EVALUATION OF INTERNATIONAL FRICTION INDEX AND HIGH-FRICTION SURFACES

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ABSTRACT

State highway agencies have an obligation to provide users with optimal surface conditions under various weather conditions throughout the year. A satisfactory pavement surface should exhibit good friction and texture depth to reduce roadway highway accidents. This is why friction is starting to receive increased attention in the pavement management process.

There have been numerous research efforts by different countries and agencies to better understand the behavior of different friction testing devices and the influence of texture, speed, and other external conditions on their measurements.

The first part of this thesis presents a research effort to compare and harmonize texture and skid resistance measurements taken with various devices on 24 pavement sections with a wide range of textures. Measurements were compared and the International Friction Index (IFI) calculated following PIARC and ASTM steps.

The results revealed discrepancies in the IFI values calculated for the different devices, suggesting that the coefficients A, B, and C proposed by PIARC may need to be adjusted for each device considered before the IFI can be implemented by the surface properties consortium participating agencies. In this research the A, B, and C coefficients were then recalculated, and the predicted values of friction using these revised coefficients are presented. The coefficients developed were also used to obtain IFI values for high-friction surfaces (HFS).

It has been found that under different conditions, different parameters and coefficients will result. It is strongly recommended equipment comparison

experiments (like the NASA and Smart Road programs) continue to better determine the coefficients necessary for harmonization.

HFS have emerged as viable high-friction pavement alternatives that mitigate the consequences of driver error, poor geometric alignment of the roadway, and insufficient friction at the tire-pavement interaction, especially during wet weather. This thesis presents a study of the HFS available in the U.S. market and their performance (friction and texture) in different applications, under different weather conditions, and in various locations. This thesis also presents the results of the benefit-cost analysis for the studied HFS.

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CHAPTER I

INTRODUCTION

Highway accidents are a leading cause of death and injury around the world. Each year 3.2 million people are injured or disabled in the United States as a result of road crashes (N.T.S. 1999). These accidents not only create an enormous social cost for individual, families, and communities but also place a heavy burden on health services and economies.

In the United States one person dies every 12 minutes in a motor vehicle crash (N.T.S. 1999). This staggering situation has led the Federal Highway Administration (FHWA) to declare safety as one of its top priorities. Wet-weather crashes and run-off-road incidents are the two types of highway accidents responsible for the majority of incidents; about 25 percent of all crashes and 14 percent of all fatal crashes occur on wet pavement while 59 percent of highway fatalities occur when a vehicle leaves its lane (Julian and Moler 2008). It is for this reason that high-friction surfaces (HFS) are starting to be considered for roadway areas where additional friction is needed. HFS have the ability of increasing friction and texture by utilizing non-polishable, rough aggregates. Different types of binders are used to hold the aggregate particles together and glued to the road surface.

State departments of transportation strive to provide users with smooth-riding, safe surface conditions throughout the year. To do so, agencies periodically monitor the pavement surface properties. The measurements taken are used to develop surface restoration alternatives, new construction specifications, accident investigations, pavement management systems network surveys, and winter road maintenance. In particular, agencies use different devices, systems, and methods to measure friction and surface texture. This emphasizes the need for friction measurements harmonization to provide comparable friction measurements among different devices (Wambold et al. 1995).

1. BACKGROUND

High-friction surfaces, or HFS, are special surface treatments that utilize a non-polishable aggregate and a resin-based binder to hold the aggregate to the road surface. This technology was originated in the 1950s when the U.K. government's Transport and Road Research Laboratory (TRRL) began to test hard aggregates with various binders to produce extremely high-friction surfaces (Nicholls 1998). In the late 1980s researchers in the United States began to investigate the effectiveness of these surfacing systems to reduce crashes on black spots. In 1989 a study for the Federal Highway Administration (FHWA) done by University of Michigan on 15 ramps at 11 interchanges in 5 states found that surface properties were related to truck crashes, along with geometry and vehicle dynamics (Julian and Moler 2008).

In addition there have been numerous research efforts by different organizations to better understand the behavior of different friction testing devices and the influence of texture, speed, and other external conditions on their measurements. These efforts include the PIARC Experiment to Compare and Harmonize Texture and Skid Resistance Measurements, the NASA Wallops Friction Workshops, and the HERMES Experiment.

2. PROBLEM STATEMENT

The main objective of this thesis is to study some of the HFS systems available in the U.S. market by measuring their performance in different applications, under different weather conditions, and in various locations (states). The results obtained in this research will inform agencies about the HFS available in the United States and will provide a practical tool to estimate the expected increase in skid resistance, the expected service life, and the cost for each available product.

A secondary objective of this thesis is to compare friction measure results for different surfaces, including HFS, and show if the previously adopted models for normalizing these measurements are valid. The calibrated models should present the resulting measurements in a universal scale.

3. OBJECTIVES

The main goal of this thesis is to study some of the High-friction surfaces available in the United States market; by measuring their performance on different applications, under different weather conditions, and in various locations (states). Thanks to the results obtained in this research, agencies will be informed on the high –friction surfaces available on United States, and a practical tool to estimate the expected increase on skid, the expected service life, and the cost for each available product.

A secondary goal is to compare friction-measuring results on different surfaces including high-friction surfaces and show if the previously adopted models to normalize these measurements are valid. The calibrated models should allow presenting the resulting measurements in a universal scale.

The specific objectives defined to accomplish these goals are the following:

- Compare friction measuring results made with different devices.
- Evaluate if available harmonization adopted models are valid.
- Investigate the high-friction surfaces in the U.S. market
- Measure their performance in different applications.
- Compile the results obtained in a practical tool to support decision-making.

4. ORGANIZATION OF THE THESIS

Complying with the Virginia Tech's graduate school guidelines that encourage publication of research results, this thesis follows a manuscript format that includes two manuscripts. Each manuscript is used as an individual chapter of the thesis. Together they represent the research work in which the author was involved at Virginia Tech during the duration of the master studies. The first chapter of the thesis is this introduction, which provides an outline for the rest of the document.

Chapter 2: Evaluation of the International Friction Index

This evaluation compares friction measurements obtained with different devices and evaluates if the previously adopted friction harmonization models are valid. The chapter compares macrotexture and skid resistance measurements taken at the Virginia Smart Road in 2008 and provides groundwork for the harmonization of friction measurements taken on different HFS with various devices. This paper is scheduled for presentation at the 88th annual meeting of the Transportation Research Board and has been recommended for publication in the *Journal of the Transportation Research Board*.

Chapter 3: Field Performance of High-Friction Surfaces

This chapter presents a critical review of the literature on HFS binders, aggregates, application processes, HFS wear rate, saved lives, and the HFS available in the United States. It also contains expected initial friction for HFS systems and a sample benefit-cost analysis for an application tested in Wisconsin.

Chapter 4: Findings, Conclusions, and Recommendations

This chapter presents a summary of the concluding ideas that result from the research presented in Chapters 2 and 3 and gives recommendations for future research in these areas of study.

5. SIGNIFICANCE

Surface properties of roads and runways play an important role in road and airport safety. Road and runway surfaces must provide adequate levels of friction and texture for the vehicles traveling on them. The purpose of this thesis is to compare friction measure results on different surfaces, including HFS, and show if the previously adopted models for normalizing these measurements are valid. The results concerning the validity of normalizing models are invaluable for achieving consistent pavement management practices across national boundaries. They also contribute to the standardization of specifications for paving materials, highway design, and runway design.

This research produced new International Friction Index coefficients to compare and harmonize texture and skid resistance measurements taken with different devices and applied these coefficients to the studied HFS surfaces to compare calculated friction to measured friction.

