a reduction in epoxy's aggregate binding capacity due to the chemical aging of the epoxy and the effect of constant polishing and shear forces caused by vehicle acceleration and deceleration.

A GIS database was created to store the location and site information of the FIST sites based on the GDOT's FIST contract let packages. The GIS database includes information on curve geometry (radius, location of point of curve, point of tangent, and super-elevation) contractor(s), material sources (aggregate and polymer binder), construction method (automatic or manual), date of installation, AADT, truck percent, speed limits, and dynamic friction test results at 5 and 90 days after installation. An experimental test design was conducted to select and monitor representative FIST sites in Georgia with diverse conditions; it used a consistent data collection procedure with DFT (including consistent criterion for selecting DFT friction testing spots) to study the sites' temporal friction behaviors and spatial friction distribution patterns. Based on the experimental test design and after consulting with GDOT, 30 sites from GDOT's 421 (342 + 69 + 10) sites were selected as representative sites for long-term performance monitoring with DFT. The 30 sites constitute less than 8 percent of GDOT's total number of sites (30/421). The following summarize the 30 sample sites:

a) Calcined bauxite HFST (19/342 sites in Districts 3 (4 sites), 4 (2 sites), 5 (4 sites) and 6 (9 sites))
b) Phonolite, or "Wyoming bauxite," (9/69 sites installed in District 1)
c) Light Weight aggregates (2/10 sites in District 2)

The three-year field performance monitoring of the 30 Friction Improvement Surface Treatments (FIST) sample sites is summarized as follows:

1. Calcined bauxite HFST (19/342 sites): Has shown very good long-term friction performance.
    a. Analyzed 9 representative calcined bauxite HFST sites installed in 2014 and 10 sample sites installed in 2017.
    b. Initial friction and deterioration at the end of the first three months: Calcined bauxite HFST has initial friction (right after installation) of DFT60 = 0.85-1.0, and friction dropped less than 10% in the first three months, as shown in Figure 29.
    c. Current condition and overall temporal deterioration: The DFT friction coefficient (DFT60) was 0.7 – 0.9 in 2018; it is 0.65 – 0.9 in 2021, including the ones installed for seven years; the overall deterioration based on three years of performance monitoring is less than 10%, as shown in Figure 28.

d. Deterioration based on ESAL: DFT60 stayed over 0.8 in the early stages of loading (less than 500 thousand ESALs). After one million ESALs, most of the calcined bauxite HFST DFT60 measurements dropped below 0.8; after two million ESALs, friction stabilized between 0.6 to 0.8.

e. When comparing the friction deterioration trend between sites with manual installation and automated installation, no noticeable performance difference was found. The two installation methods shared a very similar deterioration trend, even though the automatically installed sites are only in their "early" life cycle compared to the manual sites.

f. Overall assessment and additional observation: Calcined bauxite HFST has performed very well, so far, based on three years of performance monitoring, and it has shown minimal aggregate loss. Some older HFST sites (installed in 2014) with low AADT and truck volume still maintain high friction value (0.85) even after 6 years; other HFST sites with high AADT (greater than 10,000) and truck volume show friction that has deteriorated to 0.7 due to high traffic volume. Some calcined bauxite HFST sites have shown asphalt pop-off distress along State Route 132 in District 5.

2. Phonolite, or "Wyoming bauxite," aggregate on epoxy or phonolite TPO (9/69 sites): Showed poor long-term friction performance.

   a. Analyzed 9 representative phonolite TPO sites installed in 2017.

   b. Initial friction and deterioration at the end of the first three months: phonolite TPO has initial friction (right after installation) of DFT60 = 0.85-1.0, but friction dropped more than 40% in the first three months, as seen in Figure 29.

c. Current condition and overall temporal deterioration: The DFT friction coefficient (DFT60) was 0.4 – 0.55 in 2018; it is 0.35 – 0.55 in 2021, excluding the sections having substantial aggregate loss; the overall deterioration, based on three years of performance monitoring, is less than 10%.

d. Deterioration based on ESAL: DFT60 predominately stayed between 0.5 to 0.6 in the early stages of loading (less than 500 thousand ESALs). After one million ESALs, most of the phonolite TPO friction dropped below 0.5, and there is a tangible deterioration trend.

e. Overall assessment and additional observation: phonolite TPO have performed poorly so far based on three years of performance monitoring. Friction is low (DFT60 < 0.45) on the majority of tested sites and show a deteriorating trend based on traffic loading.

