

FINAL  
CONTRACT REPORT  
VTRC 10-CR6

**FIELD PERFORMANCE  
OF HIGH FRICTION SURFACES**

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## ABSTRACT

This report describes an evaluation of high friction surface (HFS) systems. The goal of this evaluation was to develop guidance for agencies when considering whether an HFS was an appropriate solution when addressing specific instances of low skid resistance and/or especially high friction demand. HFS systems are specially designed thin surface treatments that provide significant additional skid resistance of pavements and bridge decks without significantly affecting other qualities of the surface such as noise, ride quality, or durability. This report documents the location and climatic conditions where some of these systems are placed, recounts the experiences reported by the agencies that were responsible for their placement, and summarizes key HFS service-level indicators (friction and texture).

The agency experiences include a sample benefit-cost analysis from an installation in Wisconsin that justified an HFS application through crash reductions that resulted following the measured increase in skid resistance. Analysis of the service-level indicators included development of the coefficients necessary to obtain the International Friction Index (IFI) values for each of the tested systems. Review of the IFI values suggested that more experiments with different types of wearing surfaces, to include HFS systems as well as more conventional surface treatments, are necessary in order to demonstrate the validity of the speed gradient and friction coefficients recommended by the ASTM standard for the IFI.

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## **INTRODUCTION**

Roadway accidents are a leading cause of death and injury around the world. Each year 1.2 million people die and approximately 50 million more are injured or disabled as a result of road crashes.<sup>1</sup> In 2007, 41,059 people died in the United States (or one every 13 minutes) and 2,491,000 were injured as a result of road crashes with an estimated economic cost of more than \$230 billion.<sup>2</sup> These staggering statistics made legislators declare safety as one of the top priorities in the largest surface transportation investment law issued: the Safe, Accountable, Flexible, Efficient, Transportation Equity Act: A Legacy for Users (SAFETEA-LU).

Motor vehicle crashes result from numerous contributing factors such as driver error, poor geometric alignment of the roadway, and insufficient friction at the tire-pavement interface, especially during wet weather. It has been reported that wet pavements are involved in approximately 25 percent of all crashes and 14 percent of all fatal crashes.<sup>3</sup>

The mission of all state departments of transportation (DOTs) is to provide highway users with smooth-riding and safe surface conditions throughout the year. To achieve this, agencies periodically monitor pavement surface properties. Among the most important are friction and texture. Optimal surface conditions should exhibit sufficient friction and texture depth to reduce roadway highway accidents. The emphasis now placed on safety has increased the attention on the importance of friction in the pavement management process. In this context, high friction surfaces, or HFS systems, are becoming an appealing alternative since these systems are able to increase friction and improve texture immediately after placement without significantly affecting other pavement qualities such as noise or durability. The HFS consists of high polished stone value (PSV) aggregates mixed with some type of resin to hold the aggregate particles together and bond them to the existing pavement surface.

HFS systems can mitigate the consequences of driver error, poor geometric alignment of the roadway, and insufficient friction at the tire-pavement interface, especially during wet weather. HFS systems increase road surface skid resistance, driver awareness, and water drainage while decreasing braking distance, hydroplaning, splash, and spray. Although there are other alternatives that have the ability to increase skid resistance on pavements, including tining or grooving particularly on rigid pavements, many of these surface alterations are expensive and can compromise other surface properties (e.g., noise generated between the tire and pavement).

## **PURPOSE AND SCOPE**

The goal of this study was to help agencies decide whether an HFS was an appropriate solution when addressing specific instances of low skid resistance and/or especially high friction demand. This study also seeks to learn enough about the special characteristics of common HFS options to be able to match alternatives with appropriate location and application. This information will help decision makers answer the questions required to allocate the necessary resources that will justify HFS solutions for different safety risks in their jurisdictions.

The evaluation was limited to systems currently installed and marketed in the United States.

## **METHODS**

### **Basic Concepts and Commercial Product Review**

A literature review preceded the other activities in this project. This review produced important background information about typical application processes, the binding agents used to hold HFS constituents together and down on the original roadway surface, and aggregates used in HFS systems. It also produced a summary of similar studies of HFS systems that have been conducted across the U.S. and the U.K. This summary, combined with online marketing information, helped researchers identify HFS systems for further study and field testing. The locations for most applications were determined through the U.S. supplier of the various HFS system manufacturers.

### **Functional Performance Testing**

The second task of the project was to test the HFS systems to determine how effectively these systems are functioning to provide enhanced friction and texture. Texture and friction properties were measured with the Dynamic Friction Tester (DFT) (ASTM E1911); the Circular Track Meter (CTMeter) (ASTM E2157); and the GripTester (GT) (ASTM E2340). These devices are shown in Figure 1 and are described in the following sections. All friction and texture measurements were collected in the summer months to avoid extreme seasonal variation effects on the recorded measurements. For some locations, friction measurements from locked wheel devices (LWD) (ASTM E274) were available for reference.

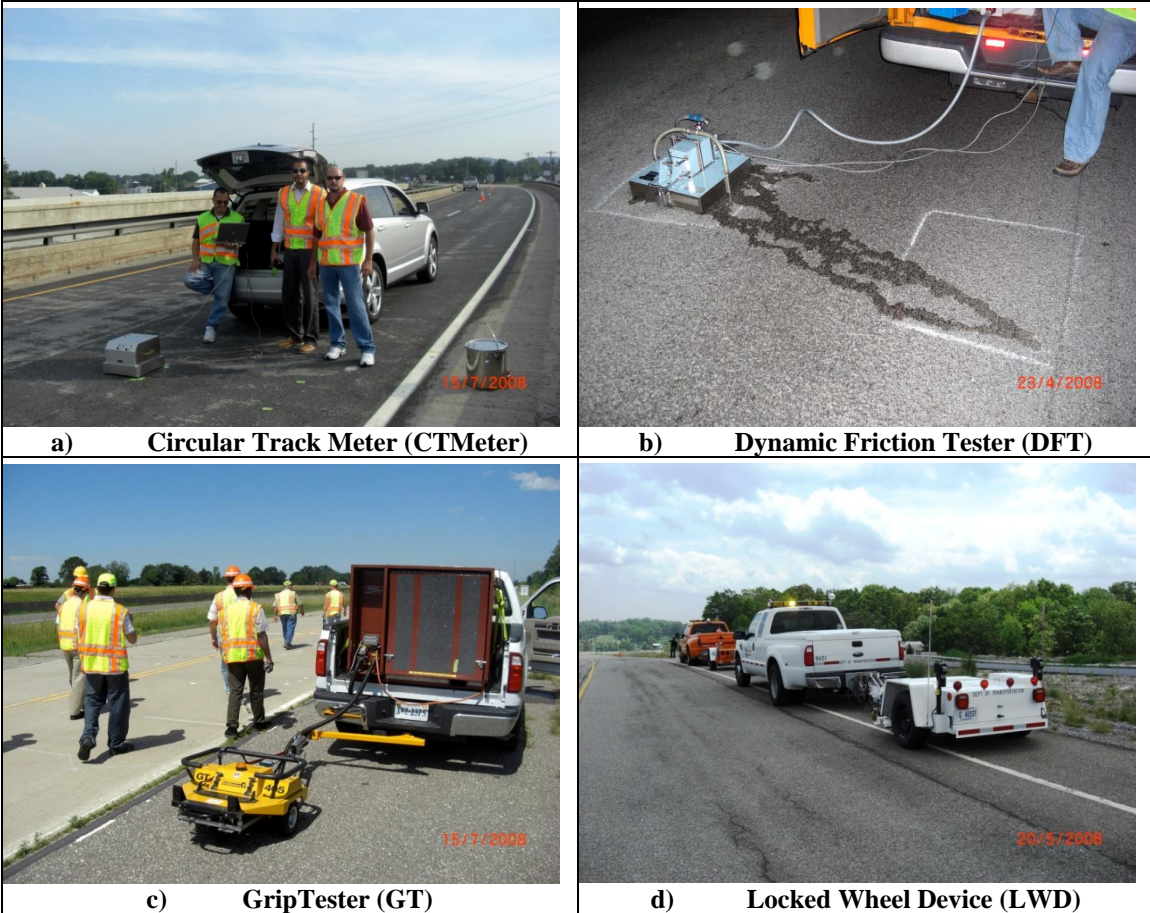


Figure 1. Data collection devices.