This thesis provides agencies with detailed information on friction and texture performance of the HFS available in the United States. In addition it presents the methodology and sample data necessary to perform benefit-cost analysis for some of the available HFS, and it presents the durability, performance, and cost of these treatments in a practical and accessible guideline.

CHAPTER II

EVALUATION OF THE INTERNATIONAL FRICTION INDEX COEFFICIENTS

ABSTRACT

This paper presents a research effort to compare and harmonize texture and skid resistance measurements taken with various devices at the Virginia Smart Road in May 2008 by the members of the Virginia Consortium for Pavement Surface Properties.

There have been numerous efforts by different countries and agencies to better understand the relationship and behavior of different friction testing devices and the influence of texture, speed, and other external conditions on these measurements. Measurements obtained with different types of equipment on 24 pavement sections with a wide range of textures were compared, and the relationship between friction and speed for the different pavement sections and devices was studied. Data was collected using two locked-wheel skid trailers, a Griptester and a Dynamic Friction Tester (DFT). Nine asphalt sections were tested; six are SUPERPAVE mixes, two are Stone Matrix Asphalt and one is an Open Graded Friction Coarse. The concrete sections tested included one Continuously Reinforced Concrete Pavement with tined finishing and two epoxy overlays.

Even though all of the steps included in the specifications derived from the experiments by the Permanent International Association of Road Congresses (PIARC) were followed, the results obtained are not satisfactory. From a theoretical stand-point all the values computed with the International Friction Index (IFI) F60

should be equal, but this is not the case. Discrepancies in the IFI values calculated for the different devices suggest that the original coefficients determined during the PIARC experiment may need to be adjusted for the devices evaluated before the IFI can be implemented by the participating agencies.

1. INTRODUCTION

A satisfactory pavement surface should exhibit good qualities in terms of friction, smoothness, durability, light reflection, tire-pavement noise, splash/spray, and rolling resistance in order to provide the driver a safe and comfortable ride. Of all the factors, friction and/or texture depth of the surface is paramount to controlling and reducing highway accidents. This is why friction is starting to receive increased attention in the pavement management process. State Highway Agencies have an obligation to provide users with optimal surface conditions throughout the year. To do so, agencies must periodically monitor the surface properties. The measurements taken could be used to develop specifications for surface restoration, specifications for new constructions, accident investigations, network surveys for pavement management systems, and measurements for winter road maintenance.

There are different devices used by state highway agencies to measure friction. Even when taken by the same type of equipment, friction measurements are not consistent and therefore sometimes cannot be compared. This phenomenon emphasizes the need for harmonization in order to provide comparable friction surfaces from one device to another or from state to state.

2. OBJECTIVE

Different research efforts have studied procedures to normalize surface measurements made by different types of friction measuring equipment. The objective of this paper is to compare friction measuring results and show if the previously adopted models are valid. The research effort is aimed at comparing and harmonizing texture and skid resistance measurements taken at the Virginia Smart Road in 2008 by the members of the Pavement Surface Properties Consortium. This consortium is a joint effort by the Federal Highway Administration (FHWA) and the Connecticut, Georgia, Mississippi, Pennsylvania, South Carolina, and Virginia departments of transportation (DOTs).

3. BACKGROUND

3.1 Harmonization Effort

There have been numerous efforts by different organizations to better understand the relationship and behavior of different friction testing devices and the influence of texture, speed, and other external conditions on their measurements. Some of them are summarized following.

3.3.1 PIARC Experiment to Compare and Harmonize Texture and Skid Resistance Measurements

The Permanent International Association of Road Congresses (PIARC) conducted a series of experiments to compare texture and friction measurements. The first one was in 1992 when PIARC undertook an experiment that encompassed 16 countries, 47 measuring systems, and 54 sites with the intention of comparing and harmonizing texture and skid resistance measurements. Under this effort a wide variety of surfaces were tested and friction was measured with fixed-slip, side-force, and locked-wheeled systems at various speeds. Texture was measured by stationary and mobile equipment.

A series of relationships were developed from the comparisons of the measurements, which produced a common harmonized index called the International Friction Index (IFI) (Wambold et al. 1995). The PIARC model, as it is later called, incorporated macrotexture measurements with side-force, fixed-slip, and locked-wheel friction measurements, to recognize the previously identified dependence of friction on speed and texture.

Macrotexture measurements were found to be excellent predictors of the speed constant gradient needed to standardize the friction measurements using the IFI. Texture classifications were proposed and a procedure to estimate macrotexture from the profile data was incorporated into the IFI to estimate the Mean Profile Depth (MPD). The IFI can then be calculated from the results of friction values and speed constant (Wambold et al. 1995).

The IFI is a method to evaluate in common scale different measurements produced by different devices. This index consists of two parameters: the speed constant (Sp), predicted through the macrotexture measurements, and the harmonized friction at 60km/h (F60) (Wambold et al. 1995; Henry 2000).

The IFI calculation follows three steps:

1) Estimate the speed gradient coefficient Sp, using the measured macrotexture:

$$Sp = a + b * TX \qquad (1)$$

where

TX = macrotexture measurement (mm)

a, b = constants for different methods/devices used

2) Obtain the friction measurement from the specified slip speed S for the friction instrument used at the standard speed, set at (60 km/h):

$$FR(60) = FR(S) * e^{\frac{S-60}{S_p}} \qquad (2)$$

where

FR(60) = Adjusted value of friction

FR(S) = Friction value at recommended slip speed S for devices used

S = Recommended slip speed for each device [km/h]

3) Calculate the IFI friction number F(60) or golden standard estimate, using the coefficients developed by PIARC for each device:

$$F(60) = A + B*FR(60) + C*TX \tag{3}$$

where

A, B, C = calibration constants for the selected friction measuring device

TX = macrotexture measurement (mm)

3.1.2 NASA Wallops Friction Workshops Program

The NASA Wallops Friction Workshops have been a multi-year program where texture, friction, and roughness data has been collected through various devices, some of which were also used for the PIARC Experiment in 1992. Measurements are taken at different speeds and all devices are operated according to the manufacturer's procedures (Wambold et al. 2004).

For self-wetting friction devices, runs are made consecutively, and some nonstandard runs are performed, with variations on water film thickness, tire types, inflation pressures, slip speeds, and normal loads.

3.1.3 HERMES Experiment

In 2001-2002 the HERMES project was formed with the objective of analyzing the results of field trials in order to optimize the procedures and precision of calibrating methods previously developed. This project considered 15 testing devices, 7 texture measuring devices, and 61 test surfaces in five countries (Descornet 2004). Nine comparison meetings were run in the five member countries—Belgium, the Netherlands, Spain, Great Britain, and France—on a wide range of surfaces covering most materials and textures available in Europe. There were three meetings in the fall of 2001, three in the spring of 2002, and three in the fall of 2002.

Some of the findings for this project state that using the power law for constant speed versus mean profile depth better fits the data. This procedure also concludes that regarding consistency the European Friction Index works satisfactorily nevertheless, regarding precision it is hardly acceptable.

4. DATA COLLECTION

In 2006, the Virginia Transportation Research Council (VTRC) and the Virginia Tech Transportation Institute (VTTI), initiated a regional pooled-fund project known as the Pavement Surface Properties Consortium to establish a research program focused on enhancing the level of service provided by the roadway transportation system by optimizing pavement surface texture characteristics. The program was set up with support from the FHWA and now includes six DOTs from the states of Connecticut, Georgia, Mississippi, Pennsylvania, South Carolina, and Virginia. Established as a five-year program, the consortium is part of the activities of the Virginia Sustainable Pavement Research Consortium (VA-SPRC) and is managed by VTRC and run by the Center for Sustainable Transportation Infrastructure at VTTI.