3. Lightweight aggregate (LWA) chip seal (2 sites):

   f. Analyzed two curve sites on a ten-mile installation in 2017.

   g. Initial friction and deterioration at the end of the first three months: LWA has initial friction (right after installation) of DFT60 = 0.75, and friction dropped less than 10% in the first three months.

   h. Current condition and overall temporal deterioration: The DFT friction coefficient (DFT60) was 0.70 – 0.75 in 2018; it is 0.60 – 0.75 in 2021, and the latest friction measurement showed friction dropping close to 0.6. The overall friction deterioration based on three years of performance monitoring is less than 15%.

   i. Deterioration based on ESAL: LWA friction performance was stable (0.7 to 0.75) until one million ESALs. The latest friction measurement showed friction dropping close to 0.6 at 1.2 million ESALs.

j. Overall assessment and additional observation: LWA have performed well during the first three years, although it does not provide very high friction values like HFST during the same stage. However, the performance outcomes are not conclusive because of the limited data, test duration and traffic volume. Flushing and mild aggregate loss are observed at these sites.

4. Alumina content in the aggregate material may potentially have a major impact on friction deterioration. Calcined bauxite with high alumina content (87%) performed well compared to phonolite with a low alumina content (<20%).
5. There is no substantial difference between automatic and manual HFST installation based on six years of calcined bauxite HFST friction deterioration data.
6. Cumulative traffic volume did not show considerable impact on calcined bauxite's long-term friction deterioration in this research timeframe, but it showed a strong impact on phonolite's long-term friction deterioration.
7. Curve radii, curve deviation angles, and traffic speeds (related to friction demand) have considerable impact on the long-term friction deterioration on FIST sites, and higher friction demand curves are more likely to deteriorate faster.
8. Spatial friction distribution patterns show that friction does not deteriorate uniformly over the entire FIST curve site.
    a. Predominately, the middle section of a curve contains the lowest friction. The beginning and end of curves have low friction if other site characteristics, like intersections, STOP signs are present.

   b. Outer wheel path positions with longer radii (the higher side of super elevation) contain the lowest friction under high-speed conditions.
   c. Inner wheel path positions with shorter radii (the lower side of super-elevation) contain the lowest friction under low-speed conditions.
9. Various site characteristics (including the curve radius, superelevation, speed, etc.), location (wheel path, non-wheel path, middle of the curve, etc.), and construction quality can impact the spatial friction distribution and its variability at each FIST curve site. However, additional testing with diverse site characteristics and longer monitoring times is required to quantify the impact of site characteristics on spatial friction deterioration behavior.

The recommendations for the three FIST materials based on three years of field performance monitoring on 30 representative sites are as follows:

1. For calcined bauxite HFST sites:
   a. Perform additional two to three years performance monitoring to study longevity of calcined bauxite HFST so that their end-of-life characteristics or early warning signs (including the friction drop, friction drop percentage and rate, aggregate loss area change, etc.) can be studied and identified to develop maintenance trigger criteria.
   b. Based on the current friction condition (DFT60 = 0.65 – 0.9), it is suggested to perform annual performance monitoring on sample sites using DFT on representative sites and alternative low-cost performance monitoring (using loss of aggregates and low-cost camera images) at the network level to

screen sites for targeted friction testing and to prevent the potential friction sharp drops at the end of life.

c. Based on its very good performance in low volume sites, it is suggested to apply calcined bauxite HFST to the sites with low traffic volume and a high rate of fatalities and serious injury (potentially due to high friction demand) so pavements can last 10-15 years (without replacing) to maximize crash reduction benefits and to produce the highest return on safety investment.

d. For calcined bauxite HFST sites with asphalt pavement pop-off,

    i. Fill the potholes created by asphalt pavement pop-off to improve the ride quality and make the roadway safer.

    ii. Conduct detailed pavement evaluation to determine the actual cause of asphalt pop-off failures on Georgia's HFST sites.

    iii. Continue monitoring friction and pavement condition regularly to ensure the surface provides adequate friction and pavement does not disintegrate suddenly.