### Dynamic Friction Tester (ASTM E1911)

The DFT measures friction by spinning a horizontal disk fitted with three spring-loaded rubber sliders that contact the wetted pavement surface. This causes the disk's rotational speed to decrease due to the friction generated between the sliders and the paved surface. A water supply unit delivers water to the paved surface being tested. The torque generated by the sliding is measured during the spin down and then used to calculate the friction as a function of speed. This device continuously measures the dynamic friction of the pavement, and the results are typically recorded at speeds of 12, 25, 37, and 50 mph (20, 40, 60, and 80 kph). For this study, the DFT measurements were taken at least on six different locations along the HFS section, three in each wheel path. Only travel lanes were measured because the lanes had to be closed to traffic to make these measurements. New DFT friction pads were used at each different HFS section tested.

### Circular Track Meter (ASTM E2157)

The CTMeter consists of a charge coupled device (CCD) laser-displacement sensor mounted on an arm that rotates such that the displacement sensor follows a circular track with a diameter of 11.2 in (284 mm). The CTMeter is designed to measure the same circular track that is measured by the DFT. It reports the mean profile depth (MPD) and the root mean square



(RMS) values of the macrotexture profiles. The values stated in SI (metric) units are regarded as the standard. The CTMeter was used in this study to measure surface texture at the same six spots used for the friction measurements of the DFT.

### **GripTester (ASTM E2340)**

A Findlay Irvine GT was used to measure continuous skid resistance measurements along the left wheel path of the travel lane of the test sections. This GT system consists of a fixed slip device where the test tire is connected to the trailer wheel axle by a chain, allowing it to measure the rotational resistance of a constantly slipping smooth tire. The GT uses a constant slip ratio of 15.6 percent, which means that the test tire is rotating at a speed that is 15.6 percent slower than the other similarly sized tires on the trailer.

Measurements were taken at speeds of 50 mph (80 kph) on interstates and 40 mph (64 kph) on other roadways using a constant water film thickness of 0.02 inch, or 0.5 mm, equivalent to 8.9 gal/min at 50 mph. Raw data for longitudinal friction forces and test wheel loads were by default recorded every 3 ft. Due to the location of the test wheel when the GT is attached to the vehicle, only the outside wheel path friction is recorded (see Figure 1c).

### **Locked Wheel Device (ASTM E274)**

The LWD, a friction measuring device, records the steady state friction force of a locked wheel on a wetted pavement surface as the wheel slides at constant speed. The LWD consists of a vehicle towing a trailer equipped with test wheels. During the test, when the vehicle reaches the desired speed, water is delivered ahead of the test tire and the braking system is activated, producing a 100 percent slip ratio. The wheel remains locked for approximately one second, and the data is measured and averaged. The skid resistance of the paved surface is reported as the 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 multiplied by 100 (ASTM E274).

## **Economic Assessment**

The final task of the project was to provide an economic assessment of the HFS applications. Rather than create a new methodology, this report applies an approach from previous HFS research using installations that were newly surveyed and assembled for this study. The adopted approach is a simplified cost-benefit analysis that compares an HFS alternative with the base (i.e., no HFS). The approach considers the costs associated with the initial construction of an HFS application without including any maintenance as rehabilitation typically means a new overlay for the HFS systems. The benefits entail safety performance improvements such as reductions in deaths, injuries, and/or the property damages before and after HFS systems are installed. The objective of this analysis is to propose a methodology that can be used to analyze the feasibility of the HFS applications.

## **FINDINGS AND DISCUSSION**

### **Basic Concepts and Commercial Product Review**

#### **Background**

HFS systems refer to surface treatments that utilize aggregates that are highly resistant to polishing (PSV) and some type of resin (binder). The most commonly used aggregate is calcined bauxite. The origin of the term HFS dates to the mid-1950s when the use of epoxy-resins used as binders on surfaces were first studied.<sup>4</sup> In the 1960s, the U.K. governmental Transport and Road Research Laboratory (TRRL) began to test hard aggregates with various binders to produce surfaces with extremely high resistance to skidding. Years later, the Greater London Council (GLC) concluded that the most effective HFS resulted from the combination of calcined bauxite of 0.32 cm with a bitumen extended epoxy-resin binder. In the late 1980s, researchers in the United States began to investigate the effectiveness of these surfacing systems in reducing run-of-the-road crashes.<sup>3</sup>

A study conducted by the University of Michigan on 15 ramps at 11 interchanges in five states found that truck crashes were directly related to the geometry of the road, especially on tight curves where heavy trucks were especially vulnerable, particularly under wet-weather conditions that could potentially induce hydroplaning.<sup>3</sup> It has also been shown that there is a statistically significant effect of skid resistance on wet accident rates, which increases with decreasing skid resistance.<sup>5</sup>

Due to this relationship and the increasing number of fatalities on highways, optimum pavement skid resistance must be maintained under extreme weather conditions.<sup>1</sup> HFS systems are quickly becoming an appealing alternative for situations that require superior pavement friction without negatively affecting other pavement qualities such as noise and durability.

#### **Application Processes**

All HFS systems can be classified into two categories depending on the temperature of the binder during their construction: cold-applied and hot-applied processes.<sup>6</sup> Cold-applied HFS systems use thermosetting resins such as epoxy or polyurethane, which are supplied in different containers and, when mixed, begin a heat-producing chemical reaction that results in hardening. In the hot-applied process, the premixed granular material is provided in bags, heated in a boiler and then applied to the surface while still hot. In this case, the resin used is referred to as thermoplastic.

#### **Surface Binders**

There are several types of resins used as binders, and each adds unique capabilities to the system. The main resins used are: epoxy-resin, rosin-ester, polyurethane-resin, and acrylic-resin.<sup>4</sup>

### *Epoxy-Resin*

The oldest resin that has been used in HFS systems is the epoxy-resin. It consists of a two-component system mixed on site at equal quantities by weight. One component contains the resin with a portion of oils that reduce the viscosity of the resin allowing it to flow (extender), while the other component contains the curing agent (hardener). The properties of the binder can be adjusted by changing the proportions of the components of the system, but a typical curing time varies between 3 and 4 hours for applications at pavement temperatures greater than 10° C.

### *Rosin-Ester*

A pre-blended system such as the rosin-ester facilitates in situ installation operations since the resin and aggregates are already mixed and bagged together, ready to be heated at the specified temperature and placed on the surface. This type of HFS system is applied with a handheld box, resulting in a 5 mm thickness that stiffens quickly because of its thermoplastic nature, allowing DOTs to reopen the road with minimum delay.

### *Polyurethane-Resin*

The polyurethane-resin was mainly developed to achieve quicker curing times at lower temperatures than other existing systems. It is a chemically curing, multiple-component system. The components are mixed together with a handheld beater and laid by hand. Afterward, the aggregate is spread separately by hand or mechanically.

### *Acrylic-Resin*

This is another two-component system with a much faster curing time than epoxy-resin. The curing process does not begin until the aggregate, which contains the curing agent, is spread over the surface. The consistency of this binder is designed to sufficiently wet the aggregate in order to provide an adequate bond without the binder submerging the crush stone particles, or chips.