Every year since its inception two years ago, all of the participant members meet for one week in May at the Virginia Smart Road at VTTI with the goal of comparing and verifying surface property measurements on the surfaces available at the facility with each of the member's different devices. This event is termed the Surface Properties Rodeo, which is a collaborative research effort of the Consortium that helps the participant organizations verify the operation, reliability, and accuracy of the equipment used for pavement evaluations and road construction quality control.

The may 2008 friction testing included two locked-wheel skid trailers, a Griptester and a dynamic friction tester (DFT). One of the locked-wheel trailers (LWS1) used only a smooth tire (ASTM E-524) while the other trailer (LWS2) tested the sections twice, once with the smooth tire and then with the ribbed tire (LWR1) (ASTM E-

501). The testing was conducted in accordance with ASTM E-274 (Henry and Siato 1983). Testing done with the Griptester utilized the test tire suitable for this fixed-slip device in accordance with (ASTM E 1844) (Wambold et al. 2006). The macrotexture data was collected with a circular texture meter (CT meter) (Flintsch et al. 2003) in accordance with ASTM E2157 . Figure 1 shows pictures of some of the participant devices.

The Virginia Smart Road is a 3.2 km (2-mile), test-adaptable facility for transportation research and evaluation. The test road includes 12 flexible pavement test sections; a transversally tined continuously reinforced concrete pavement (CRCP) section, a jointed reinforced concrete pavement (JRCP) section with some ground areas, and two high-friction epoxy-based surface treatments. The road has a maximum longitudinal grade of 6 percent. Since the two lanes were paved at slightly different times, the uphill (westbound) and downhill (eastbound) lanes have slightly different surface micro- and macrotexture. Both directions were tested in each run. Twelve sections each approximately 100 meters (300 feet) long were selected for the friction comparisons, and each section was tested in both lanes/directions, resulting in a total of 24 test locations. Five repetitions were completed for each device at each location.

Of the nine asphalt sections tested, six are SUPERPAVE mixes, two are Stone Matrix Asphalt (SMA) and one is an Open Graded Friction Coarse (OGFC). The concrete sections included a CRCP with tined finishing, and two epoxy overlays consisting of a double layer of aggregate bonded by epoxy coatings. Figure 2 shows example of the different types of pavement surfaces tested. Within each pavement section, friction data was collected with the locked-wheel skid testers and the Griptester tires aligned to the center of the left wheel path. Five repetitions were planned at target speeds of 20, 40 and 50 mph to analyze the effects of speed on skid resistance. Friction at speeds of 20, 40, 60 and 80 km/h were recorded for the DFT (as per ASTM E 1911,(ASTM 1998).

a) Locked wheel smooth/ribbed (LWS1) and (LWR1)

b) Griptester (GT)

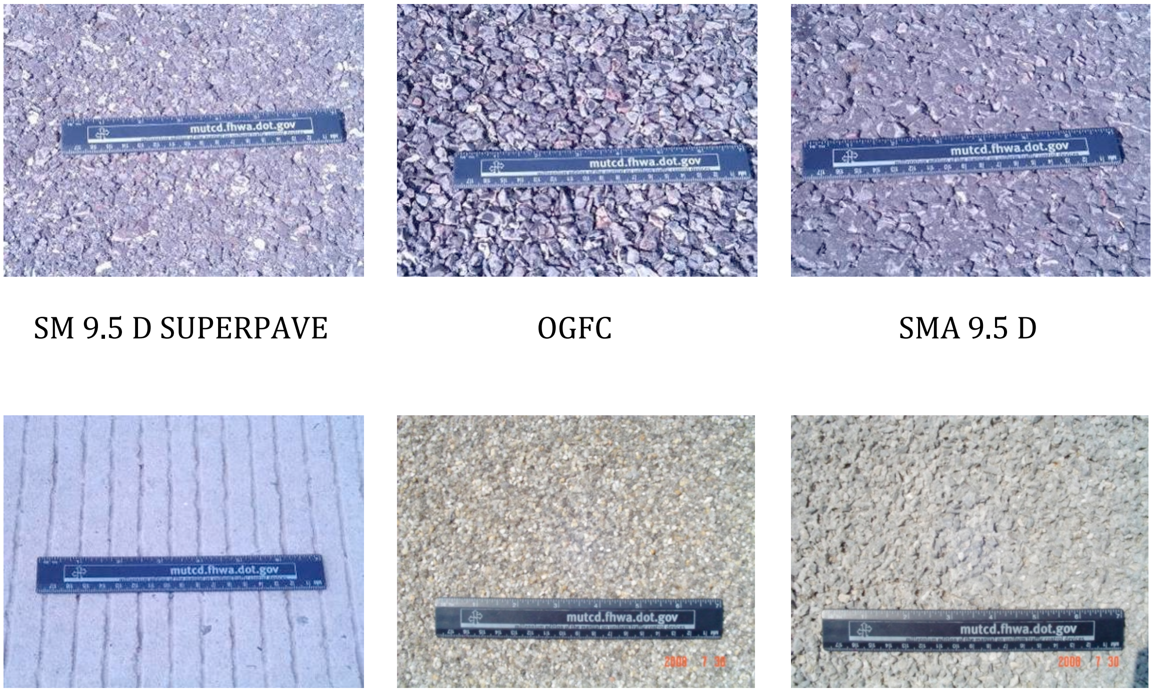
c) Locked wheel smooth (LWS2)

d) Skid wheel testers (LWS2)

e) Circular Track Meter (CTM1)

f) Dynamic Friction Tester (DFT)

FIGURE 1. Friction and macrotexture testing equipment



SM 9.5 D SUPERPAVE | OGFC | SMA 9.5 D

Tined CRCP | Standard VDOT epoxy overlay (EP) | Proprietary epoxy overlay (Cg)

FIGURE 2. Sample of pavement surfaces available at the Virginia Smart Road.

5. RESULTS AND ANALYSIS

5.1 Changes of Friction with Speed

In order to standardize the results of the friction measurements at various speeds, an exponential regression curve was fitted to the set of points on the friction versus speed relationship for each section and for each device. The equations were used to obtain normalized values of friction for the specific slip speeds as recommended by Wambold et al. (Wambold et al. 1995). The exponential regression fit was selected based on the recommendations of the Penn State Model, on which the PIARC model was established, to calculate the skid number at the specified S slip speed (Henry 2000):

$$\mu = \mu_0 * e^{-(\frac{PNG}{100}) \cdot S} \tag{4}$$

where,

μ = calculated coefficient of friction at the specified slip speed for each device

μ_0 = projected coefficient of friction intercept at zero speed

PNG = percent normalized gradient (the speed gradient times 100 divided by the friction, as defined by:

$$PNG = -\frac{100}{\mu}\frac{d\mu}{ds}$$

S = sliding velocity

5.2 IFI Comparisons

To evaluate whether or not the coefficients developed during the PIARC experiment apply to the devices, the IFI values were computed using the different friction values (FR) measured by the various devices used in the equipment comparison.