2. For phonolite TPO sites:

    a. Based on the three-year performance monitoring of phonolite TPO on Georgia State Route 2, we do not recommend GDOT continue using phonolite TPO as the future friction improvement surface treatment alternative.

    b. Because of its current friction values (DFT60 + 0.35 – 0.55) and deterioration, existing phonolite TPO sites need to be monitored closely and friction tested routinely to minimize the low friction concerns and potential safety risks. Set up signs to advise drivers to drive with caution, since the phonolite TPO performance is not as high as calcined bauxite HFST.

c. Continue to collect friction data every three months to monitor the safety risk at these sites. It is also useful to record the terminal life performance, which is non-existent at this time (unlike calcined bauxite on epoxy whose terminal life has been observed in the NCAT test sections).

3. For lightweight aggregate chip seal sites: It is recommended to perform additional LWA friction testing for two to three years to determine its long-term performance (greater than five years). Since there are only a limited number of sites available for this project and the large curve radii of the curve suggest no significant traffic loading, it is also recommended that more sites with diverse curve geometries and traffic conditions be included in the long-term monitoring.

A technical and managerial integrated framework with nine technical modules was developed to enable researchers and transportation agencies to cost-effectively manage the complicated lifecycle activities of epoxy-based friction improvement surface treatments, such as HFST. The nine modules of the framework are as follow:

1. Site selection and optimal HFST installation limits,
2. HFST binder specification, quality control assessment, and recording of construction data,
3. HFST performance measures,
4. Performance measurement technologies and procedures,
5. Sampling representative sites and testing locations,
6. Performance monitoring frequency,
7. Network-level HFST performance monitoring and rating system,

8. Performance forecasting, and
9. HFST maintenance and replacement (M&R).

This report presents a recommended guide for Georgia's network-level HFST (and FIST) long-term performance monitoring and maintenance program based on the developed integrated framework. This guide provides recommendations on performance measures, testing locations and positions, frequencies, and performance evaluation and trigger criteria thresholds in support of the optimized FIST long-term performance monitoring system that uses DFT and aggregate loss performance measures. Thus, GDOT can better establish its FIST long-term performance monitoring and maintenance program using internal resources and/or external contactors. The recommended guidance consists of the following eight steps:

- Step 1: Select the performance measures and the measurement method.
- Step 2: Group curve sites with similar materials, ages, construction methods, and site characteristics in the networks that have similar performance and deterioration behaviors.
- Step 3: Select the representative sites within each group to perform targeted testing.
- Step 4: Select critical section and critical wheel path positions within curve sites to measure performance.
- Step 5: Determine the number and locations of the friction measurements within critical sections and critical positions.
- Step 6: Determine the testing frequency for routine monitoring and intensive monitoring.

- Step 7: Establish the trigger criteria for intensive monitoring and detailed field investigations based on observed friction/aggregate loss deterioration attributes.
- Step 8: Determine follow-up actions based on the detailed field investigation.

Based on the outcomes of this research and the modules discussed in the integrated framework, additional recommendations are made:

1. For the thirty 30 representative sites with DFT performance monitoring, it is recommended to perform an additional two to three years of DFT testing along with the new aggregate loss performance measures.
    a. Develop proper trigger points for taking proactive safety and maintenance actions for addressing the potential risk due to end-of-life FIST deterioration based on the early warning signs.
    b. Study the longevity of calcined bauxite and lightweight aggregate, especially their high friction performance (DFT60 > 0.65).
    c. Validate the preliminary findings in the report, including the deterioration trends, correlations between different factors impacting the long-term friction deterioration, and confirm the spatial friction distribution.
    d. Correlate a friction coefficient measured using DFT with the low-cost performance measure (loss of aggregates) in Georgia so GDOT can apply the aggregate loss-based, inexpensive FIST performance measurement. The preliminary study has been performed at the NCAT test track; additional tests need to be performed to validate the correlation for GDOT implementation.

e. Establish an aggregate loss baseline using devices like smartphones, GoPro cameras, and aggregate loss performance measures (aggregate loss area) to compare the loss of aggregate over different time stamps in an additional two to three years of testing. Another alternative is to obtain annual data collected using video log images and 2D/3D pavement surface data collected by vendors, like Pathway, to leverage the current data collection effort.