## **Aggregates**

### *Performance Tests*

Aggregates for HFS systems should provide for skid-resistant surfaces. They should be able to resist the polishing effect caused by tire traffic, and they should be resistant to the disintegration caused by weathering. The higher the PSV of an aggregate, the longer the aggregate will provide sufficient friction when used in road surfacing. The surface layer needs to retain its texture for as long as possible to provide skid resistance to traffic. The following are some of the tests commonly performed on HFS aggregates:

**Standard Practice for the Accelerated Polishing of Aggregates Using the British Wheel (AASHTO T279, ASTM D3319).** This test method simulates the polishing action of vehicular traffic on aggregates used in pavements. The polished value is a measure of the accelerated polishing caused by a British wheel followed by a friction test. This value is used to rate or classify aggregates for their ability to resist polishing under traffic. The first step in this procedure is to determine the initial friction value of each prepared test specimen by using the British Pendulum (ASTM E303). The specimens are then clamped around the periphery of the road wheel using rubber O-rings near the edge of the specimens in order to form a continuous strip upon which the small-tired wheel shall ride freely without bumping or slipping. During the test, specimens are subjected to a 320 rpm road wheel with a total surface load of 88 lb-f (391 N) and a 66 g/min application rate of silicon carbide. After the polishing action is completed, the specimens are removed from the fixture, washed thoroughly to remove grit, and are re-tested for a friction value with the British Pendulum in order to determine the polish value.<sup>7,8</sup>

**Resistance to Degradation and Abrasion (AASHTO T96, ASTM C131).** This method simulates degradation by abrasion of small-sized aggregates. The first step in this procedure is to weigh the sample. Then the sample and the steel bearings are placed in the Los Angeles testing machine at 30 rpm for 500 revolutions. Afterward, the material is discharged and a sieve analysis is conducted. Lastly, the aggregates are washed and weighed to determine the loss by abrasion.<sup>7,8</sup>

**Soundness of Aggregates by Freeze-Thawing (AASHTO T103-91, ASTM C88).** This test method simulates the behavior of the aggregate under freeze-thaw conditions to determine disintegration. In this procedure the test specimen should be washed, oven dried, sieved, and weighed. Then the samples are immersed in water for 24 hours prior to the start of the freezing cycle and must be frozen and thawed in this completely immersed condition. In case of partial immersion, other procedures described by the American Association of State Highway and Transportation Officials (AASHTO) must be followed. In many instances a freezing period of two hours is suitable depending on the freezing equipment. Following freezing, the samples must be thawed for 30 minutes at 70° F in an alcohol-water solution. This procedure must be repeated for 50 cycles. After the completion of the final cycle, the specimens must be dried and sieved to determine the loss in each sieve.<sup>7,8</sup>

### *Commonly Used*

The aggregates used for each application will depend on the performance tests described in the previous section. The types of aggregates commonly used include the following.

**Calcined Bauxite.** Calcined bauxite aggregate comes from aluminum ore when it is exposed to prolonged heating temperatures of approximately 2,900°F (1600°C) to increase its hardness and physical stability. The density of calcined bauxite varies from 2.6 to 3.4 g/cm<sup>3</sup> depending on its source. This property is typically a good indicator of the PSV (high density usually indicates high PSVs). The typical PSVs for calcined bauxite are in the upper 60s/lower 70s.

**Dolomite.** Some recently developed anti-icing surfaces use aggregates made in large part of the mineral dolomite, which is the double carbonate of calcium and magnesium. Replacement of part of the calcium from limestone by magnesium is the most important process in the formation of dolomite. This replacement is seldom complete, and many grades exist between limestone and dolomite. Dolomite is commonly light in color and often has ferrous iron compounds that may oxidize, tinting the rock shades buff and brown.<sup>9</sup>

**Granite.** Granite comprises quartz and potassium feldspar, and its color varies from very light to medium tones of gray. Due to its mineral composition and interlocking crystals, granite is hard and abrasion-resistant. The toughness of granites is usually superior to that of sandstone, limestone, and marble. It can provide PSVs of 62 or greater.<sup>9</sup>

**Silica.** Silica occurs commonly in nature as sandstone, silica sand, or quartzite. It is the raw material used for the production of silicate glasses and ceramics. Silica is one of the most abundant oxides in the earth's crust. It can exist in an amorphous form (vitreous silica) or in a variety of crystalline forms.<sup>9</sup> There are three crystalline forms of silica: quartz, tridymite, and cristobalite with two variations of each (high and low.) Silica has quality abrasion resistance and high thermal stability. It is insoluble in all acids with the exception of hydrogen fluoride.

**Steel Slag.** Slag is a by-product of steel manufacturing produced during the separation of the molten steel from impurities in steel-making furnaces. The slag forms as a molten liquid melt and is a complex solution of silicates and oxides that solidifies upon cooling. Steel slag must be crushed and screened to produce a suitable aggregate for an HFS system.<sup>10</sup>

For use in the HFS systems, other aggregates may be selected for their natural colors, which can, by color pigmentation, achieve a greater visual impact.

## Typical Application Procedures

The typically recommended locations for the HFS installations include areas of high friction demand such as bridges, intersections, roundabouts, toll plazas, bus lanes, exit-entrance ramps, crosswalks, school crossings, corners, steep grades, horizontal curves, and other identified hazardous areas. The main benefit of the HFS systems is that they increase the available friction of a road or bridge surface, which results in accident reductions and may in turn save lives.<sup>3</sup> Additionally, the HFS applications can be quickly constructed (by hand or machine) and may also incorporate retro-reflective nighttime hazard-warning capabilities.

The general procedure for installing an HFS starts with preparation of the original traveled surface. It must be clean, dry, and free from ice, frost, loose aggregate, oil, grease, road salt, and other loose matter likely to impair adhesion of the system to the surface. This is accomplished using brooms, compressed air, and/or shot blasting (Figure 2a). The surface temperature should then be measured to ensure it is greater than the installation standard. Drains, joints, and expansion devices must be covered with duct tape and plastic to prevent them from clogging with epoxy and aggregates.

The two components of the epoxy are usually delivered in 55-gallon drums that are laid down at the site and gravity fed into buckets of predetermined volume in a pre-established proportion (Figure 2b). In this case, the combination is mixed with a slow-speed drill fitted with a helical mixing blade. However, this step is not necessary when metered spraying is used to place the epoxy.



Figure 2. An HFS application.

If the resin is spread manually, grids should be laid out with tape to control the application rate of the epoxy (Figure 2c). Immediately after the epoxy is spread, workers use shovels and brooms to evenly spread the aggregates over the binder (Figure 2d). Finally, all excess aggregate should be removed and the system left to cure for a period of 2 to 4 hours. Typical applications use 1 gallon of epoxy to cover approximately 2.6 to 3 yd<sup>2</sup> (23 to 27 ft<sup>2</sup>) and 40 lb of aggregate (200 lb/15 yd<sup>2</sup>).

Although the specific application temperature varies from product to product, the range of temperatures across which an HFS installation is recommended is between 55°F and 100°F. To apply the binder below these temperatures, the surface, the binder and the aggregates should be heated and the system's curing time extended.

A curing time of 2 to 4 hours is required for most applications under normal ambient temperatures. Curing will take longer at low temperatures, which can also compromise long-term performance.

## **Potential Sources of Failure**

An HFS system can fail because of raveling of the material, delamination, or polishing of the aggregate. The failure can be attributed to construction methods, product performance, and/or extreme environmental conditions during the application and in service. The most important concerns and recommendations are explained below.

### *Epoxy Preparation- Composition*

The two-part modified epoxy used on most of the HFS applications must be mixed at a specific ratio. Failing to maintain this ratio may affect the adhesion with the aggregate particles and/or the pavement surface. The use of creosol, an important component of most epoxy binders, has been slowly discontinued because of its strong odor and tendency to burn the skin during application. Some studies suggest that the new epoxy formulations exhibit worse performance than previous combinations that included creosol.<sup>14</sup>

### *Epoxy-Aggregate Placement*

Epoxy should be spread homogeneously over the surface and at the correct rate to prevent the aggregate from becoming immersed in the binder. There needs to be complete coverage of the wet binder with the aggregate to achieve a uniform surface, and no wet spots should be visible once the aggregate is placed. Even and complete coverage can be difficult as most of these surfaces are applied at night (when visibility can be poor) to reduce impact on traffic flow.

### *Existing Pavement-HFS Compatibility*

Some types of pavements are particularly difficult for the installation of an HFS. For example, the high permeability of porous asphalts makes it difficult to achieve a uniform epoxy surface.<sup>14</sup> It is also not recommended that an HFS system be placed on pavements that are less than 1 month old. For any application, the soundness and cleanliness of the existing surface are among the most important determinants of performance.