Table 1 shows the IFI values calculated for the various devices and for every pavement section on the uphill and downhill lanes. The procedure followed to obtain the IFI was the one specified in PIARC (1): compute F(60) values using equations (1), (2), and (3) and incorporating the respective friction values at the recommended slip [FR(S)] from equation (4). The standard IFI equation for the DFTester and CTMeter in ASTM 1960-07 (Henry and Siato 1983) were used. The specified slip speeds were 65 km/h for the skid testers, 20 km/h for the DFT. With a 15.6 percent slip ratio as (in the Griptester manufacturer specifications, the Griptester numbers (GN) were taken at 9.4 km/h to match the PIARC conditions; otherwise the coefficients to estimate F(60) would not apply.

The macrotexture measurements obtained from the CTMeter were used to determine Sp using equation (1) and a =14.2 and b = 89.7 (Wambold et al. 2006).

The friction number F60 was finally computed using equation (3), with the coefficients corresponding to each device in the original PIARC report (Wambold et al. 2006). The markers labeled are “original” in Figure 3 compare the results for each of the four devices used with the standard DFT values, as recommended in ASTM 1960-07. The computed IFI values for the same pavement sections obtained using different devices are clearly not in agreement. Using the original PIARC coefficients, the regression correlation coefficients for the measurements with smooth tires show relatively weak coefficients of determination (R2). This suggests that the coefficients A, B, and C may need to be adjusted for each device considered before the IFI can be implemented by the participating agencies.

The A, B, and C coefficients were then recalculated by plotting the F60 DFT values against all the FR60 values for all the friction instruments and fitting a linear model using regression analysis (as recommended by ASTM 1960-07). Two parameters, A and B, were determined for the measurements with the smooth tires. For the ribbed tire results (LWR1), a multiple regression was performed including all three A, B, and C coefficients, which produced a higher adjusted R^2. The predicted values using these revised coefficients are also displayed in Figure 3 (red triangles).

TABLE 1. Summary of IFI's friction component values for different equipment

Section		CTM	DFT	F60 With Original Coefficients				F60 With Revised Coefficients			
		MPD	F60	LWS1	LWS2	GT	LWR1	LWS1	LWS2	GT	LWR1
1	Loop	1.003	0.482	0.596	0.531	0.534	0.485	0.480	0.472	0.479	0.460
2	A	0.530	0.412	0.519	0.497	0.392	0.476	0.448	0.461	0.425	0.444
3	B	0.680	0.457	0.538	0.468	0.454	0.474	0.456	0.451	0.448	0.447
4	C	0.710	0.445	0.545	0.431	0.439	0.459	0.459	0.440	0.443	0.440
5	D	0.557	0.394	0.438	0.355	0.419	0.428	0.414	0.415	0.435	0.421
6	I	0.923	0.481	0.552	0.544	0.489	0.489	0.462	0.476	0.462	0.460
7	J	1.047	0.460	0.572	0.499	0.492	0.491	0.470	0.462	0.463	0.464
8	K	1.627	0.452	0.501	0.488	0.551	0.448	0.440	0.458	0.485	0.458
9	L	1.003	0.449	0.506	0.448	0.547	0.435	0.442	0.445	0.484	0.436
10	Cg	1.837	0.516	0.597	0.492	0.522	0.562	0.481	0.459	0.474	0.518
11	EP	1.197	0.432	0.520	0.436	0.428	0.467	0.448	0.441	0.439	0.456
12	CRCP	0.703	0.439	0.434	0.357	0.414	0.479	0.412	0.416	0.433	0.450
13	CRCP	0.803	0.465	0.568	0.486	0.455	0.495	0.469	0.457	0.449	0.460
14	Cg	1.860	0.538	0.607	0.552	0.537	0.609	0.485	0.478	0.480	0.541
15	EP	1.173	0.458	0.602	0.545	0.434	0.486	0.483	0.476	0.441	0.465
16	L	1.083	0.450	0.524	0.487	0.529	0.451	0.450	0.458	0.477	0.446
17	K	1.803	0.457	0.495	0.483	0.539	0.452	0.438	0.456	0.481	0.464
18	J	0.847	0.442	0.550	0.520	0.426	0.468	0.461	0.468	0.438	0.448
19	I	0.727	0.436	0.572	0.492	0.417	0.468	0.470	0.459	0.435	0.445
20	D	0.697	0.436	0.493	0.435	0.448	0.443	0.437	0.441	0.446	0.432
21	C	0.787	0.441	0.544	0.484	0.441	0.462	0.459	0.457	0.444	0.444
22	B	1.007	0.477	0.580	0.567	0.515	0.492	0.473	0.483	0.472	0.464
23	A	0.887	0.468	0.574	0.546	0.489	0.460	0.471	0.477	0.462	0.445
24	Loop	0.797	0.447	0.471	0.405	0.434	0.431	0.428	0.431	0.441	0.429