2. Develop cost-effective FIST safety condition monitoring of 411 FIST sites using low-cost performance measures (like aggregate loss) and automated field survey methods, including low-cost smartphones, 2D imaging technologies, and 3D laser technologies, to cost-effectively screen sites for targeted friction testing and detailed investigation to optimize safety condition evaluation efforts.

    a. Develop a network-level, cost-effective epoxy-based FIST performance monitoring and rating system (including visual inspection and 2D imaging using smartphones to proactively identify potentially unsafe sites) to support a risk-based, targeted, and optimal sampling and monitoring strategy. The needed epoxy-based FIST performance monitoring and rating system is like GDOT's COPACES rating system for network-level pavement condition evaluation. This system enables cost-effective and systematic identification of potentially risky sites to proactively minimize the safety risk and improve the overall safety of the epoxy-based FIST sites in the network.

b. Develop an automatic method of using low-cost video images and computer vision to monitor FIST deterioration and to screen sites for targeted testing. Explore 3D laser scanning technologies with automatic extraction of loss of aggregates and 3D texture (e.g., mean profile depth, etc.) for automatic field data collection.
c. Develop a standard and consistent FIST site condition survey protocol and rating computation that involves the following:
    i. What to measure (e.g., loss of aggregates or color contrast measured by area, by linear foot, or by percentage),
    ii. Where to measure (e.g., travel lane wheel path and roadside shoulder),
    iii. How to measure cost-effectively and sustainably (e.g., visual inspection conducted by GDOT office engineers, who take photos using low-cost smartphones with consistent procedures so these images, taken at different times, can be compared to see the loss of aggregate propagation.)
    iv. Location reference (e.g., measured at the PC, PT, or middle of the curve),
    v. Deduct and rating computation (e.g., 0-100 scale).
d. Build a GIS-based data storage and management system to store, track, process, and analyze site performance data for successful implementation of the recommended FIST condition monitoring and rating system.

    e. Establish trigger criteria based on the condition rating or friction (or aggregate loss) performance measure values (e.g., friction coefficient < 0.5, wheel path aggregate loss area > 30%, etc.) to perform additional testing and to perform detailed field investigation.

3. For optimally selecting the sites and effectively applying suitable FIST sites with the appropriate traffic conditions and roadway characteristics (right time, right treatment at the right location) that results in optimal network-level safety improvement (the highest crash reduction for dollars spent),
    a. Determine and prioritize systemic risk-factors related to roadway departure crashes to optimally select sites for FIST application.
        i. Perform a correlation study between roadway characteristics/traffic condition and crashes using advanced statistical methods and machine learning by taking full advantage of rich roadway characteristics data already collected by GDOT (using RIEKER and stored in CARS).
    b. Analyze FIST crash reduction effectiveness on different roadway conditions (e.g., high vs. low - traffic, friction demand, etc.) based on FIST service life and Georgia-specific FIST Crash Reduction Factor (CRF)).
        i. Determine the FIST service life based on materials, traffic conditions, and friction demands (based on roadway characteristics, such as curve radii, posted speeds, super-elevations, etc.).

ii. Perform Georgia-specific crash reduction factor (CRF) analysis to obtain Georgia-specific FIST CRF in support of GDOT benefit cost analysis and FIST crash reduction effectiveness analysis of countermeasure selection for the decision-making on appropriate safety counter measures.