### *Humidity and Moisture (Surface and Aggregate)*

Humidity and moisture are critical to a successful installation of an HFS. Surface humidity caused by condensation and fog impedes the full distribution and adhesion of the epoxy across the surface. Likewise, high moisture content in the aggregate before the system is installed could compromise the aggregate's ability to bond with the epoxy. This moisture could cause raveling and peel-off when the HFS system is in service. For example, moisture trapped below the impermeable layer as the surface undergoes freeze-thaw action may lead to severe raveling or delamination, as shown in Figure 3.

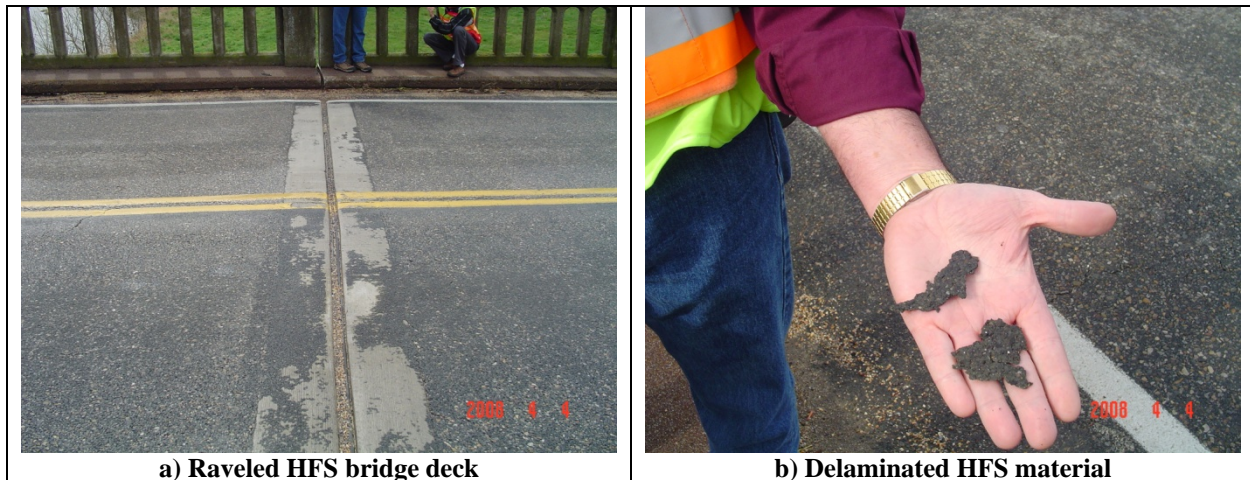


Figure 3. High friction surface raveling.

### Commercially Available Systems

HFS systems are marketed all over the world for applications that vary from airport to bridge deck to challenging roadway alignments. Table 1 lists some of the most commonly available commercial systems and provides the contact information for a U.S. supplier. These systems included products marketed as Crafcro HFS, FLEXOGRID, SafeLane, Tyregrip, Italgrip, and Safe-T-Grip. The contact information for each supplier is presented in Table 1.

Table 1. HFS products available in the United States

Products Evaluated	Contacts: Websites and E-mail	Telephone Information
Crafcro HFS (Crafcro INC)	Nick Nedas E-mail: <a href="mailto:nick.nedas@crafcro.com">nick.nedas@crafcro.com</a> <a href="http://www.crafcro.com/">http://www.crafcro.com/</a>	Office: (512) 432-5170 Mobile: (602) 228-1269
FLEXOGRID (POLY-CARB)	Punit Zen E-mail: <a href="mailto:info@poly-carb.com">info@poly-carb.com</a> <a href="http://www.poly-carb.com/">http://www.poly-carb.com/</a>	Mobile: (678) 296-9910 Office: (440) 248-1223
Italgrip® (Italgrip USA)	Robert B. Schmiedlin E-mail: <a href="mailto:schmiedlin@italgrip.com">schmiedlin@italgrip.com</a> <a href="http://www.italgrip.com/">http://www.italgrip.com/</a>	Office: (608) 592-2725 Mobile: (608) 698-1712
SafeLane™ (Cargill)	Anthony Hensley E-mail: <a href="mailto:SafeLane@Cargill.com">SafeLane@Cargill.com</a> <a href="http://www.cargillsafelane.com">http://www.cargillsafelane.com</a>	Office: (866) 900-7258 Mobile: (423) 488-6884
Safe-T-Grip (Traffic Calming USA)	Glyn Owen E-mail: <a href="mailto:glyn@trafficalmingusa.com">glyn@trafficalmingusa.com</a> <a href="http://www.trafficalmingusa.com">http://www.trafficalmingusa.com</a>	Office: (770) 505-4044 Mobile: (404) 512-1792
Tyregrip® (Prismo USA/ Ennis Paint)	Richard J. Baker E-mail: <a href="mailto:rbaker@ennispaint.net">rbaker@ennispaint.net</a> <a href="http://www.prismousa.com/">http://www.prismousa.com/</a>	Office: (804) 213-0335 Mobile: (804) 319-7456

#### *Crafcro HFS*

The HFS system offered by Crafcro INC. is a chemically engineered, modified-epoxy overlay designed to provide a flexible high friction coating for bridges, highways, and other



roadways. This epoxy-polymer overlay consists of a two-component epoxy binder that is applied to the surface, which is then covered by selected aggregates. Because of their properties, these selected aggregates ensure that upon fracture they will micro-fracture, remaining sharp and retaining high skid resistance.

The Crafcro system offers various aggregate choices, which provide distinct frictional characteristics, colors, and uses. Bauxite chippings from China and Guyana are available in natural colors and are used where high surface friction and long-term wear resistance are required. The American granite aggregate (supplied in natural silver and red) is used when quality surface friction is desired. Other color-coated aggregates may be used to improve driver awareness.

#### *FLEXOGRID (Poly-Carb Inc.)*

The FLEXOGRID system binder is a chemical combination formed by an epoxy and urethane designed to provide a flexible, waterproofing membrane with sufficient strength to withstand snow plows, cold and hot weather, and the pounding from cars and trucks. This product utilizes a flint aggregate (silica) or a combination of basalt-granite chips to provide the desired surface friction. The materials used for this application are domestic, including the binder. This application is designed to be installed on conventional concrete, concrete-filled steel grid decks, steel plate decks, fiber reinforced polymer decks, and asphalt. The aggregates and the binder are machine-applied (3,000 yd<sup>2</sup> per day).

#### *Italgrip*

Italgrip was implemented for the first time in the United States in 1999. This HFS system consists of a two-part polymer-resin placed on either asphalt concrete (AC) or PCC pavement surface and covered with an artificial aggregate of re-worked steel slag 3 to 4 mm in size. The Italgrip system provides high friction and has been found to reduce highway noise. This thin surface treatment is primarily intended for application in heavily trafficked areas experiencing friction problems or high accident rates across short sections of roadway.

#### *SafeLane (Cargill)*

The SafeLane system consists of a combination of epoxy and a proprietary domestic dolomite aggregate used to improve friction. The aggregates on the surface can be charged with standard anti-icing fluids that store the chemicals and automatically release them during periods of frozen precipitation, delaying the formation of ice on roadways and bridge decks.

#### *Safe-T-Grip*

The Safe-T-Grip system consists of a two-component polymer-resin with high skid-resistant aggregates such as bauxite or granite (1 to 3 mm) that provides a waterproof, durable and skid-resistant surface. It is usually machine-applied (7,500 ft<sup>2</sup> per hour). Hand-applied treatments need aggregates to be applied within 5 minutes of the spreading of the resin on the surface.

## *Tyregrip*

The Tyregrip system is a two-part, cold-applied exothermic treatment formed by an epoxy/amine binder and natural or pigmented aggregates, which usually are buff or gray calcined bauxite. The aggregate used in this system is graded from 1 mm to 3 mm. The level of friction for the system can be varied. For example, calcined bauxite can be used to render a PSV of 68 or greater. This HFS is available in a variety of colors. Tyregrip also offers reflective color-coated chippings as well as pigmented and un-pigmented binders for different visual effects.