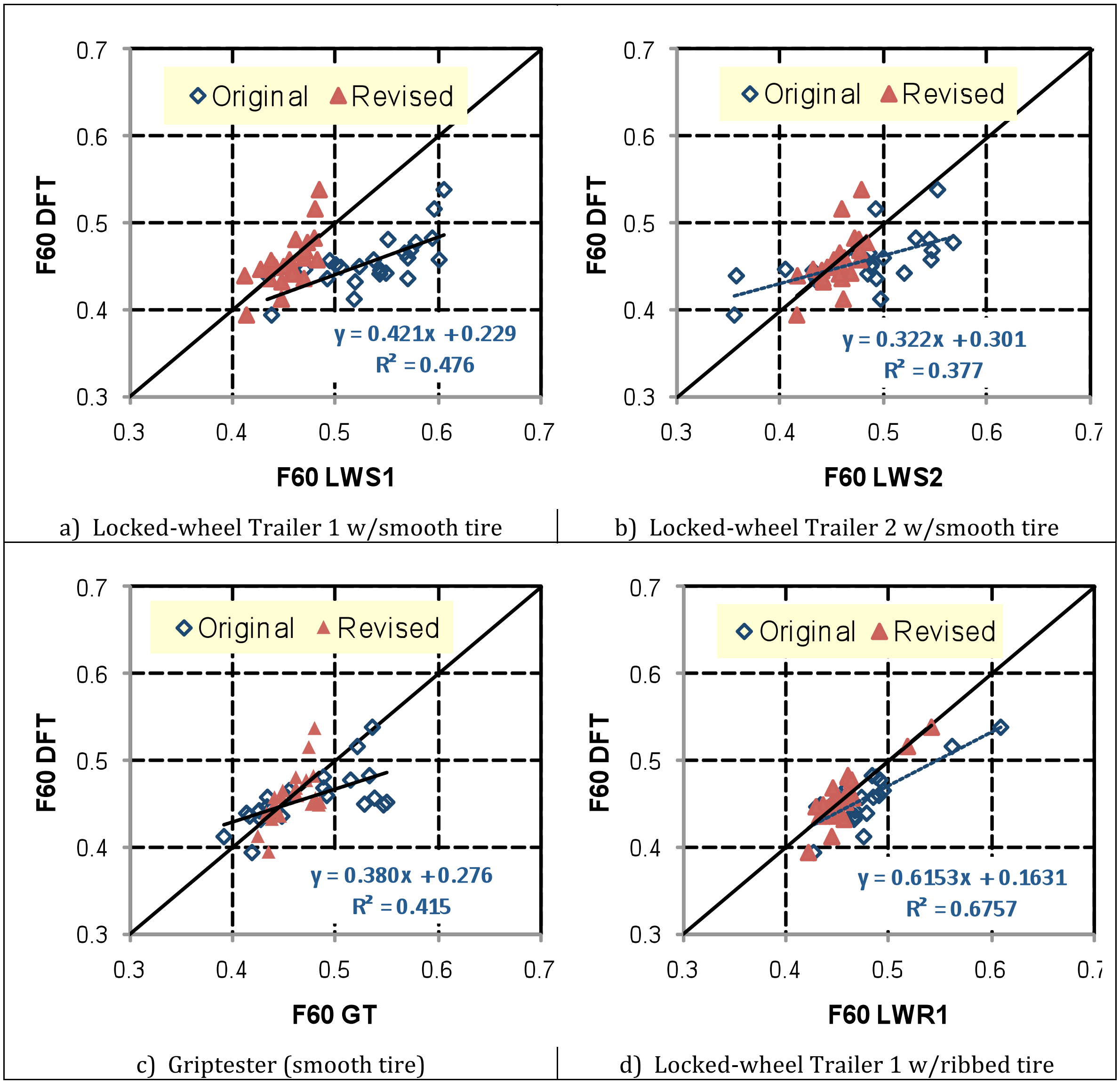


FIGURE 3. IFI F60 values for different equipment versus DFT F60 values

Furthermore, the coefficients of determination (R^2) for the smooth tires indicate relatively weak relationships (left half of Table 2), with the Griptester having a relatively better correlation. Some of the differences may be explained because of the use of the default texture-Sp relationship (equation (6)) as discussed in the Next section. Table 2 compares the PIARC coefficients with the revised coefficients computed for each of the devices.

TABLE 2. Summary of F60 IFI coefficients for different friction units

Friction Unit	Original Coefficients				Revised Coefficients			
	A	B	C	R^2	A	B	C	R^2
LWS1	0.0446	0.9250	-	0.35	0.2480	0.3898	-	0.48
					0.2595	0.2957	0.0382	0.70
LWS2	0.0446	0.9250	-	0.37	0.3152	0.2976	-	0.38
					0.3194	0.2042	0.0395	0.61
GT	0.0821	0.9104	-	0.62	0.3072	0.3460	-	0.41
					0.3385	0.2018	0.0308	0.50
LWR1	-0.0228	0.6068	0.0976	0.78	0.1905	0.2925	0.0718	0.75

Although the bias is corrected with the revised coefficients, there are still some sections for which the equations for the smooth tire do not work. Some points with low and high DFT F60 are quite far from the equality line. Since these sections had the lowest and highest macrotexture values, new linear regressions with two variables (FR (60) and TX) were determined. The best-fit coefficients are shown in blue in the right half of Table 2 and the predicted values are presented graphically (as green solid circles) in Figure 4. The fitting was significantly improved as indicated by the higher coefficients of determination obtained.

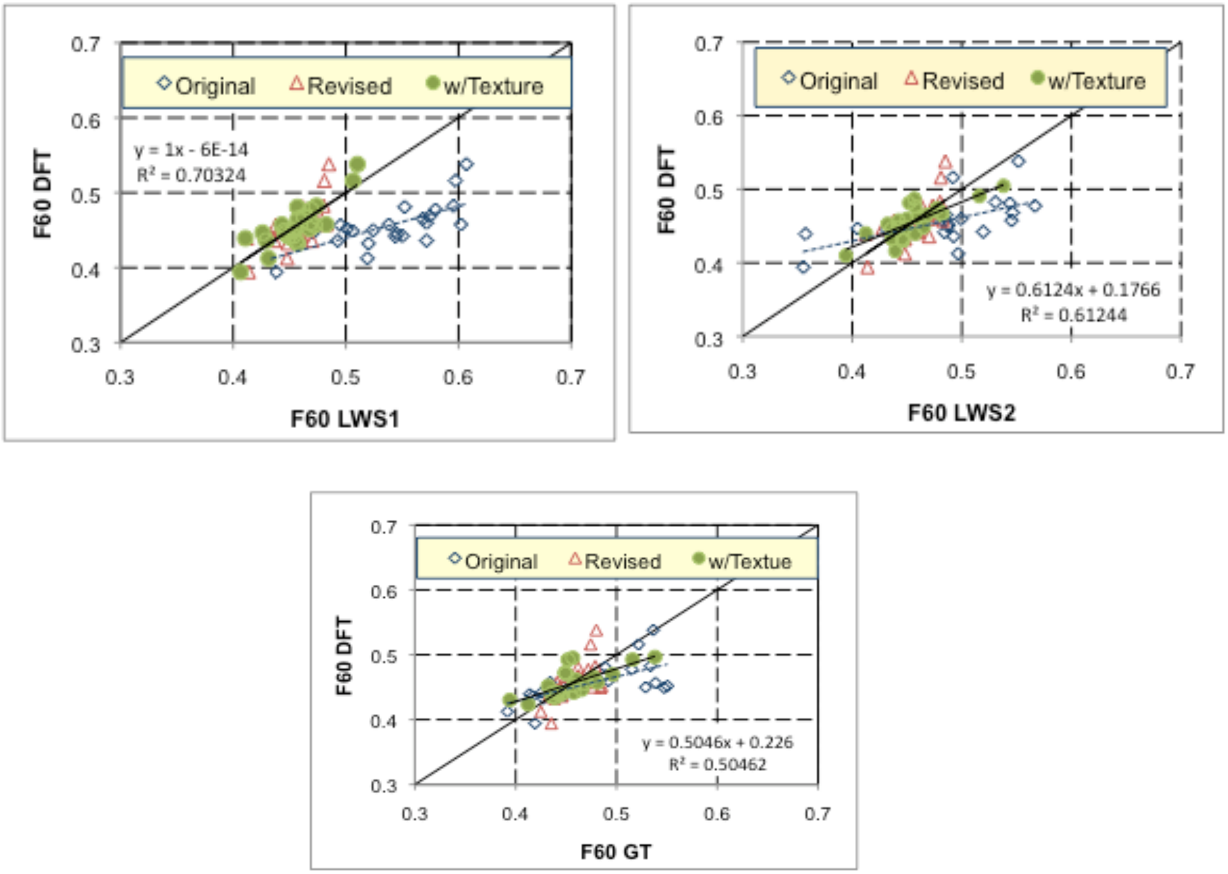


FIGURE 4. Comparison of original and revised F60 values using three-parameter (A, B, C) models.

5.3 Speed Parameter Calculation

To evaluate the appropriateness of the coefficients used to compute the Sp based on the MPD values obtained with the CT Meter, the computed Sp values were compared with the experimental values obtained from the model fitting with equation 4 (Pennsylvania State University model). Theoretically, the Sp factor should be equal to the inverse of the PNG value in decimal form (100/PNG), or as referred in other publications as the So (Henry 2000). Since the exponential models were defined for the various devices and the various pavement sections, it was possible to determine an experimental Sp that could be compared with the Sp value computed as a function of texture. It is important to note that the resulting relationships are valid only for the surfaces evaluated. Table 3 shows the results of comparing the experimental values of Sp and the computed value in accordance with the ASTM coefficient calculation procedure. Figure 5 compares the experimental and computed Sp values and shows the best-fit lineal (Sp = a + b∗TX) and power (Sp = a∗TX^b) models.