4. For deployment of continuous friction measurement (CFMD) like SCRIM, Grip Tester for site selection, optimal installation limit determination, long-term monitoring, and critical spot identification.
    a. Establish Georgia's network-level friction-based safety management program to leverage FHWA's pool fund effort on friction data collection using CFMD and friction management.
        i. Identify the importance of using CFMD by establishing the relationship between crashes with CFMD friction.
        ii. Determine Georgia-specific trigger point (e.g., friction demand thresholds) for friction improvement candidate site selection and field investigation using a pilot CFMD dataset.
    b. Develop a CFMD-based friction measurement method (spatial aggregation unit, location) and test the accuracy and consistency of the developed method to measure the friction on FIST sites and support long-term monitoring.
    c. Study the critical and optimal locations on curve sites for 1) determining FIST beginning and ending installation limits, and 2) FIST friction performance sampling using CFMD.

i. Determine optimal installation limits of FIST by analyzing the location referenced CFMD friction distribution on the asphalt pavement curved roadway sections.

ii. Identify and confirm critical sections (e.g., around point of curve, middle of curve, locations of cross slope transitions, etc.) and positions (wheel path or non-wheel path) on FIST sites to perform sampled DFT testing based on low friction values using CFMD (rather than DFT spot tests).

5. For epoxy-based FIST construction quality control.

   a. Develop an automatic and cost-effective method using 3D pavement scanning technologies to improve the current manual and sampled aggregate embedment depth measurements for epoxy-based FIST construction quality control. This is necessary to prevent premature failures due to insufficiently embedded aggregates in the epoxy binder during construction.

   b. Record the installation method, site preparation, temperature, moisture content, binder composition, binder thickness, etc., during construction, as they are key factors impacting epoxy-based FIST deterioration. In addition, record the pavement images (using a smartphone), surface friction (using a DFT or skid trailer), and texture (using a circular texture meter or 3D scanning technologies). Images, friction, and texture can be used as a baseline to analyze deterioration by comparing the initial outcomes with outcomes in the later parts of the epoxy-based FIST life.

6. For performing maintenance and replacement of epoxy-based FIST.
    a. Identify epoxy-based FIST maintenance and replacement treatment alternatives by applying existing asphalt pavement maintenance treatments on deteriorated epoxy-based FIST sites and synthesize their successes and failures.
    b. Develop a treatment decision tree to determine adequate maintenance treatment timing and method. Further develop the epoxy-based FIST pavement condition evaluation system to support the treatment decision tree based on 1) overall rating, 2) the friction coefficient and aggregate loss measures, and their deterioration (e.g., friction dropped value, aggregate loss rate, etc.), 3) pavement and site conditions (such as age of underlying pavement, cracking, rutting, and other distresses, etc.), and 4) traffic conditions.
    c. Develop strategies and plans for optimizing the treatment by coordinating with the surrounding resurfacing project's schedule.
7. Other recommendations for alternate friction improvement surfacing, performance forecasting, and curve safety evaluation using vehicle simulations.
    a. Explore new materials and develop new asphalt pavement mix designs with good friction capability to improve the friction cost-effectively and safely on the challenging roadway sections, such as curves with relatively higher friction demand.
    b. Install lightweight aggregate chip seal on the sharp curves (to have a fair comparison with HFST), study its friction longevity and deterioration

behavior, and explore its feasibility as an additional friction improvement treatment option (besides calcined bauxite HFST). Continue to monitor the existing lightweight aggregate FIST sites. Unlike HFST, lightweight aggregate FIST is not based on epoxy and does not have an end-of-life safety risk associated with the smooth, glossy epoxy surface left by loss of aggregates; they are significantly cheaper than HFST.

c. Develop an enhanced FIST safety risk forecasting model using friction (based on skid number with locked wheel skid tester) along with supplementary measurements, like aggregate loss, texture depth, aggregate loss area covered, etc., to forecast the epoxy-based FIST deterioration or risk level accurately and reliably using advanced techniques, such as machine learning.

d. Conduct vehicle simulation using software like CarSim to explain the locations of aggregate loss, low friction based on vehicle dynamics (e.g., high acceleration and deceleration spots, lateral forces, etc.) by modeling selected curve sites and its friction value.

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