## **Previous Studies of High Friction Surfaces**

There have been several efforts by different agencies to determine when HFS systems are suitable, durable, and/or cost-effective techniques for enhancing the safety and drainage characteristics of roadways. The most relevant are briefly described in this section.

### *Investigative Study of the Italgrip System–Noise Analysis*

The Wisconsin DOT conducted a study 10 years ago<sup>11</sup> to identify and quantify the impact on exterior vehicle noise when Italgrip was applied on a portland cement concrete (PCC) pavement. The surface treatment was installed on a jointed, un-doweled, transversely tined PCC pavement in Waukesha County. A 3 mm aggregate was applied to both eastbound lanes, while 4 mm aggregates were applied to the westbound lanes. This study concluded that Italgrip produces a 2 to 3 decibel decrease in noise level when compared to other pavements at speeds of 60 mph and 65 mph, a noticeable change in sound to the ear. It also found that the noise level difference between 3 mm and 4 mm aggregates is insignificant.

### *Trials of High Friction Surfaces for Highways*

The Transport Research Laboratory (TRL) in the U.K. conducted a project designed to better understand the main features and performance of the different HFS systems.<sup>4</sup> The binders studied were epoxy-resin, rosin-ester, polyurethane-resin, and acrylic-resin. The report described a series of tests conducted at different stages in the life of different types of the HFS. The HFS systems were ranked in terms of maintained skid resistance, texture depth, and longevity. The study showed that the epoxy-resin and polyurethane-resin systems most consistently maintained their binder properties, followed by the acrylic-resin system and the rosin-ester system. It was also found that the polyurethane and acrylic-resin systems have shorter curing times than the epoxy-resin systems, although not as short as the rosin-ester, which allows the road to be opened to traffic faster.

### *Evaluation of Cargill SafeLane Epoxy Overlay*

An evaluation of the performance of the SafeLane system when compared to a conventional modified-epoxy concrete overlay (EP-5) with silica aggregates was conducted in Virginia.<sup>12</sup> Two SafeLane and two EP-5 systems were placed on I-81 bridge decks and on the Virginia Smart Road hydraulic cement concrete pavement section.

The study showed that the SafeLane overlay can provide a skid-resistant wearing and protective surface for bridge decks. The evaluation was unable to find a difference in the ability of the systems to resist accumulation of ice or snow, a primary objective of the project.

#### *Performance of FLEXOGRID (POLY-CARB, Inc.) Bridge Overlay System*

A study made by the Iowa DOT evaluated the performance of the FLEXOGRID system on a highway bridge deck in the state of Iowa during a 5-year period.<sup>13</sup> Results showed that this HFS system increased friction measured with a locked-wheel trailer from 36.5 SN to 67.5 SN. Four years later, a friction value of 64.5 SN was recorded. Initial delamination problems were detected after the first year, and, by the end of the sixth year, 530 ft<sup>2</sup> of the 14,080- ft<sup>2</sup> bridge overlay application had delaminated. This research attributed the delaminating problem to moisture trapped below the impermeable HFS layer at the time of construction. The overlay was stripped off after 6 years of service.

#### *Evaluation of Innovative Safety Treatments*

A report by the Florida DOT evaluated innovative safety treatments implemented in Florida and other state highway agencies to determine the impact of safety treatments on crashes and other surrogate measures of safety.<sup>14</sup> These treatments included temporary rumble strips, white enforcement lights, a motorist awareness system, countdown pedestrian signals, in-roadway lights and Tyregrip high-friction surfaces. This evaluation concluded that the Tyregrip HFS overlay system is effective in increasing friction between the roadway and vehicle tires, as well as helping drivers maintain their lane position under wet pavement conditions. This research also inferred that drivers tend to slow down when traveling across the HFS section.

#### *Investigative Study of Italgrip System 2008*

In 2008, the Wisconsin DOT conducted a follow-up study of the Italgrip system to assess if it was a suitable, durable, and cost-effective technique to enhance the safety and drainage characteristics of roadways.<sup>15</sup> Locked-wheel friction testing showed that the system increased the friction number from an average of 42.9 SN to 72.6 SN after application. After 5 years in service the sites averaged 59.4 SN. Even though friction decreased after 5 years, the average friction number was still 38 percent greater than before the application. The results also showed that the number of accidents at the sites decreased by 93 percent, the number of vehicles involved in accidents decreased by 89 percent, and the number of accident-related injuries decreased by 86 percent during a 3-year period. It was also found that 4 mm aggregates showed better friction than 3 mm aggregates and that this HFS system could reduce the tire-pavement noise by four decibels.

## **Functional Performance**

### **Locations and General Description of Applications**

Table 2 provides the locations of HFS applications that were selected for functional performance testing during the survey conducted for this study in 2008. The diversity of the

testing sites and the unique weather conditions of each location provided the opportunity to obtain a comprehensive idea of the HFS system performance. Due to funding restrictions, the locations were located mainly on the east coast and eastern mid-western areas of the country. The overall goal of the study was to test each system at least one time. As it turned out, some suppliers had multiple small-area applications within relatively close proximity. This enabled multiple samples of the same system in slightly different applications. All of the locations analyzed and listed in Table 2 correspond to bridge deck overlay applications.

**Table 2. HFS locations investigated.**

<b>HFS</b>	<b>State</b>	<b>Code</b>	<b>Location</b>
Crafco HFS	Tennessee	TN-C	Spring Hill, Westbound End Southern parkway toward Columbia
FLEXOGRID	Wisconsin	W-P	La Crosse, Highway 35 S Wisconsin
Italgrip	Tennessee	TN-I-4	Spring Hill, Westbound End Southern parkway toward Columbia
Italgrip	Wisconsin	W-I-1	La Crosse, Wisconsin Highway 35 N
Italgrip	Wisconsin	W-I-2	La Crosse, Wisconsin Highway 16 W
Italgrip	Wisconsin	W-I-3	La Crosse, Wisconsin Highway 16 E
SafeLane	Virginia	VA-S-1	I-81 Mile Marker 219 S
SafeLane	Virginia	VA-S-2	I-81 Mile Marker 239 N
Safe-T-Grip	Tennessee	TN-G	Spring Hill, Westbound End Southern parkway toward Columbia
Tyregrip	Virginia	VA-T	I-81 Mile Marker 210 S
EP-5*	Virginia	VA-E	I-81 Mile Marker 240 S

\*Standard epoxy overlay for bridge deck used by the Virginia Department of Transportation; evaluated for comparison only.

Figure 4 includes pictures of the HFS applications that were tested during the performance review. Figure 4a was taken at night during the construction of the Safe-T-Grip section in Tennessee. Figure 4b shows both SafeLane and EP-5 sections as constructed on the Virginia Smart Road, identical to the ones constructed on I-81 bridges. Figures 4c and 4d show the bridge applications of Italgrip and FLEXOGRID that have been in place for more than nine years. The Italgrip overlay was placed in a single application whereas the FLEXOGRID consisted of a two-layer application; thus, a significant difference can be noticed. Finally, SafeLane and Tyregrip applications on I-81 in Virginia can be seen in Figures 4e and 4f.



**Figure 4. Examples of HFS locations that were investigated.**

### Measurement of Friction and Texture Properties

As explained previously, the locations in Table 2 were visited in 2008, and friction and macrotexture measurements were taken with the DFT, the CTMeter and the GT. This section presents the data collected.

Average and standard deviations as computed for each of the friction and texture properties are presented in Table 3. For the GT values reported, six measurements obtained from the beginning and end of each different surface location were omitted from the data set to account for possible triggering error. Additionally, data were also omitted when it became apparent that, especially on bridge decks, the joints caused the equipment to jump at greater speeds, resulting in outlier values recorded in these transition points between sections. All DFT and CTMeter averages and standard deviation values are for the six measurements for each HFS application. The values provide an indication of typical values of initial friction and texture that could be expected of an HFS system on highways and bridges. For comparison purposes, the table also includes values of friction and texture for typical flexible and rigid pavement surfaces constructed in 1999 on the Virginia Smart Road.