TABLE 3. Experimental and Calculated Sp Values

Section		CTM MPD	ASTM Sp (MPD)	Experimental Sp (km/h)				
				LWS1	LWS2	GT	LWR1	DFT
1	Loop	1.00	104	68	75	40	109	293
2	A	0.53	62	51	50	16	127	291
3	B	0.68	75	44	49	20	154	301
4	C	0.71	78	40	63	21	159	316
5	D	0.56	64	32	38	24	167	328
6	I	0.92	97	68	56	27	141	337
7	J	1.05	108	53	83	125	132	338
8	K	1.63	160	76	86	28	87	326
9	L	1.00	104	53	67	31	99	307
10	Cg	1.84	179	48	127	45	169	599
11	EP	1.20	122	55	88	53	200	
12	PCC	0.70	77	30	34	15	156	546
13	PCC	0.80	86	51	69	29	156	515
14	Cg	1.86	181	54	89	93	159	588
15	EP5	1.17	119	104	175	83	164	
16	L	1.08	111	69	81	23	99	392
17	K	1.80	176	84	83	127	69	402
18	J	0.85	90	67	62	70	161	441
19	I	0.73	79	47	64	29	139	331
20	D	0.70	77	42	45	25	147	332
21	C	0.79	85	53	58	28	164	365
22	B	1.01	104	75	73	68	175	395
23	A	0.89	94	68	81	54	164	332
24	Loop	0.80	86	45	46	19	97	282

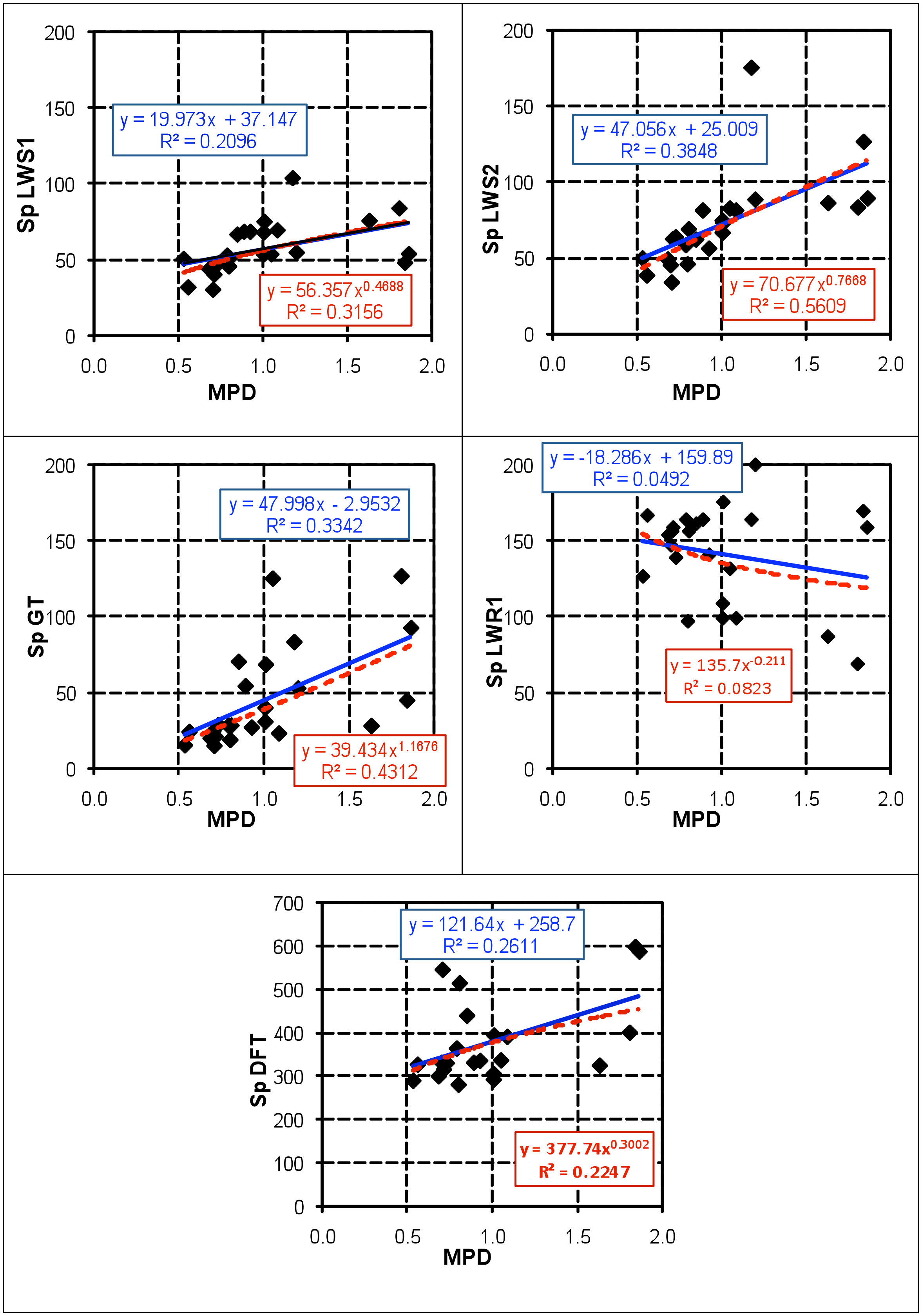


FIGURE 5. Comparison of computed and experimental Sp values

The best-fit model parameters for each device are presented in Table 4. The plots in Figure 5 show that neither of the models results in high coefficients of determination. Although it was reported in the results of the HERMES experiment that Sp had better correspondence when using a power model of the form $Sp = a*TX^b$, the results of the measurements show that the experimental data analyzed only confirmed this for the devices with smooth tires, whereas the coefficients of determination for the DFT and ribbed tire do not improve with a power model.

TABLE 4. Coefficients a and b.

Devices	**Lineal**			**Power**		
	a	***b***	***R^2***	***a***	***b***	***R^2***
DFT Sp	122	259	0.2611	378	0.300	0.2247
LWR1 Sp	18.3	160	0.0492	136	-0.211	0.0823
LWS1 Sp	20.0	37.1	0.2096	56.4	0.469	0.3156
LWS2 Sp	47.1	25.0	0.3848	70.7	0.767	0.5609
GT	48.0	-2.95	0.3342	39.4	1.168	0.4312

6. FINDINGS AND RECOMMENDATIONS

In this paper measurements obtained with different types of friction measuring equipment on 24 pavement sections with a wide range of textures were compared. The relationship between friction and speed for the different pavement sections and devices was studied. The main conclusions of the analysis of the data collected are presented following.

The data collected for this project showed that the model developed by PIARC does not produce harmonious results among the devices used by the consortium members in the Virginia Smart Road Rodeo for the surfaces tested. Discrepancies in the IFI values calculated for the different devices suggest that the original coefficients determined during the PIARC experiment may need to be adjusted for the devices evaluated before the IFI can be implemented by the participating DOTs.

There seems to be a slightly better correlation of the speed constant gradient value with the power model as recommended by the HERMES Project than with the linear model as used in the original PIARC model, particularly for instruments using smooth tires. Based on the results, new coefficients have been proposed for the equipment used in the Smart Road Rodeo for the types of surfaces tested.

Starting with the PIARC experiment, harmonization initiatives are done regularly because it has been found that under different conditions different parameters and coefficients will result. It is strongly recommended equipment comparison experiments (like the NASA and Smart Road programs) continue in order to better determine the coefficients necessary for harmonization.

7. ACKNOWLEDGEMENTS

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CHAPTER III

FIELD PERFORMANCE OF HIGH-FRICTION SURFACES

ABSTRACT

Even though the relationship between roadway safety and pavement friction has long been recognized, the lack of sufficient friction at the tire-pavement interaction is still one of the major contributing factors to vehicle accidents. Due to the relationship between skid resistance and accidents and the increase of fatalities on highways(N.T.S. 1999) , optimum levels of skid resistance must be maintained on pavements under extreme weather conditions. High-friction surfaces (HFS) are consistently being considered because they provide the pavement friction needed without negatively affecting other pavement qualities, like noise or durability.