Table 3 shows that, when new, the HFS applications exhibit considerably higher friction than conventional pavement surfaces. The difference in initial friction between these and the rigid or flexible pavements emphasizes that the HFS systems are very effective in increasing the friction in trouble spots where it has been documented that wet-weather crashes or crashes caused by deficient surface properties occur frequently and additional friction may be needed.

**Table 3. Friction and texture measurements for selected HFS.**

HFS	Code	Appl. Date	Friction (GN) at 40 mph	Std Dev	Friction (DFT) at 20kph	Std Dev	Texture (MPD)	Std Dev
Crafco	TN-C	2008	1.05	0.05	0.98	0.02	1.46	0.09
Italgrip	TN-I	2008	1.02	0.04	1.01	0.01	1.61	0.12
Italgrip	W-I-1	1999	0.67	0.07	0.78	0.04	1.03	0.10
Italgrip	W-I-2	1999	0.53	0.08	0.68	0.04	1.07	0.06
Italgrip	W-I-3	1999	0.63	0.07	0.68	0.02	1.04	0.08
FLEXOGRID	W-P	1999	0.69	0.03	0.65	0.02	1.07	0.24
Safe-T-Grip	TN-G	2008	0.90	0.12	1.01	0.02	1.57	0.23
SafeLane	VA-S-1	2005	0.50	0.05	0.48	0.04	1.53	0.16
SafeLane	VA-S-2	2005	0.57	0.06	0.55	0.05	1.56	0.20
Tyregrip	VA-T	2006	0.90	0.14	1.00	0.02	1.28	0.10
EP-5	VA-E	2005	0.65	0.11	0.62	0.03	1.16	0.09
<i>SM-9.5D</i>	<i>Ref.</i>	<i>1999</i>	<i>0.77</i>	<i>0.01</i>	<i>0.82</i>	<i>0.03</i>	<i>1.05</i>	<i>0.11</i>
<i>SMA-12.5</i>	<i>Ref.</i>	<i>1999</i>	<i>0.74</i>	<i>0.01</i>	<i>0.72</i>	<i>0.04</i>	<i>0.91</i>	<i>0.13</i>
<i>OGFC</i>	<i>Ref.</i>	<i>1999</i>	<i>0.68</i>	<i>0.01</i>	<i>0.63</i>	<i>0.04</i>	<i>1.58</i>	<i>0.09</i>
<i>Tinned CRCP</i>	<i>Ref.</i>	<i>1999</i>	<i>0.82</i>	<i>0.02</i>	<i>0.77</i>	<i>0.01</i>	<i>1.17</i>	<i>0.09</i>

Notes: The measurements presented in italics are for non-HFS pavements on the Virginia Smart Road, which experience limited and controlled traffic. The GT measurements were made at vehicular test speeds of 40 and 50 mph, which correspond to slip speeds between 6.2 and 7.8 mph. The Safe-T-Grip system in Tennessee was not completely cured at the time of measurement. The locked-wheel friction measurements used in this study (not shown in this table) were obtained only from the Wisconsin DOT, which used them for reference. This information should be compared only on sections longer than 150 feet because the locked-wheel devices cannot accurately measure small test sections at high speeds.

As can be seen, there is no direct correlation between the texture results and the friction performance. This is a very interesting discovery because it is contraindicative of the normal assumptions made in previous studies<sup>16, 17</sup> that promote a fixed relationship between texture and friction with the concept of a speed gradient ( $S_p$ ) to correlate the two. This indicates that the material properties of the aggregates used in the HFS alternatives evaluated are more dominant

to evaluate their frictional performance than the texture size of the surface, at least within this range of textures.

Under normal conditions, it is desirable to have a greater texture depth to more rapidly displace water from the surface, but it is clear now that friction is more dependent on the types of aggregates used, and perhaps greater emphasis should be placed on them when selecting the materials for the pavement surface layers. Figure 5 illustrates the average and variability of the friction and texture data collected using whisker box plots for all of the HFS systems.

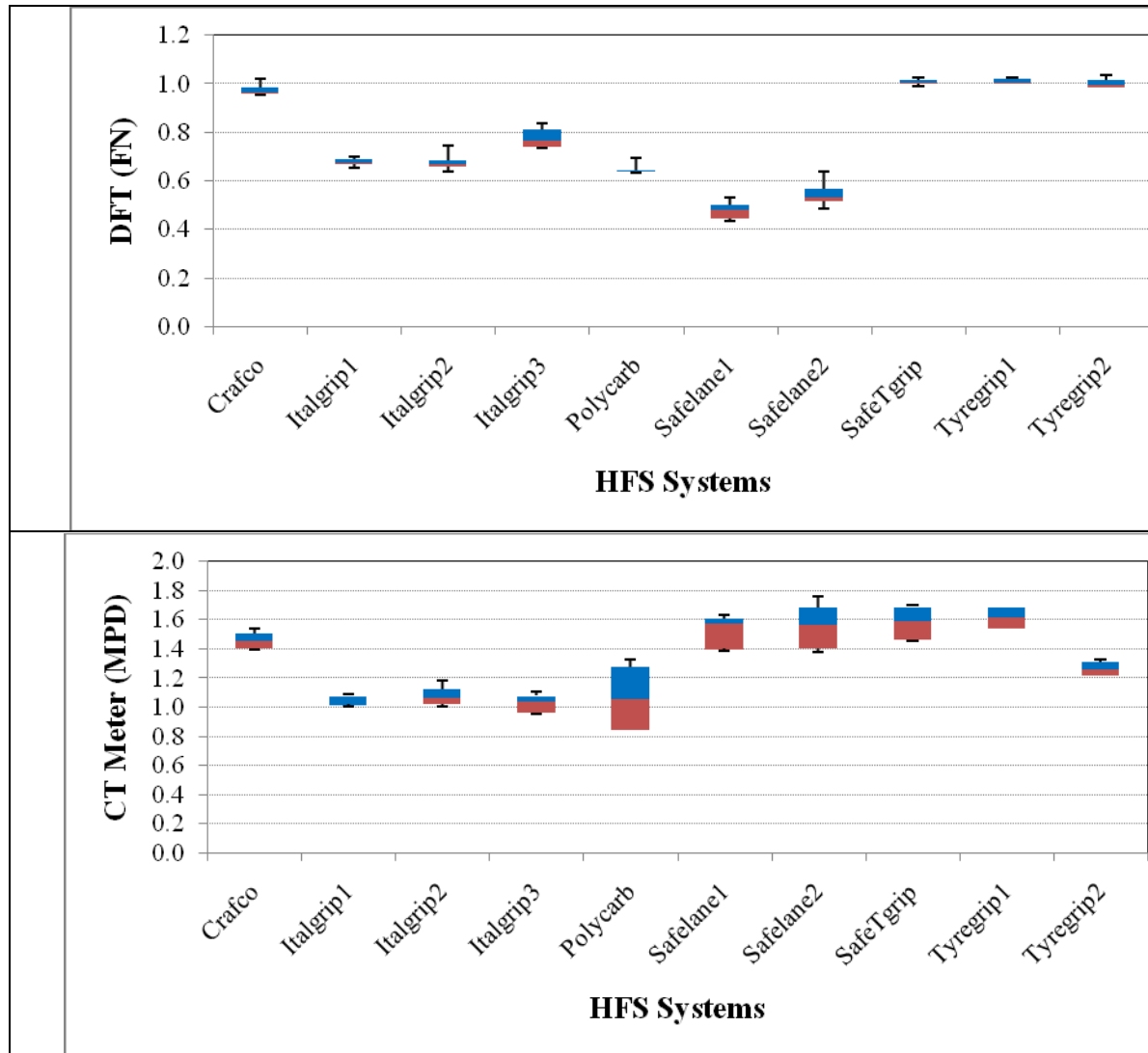


Figure 5. Texture and friction whisker box plot for all HFS systems.

To illustrate the influence of the friction coefficients on a real-life situation, the following example scenario was calculated. If a 2,500-lb vehicle was traveling at 65 mph on a 2 percent downhill grade under dry pavement conditions with a brake efficiency of 100 percent, it would require 210 ft of minimum stopping distance on a pavement with a friction of 0.74 DFT (average initial friction of non-HFS pavements from Table 3).

If under the same vehicular and pavement conditions, the same vehicle traveling on an HFS surface with a coefficient of friction of 0.96 DFT (average initial friction of HFS from Table 3) it would only require 158 ft as the minimum stopping distance. This is a reduction of 25 percent in the required minimum stopping distance. If evaluated under wet-pavement conditions the total length would increase with a similar reduction, if not more.

### International Friction Index for High Friction Surfaces

Improved skid resistance is the primary objective with any HFS system. Although those systems surveyed and discussed in this research were from domestic highway projects, many relevant systems exist around the world on facilities that are not intended for ground vehicle travel (e.g., runways). Even when these systems are used for roadways, the equipment used to characterize friction varies broadly from one country to the next. For these reasons, it made sense to develop standard reference values for the different products that were evaluated using the International Friction Index (IFI) parameters  $F(60)$  and  $S_p$ , as computed using ASTM 1960 with some small modifications. Table 4 reports the results based on the DFT and CTMeter measurements using the original IFI coefficients<sup>16</sup> and revised coefficients as presented in another report and used in the derivations.<sup>18</sup>

Table 4 presents the results of the as-measured Grip Numbers (GN Field) and the “estimated” values that would result from a back-calculation approach using the original and revised IFI coefficients to obtain Grip Numbers (ORIG COEFF FR[S] and REVISED COEFF FR[S]). As can be seen, none of the sets of coefficients were accurate in harmonizing the DFT and GT measurements since the estimated Grip Numbers do not match the actual field measurements. This confirms the suggestion made earlier about the discrepancy in the exclusive relationship between the texture parameter and the friction. It is suggested that more data on a wider range of pavement surfaces, including positively textured surfaces such as an HFS, may be needed to accurately determine better harmonization coefficients, probably by including some aggregate material parameter based on the PSV.

**Table 4. HFS friction measurements using the IFI.**

CODE	TX	Sp	F(60)	ORIG COEFF FR(S)	REVISED COEFF FR(S)	GN FIELD
TN-C	1.46	145.16	0.625	0.84	0.47	1.05
TN-I-4	1.61	158.62	0.655	0.86	1.02	1.02
W-I-1	1.03	106.59	0.473	0.69	0.35	0.67
W-I-2	1.07	110.18	0.427	0.60	0.14	0.53
W-I-3	1.04	107.49	0.424	0.60	0.12	0.63
W-P	1.07	110.18	0.412	0.57	0.07	0.69
VA-S-1	1.53	151.44	0.351	0.41	-0.19	0.50
VA-S-2	1.56	154.13	0.392	0.47	-0.02	0.57
TN-G	1.52	150.54	0.648	0.87	1.01	0.90
VA-T	1.28	129.02	0.623	0.87	0.96	0.90



## Economic Assessment

### Construction Costs

Each of the contacts from the companies listed in Table 1 provided an approximate cost estimate for a typical application of each product. These prices are listed in Table 5, but what these estimates include vary considerably from one product to another. For instance, some prices may only cover delivery of the binder and aggregate to the job site, while others may incorporate use of proprietary installation equipment. It should also be noted that the HFS cost values presented in Table 5 do not include traffic control, supervision, or other secondary costs.

Because most of these applications are relatively new and, for the most part, have not seen widespread use in the United States, cost estimates from the pricing data gathered for this study will vary considerably among the alternatives. In all of the HFS sections surveyed, the options varied diametrically. For example,

- Suppliers have donated the products for demonstration projects and the state DOTs have provided the necessary manpower, traffic control, and other equipment such as air compressors, blowers, mechanical brooms, etc. as was the case in Tennessee; or
- Complete installations have been conducted with private contractors who were hired by the supplier (as was the case in the SafeLane overlays placed on the Virginia Smart Road) to ensure quality control standards for the installation of their products.

At this point, a direct comparison between the different products and their observed performance is not possible. Most of the surveyed applications have not been in place long enough to analyze the wear that traffic and time will have on the frictional capacity of the installed system.

**Table 5. Type of aggregate and price for selected HFS systems.**

Product	Type of Aggregate	Total Price per ft <sup>2</sup>
Crafc0	Bauxite (China-Guyana)	\$ 3.00
	Granite	\$ 2.25
FLEXOGRID	Basalt + granite	\$ 4.50–\$ 5.00
	Silica	\$ 2.20–\$ 2.70
Italgrip	Steel slag (patented)	\$ 2.20
SafeLane (Cargill)	Dolomite	\$ 6.00
Safe-T-Grip	Granite	\$ 1.60
Tyregrip	Calcined bauxite (buff and grey)	\$ 1.70

### Accident Costs

The analysis performed in this study is illustrative of the type of analysis that can be used to determine whether an HFS system can be economically justified. This evaluation used the Wisconsin Italgrip applications because they were the only applications that have been in place long enough and had crash data available to conduct the analysis. Typical monetary values suggested by the Minnesota DOT were used for the cost of fatalities, injuries, and property damages and are listed in Table 6.<sup>19</sup> It should be noted that these costs also vary depending on

the source as another report places the cost of an average fatality at \$977,000, but the cost associated with a critically injured crash survivor at \$1.1 million.<sup>20</sup>

**Table 6. Crash values for economic study.**

MN/DOT Crash Values	Dollars per Crash
Fatal	\$3,600,000
Injury Type A only	\$280,000
Injury Type B only	\$61,000
Injury Type C only	\$30,000
Property damage only	\$4,400

Accident data for the Wisconsin Italgrip applications were collected during a 6-year period (3 years prior to the installation and three years afterward). Note that the Wisconsin DOT report states that it is possible that some accidents may not have been accounted for. It is not unusual, for example, for vehicles to leave the scene, accidents to not be reported, and/or exact locations to be incorrectly documented on the accident reports or missed by the database search.<sup>15</sup>

### **Estimated HFS Functional Service Lives**

Although there were three Italgrip HFS sections placed in Wisconsin that were surveyed, historical friction data were only available for one for a 6-year period between 1999 and 2004. This section was in La Crosse County Highway 16 westbound (W-I 2). The other two sections were included in the accident analysis report but are lacking historical friction data. Figure 6 shows the locked-wheel friction measurements at 40 mph using both the smooth and the ribbed tires collected by the Wisconsin DOT.<sup>15</sup>

Notice in Figure 6 that it seems that the friction of the section seems to increase over time. The report attributes this apparent increase in friction to several factors. Measurements after heavy rains tend to reflect some “cleaning” of the HFS system resulting in higher friction numbers. Measurements at greater temperatures also tend to read higher. Finally, depending on the skill of the operator and the configuration of the HFS installation, measurements with the locked wheel devices may incorporate surface material and features that are not representative of the HFS, especially on repeat runs.<sup>15</sup> Nonetheless, the friction numbers in general were found to be approximately 38 percent higher than before the Italgrip HFS applications were made.

Based on these observations and the results obtained with the GT evaluations in Wisconsin in 2008, it seems safe to state that these HFS applications have exhibited acceptable service lives during the 10 years they have been in service. The data in Table 3 confirm that it is reasonable to expect most HFS systems to maintain acceptable friction for approximately 10 years. It must be added that, although the overall level of friction and macrotexture is still acceptable, all of the Italgrip sections showed advanced degrees of raveling, as can be seen in Figures 3a and 4c. It must also be understood that it is hard to quantify the effect of raveling on the performance of the friction parameters. It is imperative to continue monitoring all of the other sections constructed to confirm or deny the 10-year period of service life for an HFS.