The objectives of this paper are to study some of the high-friction surfaces available in the United States market; measure their performance (friction and texture) on different applications, under different weather conditions, and on various locations; and present agencies the results obtained in a practical, easy-to-use form. The results of the benefit-cost analysis for the studied HFS show that on all four studied sections the HFS alternative is economically justified compared to the base case.

The coefficients developed were used to obtain International Friction Index (IFI) values for each HFS studied. It is recommended that more experiments be run with different types of pavements surfaces, including HFS and other types of surface treatments, to demonstrate the validity of the speed gradient coefficient Sp coefficients recommended by ASTM and also the validity of using the Dynamic Friction Tester as the standard device to measure friction for the IFI calculations. Research is recommended on predicting minimum surface friction values indicating the necessity of roadway rehabilitation. To develop these parameters, it is necessary to study, monitor, and correlate texture, friction, and accident data.

1. INTRODUCTION

Roadway accidents are a leading cause of death and injury around the world. Each year 1.2 million people die and millions more are injured or disabled as a result of road crashes (Hayes et al. 2007). This not only creates an enormous social cost for individuals, families, and communities but also places a heavy burden on health services and economies.

The relationship between roadway safety and pavement friction has long been recognized, but one of the major contributing factors to vehicle accidents on highways is still insufficient friction at the tire-pavement interaction. It has been reported that wet pavements are involved in 25 percent of all crashes and that vehicles leaving their lane or running off the road are involved in 59 percent of roadway fatalities (NTS 1999).

The volume and severity of motor vehicle crashes in the United States has led the Federal Highway Administration (FHWA) to declare safety as one of their top priorities. It is for this reason that high-friction surfaces (HFS) are becoming an appealing pavement high friction application alternative since they have the ability to increase friction and improve texture by utilizing a high-polished-stone-value (PSV) aggregate and some type of resin to hold the aggregate particles together and glued to the road surface.

Motor vehicle crashes result from numerous contributing factors, including driver error, poor geometric alignment of the roadway, and insufficient friction at the tire-pavement interaction, especially during wet weather. HFSs have emerged as viable pavement high-friction alternatives that mitigate some of these factors.

Besides HFS there are other alternatives that have the ability to increase skid resistance on pavements, such as tinning or grooving on rigid pavements. However, most of these surface alterations adversely affect other surface properties, such as noise generated between tire and pavement. HFS are used for increasing road surface skid resistance, driver awareness, and water drainage and decreasing braking distance, hydroplaning, splash, and spray.

2. OBJECTIVE

A study conducted by the University of Michigan on 15 ramps at 11 interchanges in 5 states found that surface properties were related to truck along with geometry, and vehicle dynamics (Julian and Moler 2008) .

It has also been shown there is a statistically significant effect of skid resistance on wet accident rate: the wet accident rate increases with decreasing skid resistance (Kuttesch 2004). Due to this relationship and the increasing number of fatalities on highways, optimum pavement skid resistance must be maintained under extreme weather conditions (N.T.S. 1999). High-friction surfaces (HFS) are becoming an appealing pavement high friction application alternative because they supply the needed pavement friction without negatively affecting other pavement qualities, such as noise and durability.

The objectives of this paper are:

1) To identify the main HFS available in the United States market.

2) To measure their performance (friction and texture) on different applications, under different weather conditions, and on various locations, and

3) To present agencies the results obtained in a practical, easy-to-use format.

This paper is aimed at helping agencies decide whether or not an HFS should be applied at a particular location and which HFS is the most appropriate for a specific application. The information compiled will help decision makers allocate the needed resources to address the most serious safety risks.

In 2006, the Virginia Transportation Research Council (VTRC) and the Virginia Tech Transportation Institute (VTTI) initiated a regional pooled-fund project known as the Pavement Surface Properties Consortium. This project established a research program focused on enhancing the level of service provided by the roadway transportation system by optimizing pavement surface texture and friction characteristics. The program was set up with support from the FHWA and includes six DOTs from the states of Connecticut, Georgia, Mississippi, Pennsylvania, South Carolina, and Virginia. This five-year program is part of the activities of the Virginia Sustainable Pavement Research Consortium (VA-SPRC) and is managed by VTRC and run by the Center for Sustainable Transportation Infrastructure (CSTI) at VTTI.

3. BACKGROUND

The term *high-friction surface*, or HFS, refers to surface treatments that utilize a non-polishable aggregate (with high polished stone value, PSV) and some type of resin (binder) to hold the aggregate particles together and glued to the road surface. The most commonly used aggregate is calcined bauxite.

The origin of HFS dates to the mid 1950s when the use of epoxy-resins as binders on surfaces was first studied (Nicholls 1998). In the 1960s the U.K. government's Transport and Road Research Laboratory (TRRL) began to test hard aggregates with various binders to produce extremely high-friction surfaces. 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 (Julian and Moler 2008). In the late 1980s researchers in the United States began to investigate the effectiveness of these surfacing systems in reducing crashes on black spots.

3.1 High-Friction Surfaces Application Processes

According to the form of application, HFS can be classified into two categories: cold-applied and hot-applied processes (Nicholls 1997). Cold-applied HFS use thermosetting resins like epoxy or polyurethane, which are supplied in different containers and then mixed to begin a heat-producing chemical reaction that results in hardening. In the hot-applied process the premixed granular material is provided in bags, then heated in a boiler and applied to the surface while still hot. In this case the resin used is thermoplastic.

3.2 High-Friction Surface Binders

There are several types of resins used on HFS, and each adds unique capabilities to the system. The main resins are: epoxy-resin, rosin-ester, polyurethane-resin, and acrylic-resin (Nicholls 1998).

3.2.1 Epoxy-Resin

The oldest resin used on HFS is the epoxy-resin. It consists of a two-component system mixed on site at equal quantities by weight. One component contains the resin together with a proportion of oil that reduces the viscosity of the resin and acts as an extender, while the other contains the curing agent together with bitumen, an oil extender, and accelerators. The properties of the binder can be adjusted by changing the proportions of the components of the system; nevertheless, a typical curing time oscillates between three to four hours for temperatures above 10°C.

3.2.2 Rosin-Ester

A pre-blended system like 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 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.

3.2.3 Polyurethane-Resin

The polyurethane-resin was mainly developed to achieve quicker curing times at low 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 and also by hand.

3.2.4 Acrylic-Resin

This is a two-component system with much faster curing time than epoxy-resin. Consequently, 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 wet the aggregate sufficiently, in order to provide an adequate bond without the binder submerging the chips.

3.3 Properties of Aggregates for High-Friction Surfaces

Aggregates on HFS should provide a skid-resistant surface while being non-polishable, durable against the abrasion effects of traffic, and resistant to the disintegration provoked by weathering. The surface layer needs to retain its texture for as long as possible to provide skid resistance for traffic. The higher the PSV, the longer the aggregate will remain rough when used in road surfacing.

3.3.1 Standard Practice for the Accelerated Polishing of Aggregates Using the British Wheel (AASHTO T279, ASTM D3319)

This method simulates the polishing action of vehicular traffic on aggregates used in pavements. Polish value, is a measure of the state of polish reached by test specimens subjected to a specified number of hours of accelerated polishing using the British wheel, this value may be 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, then the specimens are clamp around the periphery of the road wheel using rubber o-rings near the edge of the specimens in order to form a continuous strip of particles upon which the 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 391 N (88 lbf), and a 66 g/min rate of silicon carbide. After the polishing action has passed the specimens are removed from the fixture, wash thoroughly to remove grit and its friction value obtained thru the British pendulum, in order to determine the polish value (ASTM 2006).