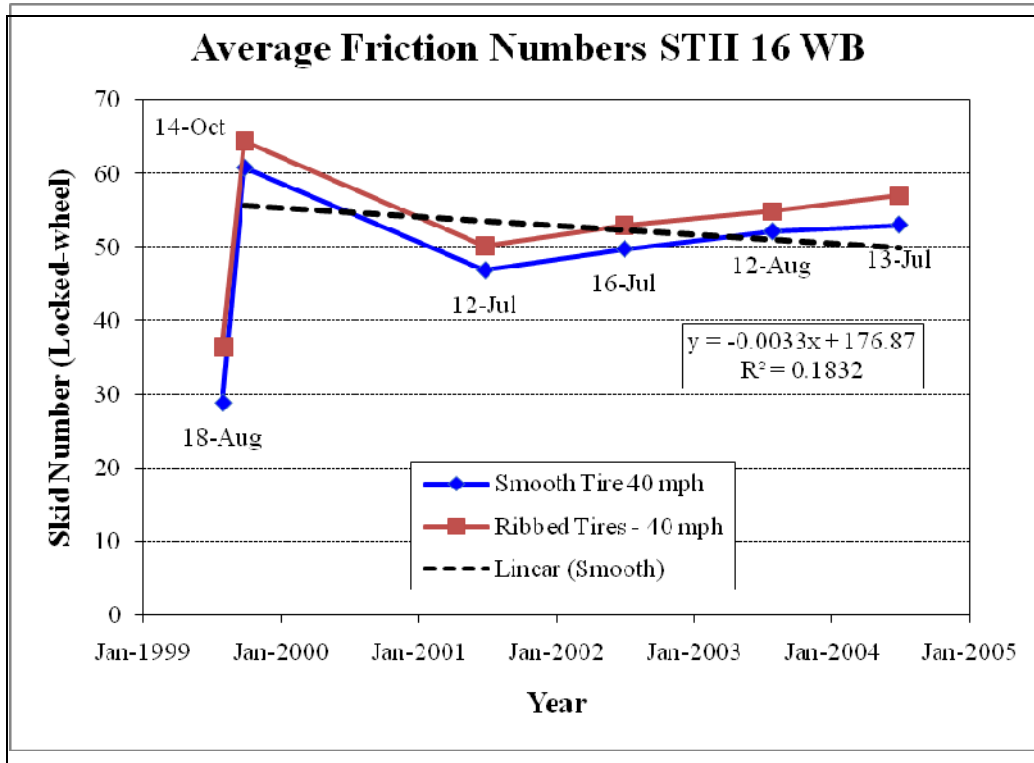


Figure 6. HFS friction deterioration rate.

### Benefit-Cost Analysis

For the HFS systems surveyed through this study, typical construction costs can be extracted from those reported in Table 5. Routine maintenance costs are assumed to be the same for the base and alternative scenarios since the alternative does not have a significantly different effect on maintenance and since they both require plowing, debris removal, etc. Typical accident costs were reported in Table 6 and should be used to compute benefits. Table 7 presents an example set of benefit-cost calculations from the Italgrip sections in Wisconsin. In this example, the Wisconsin DOT estimated the construction costs for the Italgrip sections in 1999 to be approximately \$13 per yd<sup>2</sup> and that 2008 costs are estimated at approximately \$20 per yd<sup>2</sup>.<sup>15</sup> The numbers of incidents after the applications are subtracted from the ones that occurred before the applications and multiplied by their respective costs (\$4,400 for vehicles and \$30,000 for injuries; see Table 6) to quantify the benefits. The costs are basically the covered areas at each of the sites multiplied by \$13 per yd<sup>2</sup>. Obtaining the benefit-to-cost ratios, the results show that in three of the four sections the alternative is economically justified compared to the base scenario, with benefit cost ratios ranging between 2 and 8.

The only HFS application with a benefit-to-cost ratio less than one is an application in Waukesha County. This single application is larger than the three combined applications in La Crosse County (14,911 yd<sup>2</sup> versus 10,200 yd<sup>2</sup>), which results in a greater cost of \$193,843 compared to \$132,600 in La Crosse County. The combined benefits in the reductions in the number of damaged vehicles and the number of injuries for the three applications in La Crosse County is \$515,600 compared to only \$90,800 in Waukesha County. It could be argued that,

**Table 7. Benefit-cost analyses for HFS locations in Wisconsin.**

<b>Waukesha County STH 16</b>		-	<b>La Crosse County STH 16 NB &amp; SB</b>	
Before Italgrip (Oct 96 - Sep 99)			Before Italgrip (Oct 96 – Sep 99)	
5 incidents			11 incidents	
7 vehicles			30 vehicles	
2 injured / 0 killed			6 injured / 0 killed	
After Italgrip (Nov 99 - Oct 02)			After Italgrip (Nov 99 - Oct 02)	
0 incidents			1 incidents	
0 vehicles			4 vehicles	
0 injured / 0 killed			0 injured / 0 killed	
Accident Benefit/Cost			Accident Benefit/Cost	
Vehicle Properties Benefit (7)	\$30,800		Vehicle Properties Benefit	\$114,400
Injuries-Death Benefit (2)	<u>\$60,000</u>		Injuries-Death Benefit	<u>\$180,000</u>
Total Benefits	\$90,800		Total Benefits	\$294,400
Section area yd <sup>2</sup>	14,911		Section area yd <sup>2</sup>	6,640
price per yd <sup>2</sup>	\$13		price per yd <sup>2</sup>	\$13
Total cost of HFS	\$193,843		Total cost of HFS	\$86,320
<b>B/C Ratio</b>	<b>0.47</b>		<b>B/C Ratio</b>	<b>3.41</b>
<b>La Crosse County STH 35 NB</b>			<b>La Crosse County STH 53 NB &amp; SB</b>	
Before Italgrip (Oct 96 - Sep 99)			Before Italgrip (Oct 96 – Sep 99)	
3 incidents			9 incidents	
16 vehicles			10 vehicles	
3 injured / 0 killed			3 injured / 0 killed	
After Italgrip (Nov 99 - Oct 02)			After Italgrip (Nov 99 - Oct 02)	
0 incidents			1 incidents	
0 vehicles			3 vehicles	
0 injured / 0 killed			2 injured / 0 killed	
Accident Benefit/Cost			Accident Benefit/Cost	
Vehicle Properties Benefit	\$70,400		Vehicle Properties Benefit	\$30,800
Injuries-Death Benefit	<u>\$90,000</u>		Injuries-Death Benefit	<u>\$30,000</u>
Total Benefits	\$160,400		Total Benefits	\$60,800
Section area yd <sup>2</sup>	1,460		Section area yd <sup>2</sup>	2,100
price per yd <sup>2</sup>	\$13		price per yd <sup>2</sup>	\$13
Total cost of HFS	\$18,980		Total cost of HFS	\$27,300
<b>B/C Ratio</b>	<b>8.45</b>		<b>B/C Ratio</b>	<b>2.23</b>

overall, the HFS installations have resulted in a benefit-cost ratio of 1.86, so the decision to implement the HFS applications for the state of Wisconsin has been positive. Given the multitude of factors that contribute to vehicle crashes, approaching the use of HFS applications on a network basis really makes more sense.

## CONCLUSIONS

- *HFS systems provide very high initial levels of friction and macrotexture, and it is reasonable to expect them to maintain high friction values for 10 years of service.*
- *In the few applications where before-and-after crash data were recorded, a benefit-cost analysis justifies the use of an HFS system. The reduction in crash cost is 2 to 8 times the cost of the treatments for these locations.*
- *Comparisons between friction data collected with the DFT and the GT indicate that the available harmonization models (i.e., the IFI) cannot be accurately applied to the HFS system.*

## RECOMMENDATIONS

1. *Both local and state highway agencies should consider the use of the HFS systems for localized situations in which skid resistance of the existing surface material is low and/or the friction demand is very high.*
2. *The cost-benefit analysis presented in this report can be used by these agencies to assess other products and installation locations and/or conditions.*
3. *The community of researchers engaged in the study of traveled surface characteristics should pursue more harmonization experiments with a wider range of pavement surfaces, including an HFS system and other types of surface treatments, to improve the IFI coefficients recommended by ASTM 1960.*

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