During testing aggregates should be subjected to a polishing action of 10 h, unless maximum polish is achieved in a shorter time. Maximum polish is achieved when no change is detected on successive measurements.

3.3.2 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 charge are placed in the Los Angeles testing machine at 30 rpm for 500 revolutions. Afterward, the material is discharged and a sieve analysis is done. Lastly, the aggregates are washed and weighed to determine the abrasion (AASHTO 1991).

3.3.3 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 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 AASHTO must be followed.

In many instances a freezing period of two hours is suitable, depending on 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 determined the loss in each sieve (AASHTO 1991).

3.4 High-Friction Surfaces Aggregates

The selection of aggregates will depend on their performance during the tests described in the previous section. Table 1 presents the types of aggregates used in the studied applications. The most commonly used sources are described below.

TABLE 1. Type of Aggregate and Price for Selected HFS

Product	Type of Aggregate	Aggregate Size
Crafco HFS	Bauxite (China-Guyana) Granite	1-3 mm 1-3 mm
Flexogrid	Basalt + granite Silica	2-3 mm 2-3 mm
Italgrip	Steel slag (patented)	3-4 mm
Safelane (Cargill)	Dolomite	1-3 mm
Safe-T-Grip	Granite	1.5-3.2 mm
Tyregrip	Calcined bauxite (buff and grey)	1-3 mm

3.4.1 Calcined Bauxite

Calcined bauxite aggregate comes from an aluminum ore commonly mined in China that is exposed to prolonged heating at temperatures of 1,600°C to increase its hardness and physical stability.

The density of calcined bauxite varies from 2.6 to 3.4 g/m^3 depending on its source. This property is typically a good indicator of the PSV: high density indicates high PSV. Guyanan bauxite (dark grey) has a PSV of 72 while Chinese bauxite (buff/creamy color) exhibits values of 67 PSV.

3.4.2 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 gradations exist between limestone and dolomite (Huhta et al. 2001). Dolomite is commonly light in color and often has ferrous iron compounds that may oxidize, tinting the rock shades of buff and brown.

3.4.3 Granite

Granites are composed of 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 granite is usually superior to that of sandstone, limestone, and marble (Huhta et al. 2001). It provides a PSV of 62 or greater.

3.4.4 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 (Huhta et al. 2001).

There are three crystalline forms of silica: quartz, tridymite, cristobalite and two variations of each (high and low.) Silica has good abrasion resistance and high thermal stability. It is insoluble in all acids with the exception of hydrogen fluoride (HF).

3.4.5 Steel Slag

Slag is a by-product of steel making, 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 HFS (Shi 2004).

Other aggregates may be selected for use on HFS for their natural colors, which can, by color pigmenting, accentuate the aggregate for greater visual impact.

3.5 Previous High-Friction Surfaces Studies

There have been several efforts by different agencies to evaluate if HFS are suitable, durable, and cost-effective techniques to enhance the safety and drainage characteristics of roadways. The most relevant are briefly described in this section.

3.5.1 Investigative Study of the Italgrip System – Noise Analysis

The Wisconsin Department of Transportation conducted a study to identify and quantify the impact on exterior vehicle noise of applying Italgrip on a Portland Cement Concrete (PCC) pavement. The surface treatment was installed on a jointed, undoweled, transversely-tined PCC pavement in Waukesha County. A 3-mm aggregate was applied to both eastbound lanes, while 4-mm aggregates were applied to westbound lanes (Kuemmel et al. 2000).

This study concluded that Italgrip produces a 2-3 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 was also found that the noise level difference between 3-mm and 4-mm aggregates is insignificant.

3.5.2 Trials of High-Friction Surfaces for Highways

The Transportation Research Laboratory in the United Kingdom conducted a project to better understand the main features and performance of the different binder systems available for HFS application. The binder systems studied were epoxy-resin, rosin-ester, polyurethane-resin, and acrylic resin.

This report describes a series of trials conducted at different times using different types of HFS. The systems were ranked in terms of maintained skid resistance, texture depth and longevity. The study showed that the epoxy-resin and polyurethane-resin systems maintained their properties most consistently, followed by the acrylic-resin system and then the rosin-ester system. It was also found that 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 (Nicholls 1998).

3.5.3 Evaluation of Cargill Safelane Epoxy Overlay

(Sprinkel et al. 2008)) evaluated the performance of the Safelane system when compared to a conventional modified-epoxy concrete overlay. Two Safelane and two EP5 systems were placed on an interstate's bridge decks and on the Virginia Smart Road.

The study showed that Safelane overlay could provide a skid-resistant wearing and protective surface for bridge decks. The project was not able to determine the performance of the overlay with respect to providing a surface with less accumulation of ice or snow when compared to the conventional epoxy overlay.

3.5.4 Performance of Poly-Carb, Inc. Flexogrid Bridge Overlay System

(Adam and Gansen 2001) evaluated the performance of the FlexoGrid system on a highway bridge deck in the state of Iowa over a five-year period. Results showed that this HFS system increased friction measured with a locked-wheel trailer from 36.5 SN to 67.5 SN, and four years after application a recorded friction of 64.5 resulted. It was also found that on the sixth year, 530 ft^2 of the 14,080-ft^2 bridge was already delaminated. This research attributes the delaminating problem to moisture trapped below the impermeable Polycarb layer.

3.5.5 Florida DOT - Tyregrip Forensic Report

In 2008 the Florida DOT (FDOT) studied one of their Italgrip HFS applications to investigate mixed reviews from those involved with the application concerning the causes of raveling on the system. The research discovered that the main causes of raveling on this application were improper epoxy preparation, humidity of surface prior to application, and thinning of epoxy application. This study shows the importance of mechanical application in achieving uniformity along the surface and avoiding raveling (Kelly 2008).

3.5.6 Evaluation of Innovative Safety Treatments

(Reddy et al. 2008) evaluated innovative safety treatments implemented by (FDOT) and other agencies to determine their impact on crashes and other surrogate measures. These treatments included temporary rumble strips, white enforcement lights, motorist awareness system, countdown pedestrian signals, in-roadway lights and Tyregrip high-friction surface. This evaluation concluded that the HFS (Tyregrip) are effective in increasing friction between the roadway and vehicle tires. The system is effective in assisting drivers in maintaining their lane position under wet pavement conditions. This research also infers that drivers tend to slow down when traveling over the HFS section.

3.5.7 Investigative Study of Italgrip System 2008

(Bischoff 2008) studied five different Italgrip applications to assess if this system is a suitable, durable, and cost-effective technique to enhance the safety and drainage characteristics of roadways. 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 five years in service the sites had an average of 59.4 SN. This showed that even though friction decreased, the average friction number was still 38 percent higher than before the application. The results also showed that number of accidents at sites decreased by 93 percent, the number of vehicles involved in accidents decreased by 89 percent, and the number of accident-related injuries by 86 percent during a three-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 4 decibels.

3.6 High-Friction Surface Systems Studied

The HFS investigated for this thesis were selected by searching on the world wide web for HFS available all over the world and then contacting those companies to find a U.S. supplier. In addition, the Federal Highway Administration (FHWA) provided a list of departments of transportation that had tried some of the high-friction products, and they were contacted. The products evaluated are discussed below.

3.6.1 Crafco HFS

The HFS offered by Crafco 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 (Crafco, 2008).

The Crafco system offers various aggregates 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. American granite aggregate (supplied in natural silver and red) is used when good surface friction is wanted. Other colored-coated aggregates may be used to improve driver awareness.

Crafco HFS is composed of a thermosetting, primerless, low-odor epoxy compound, which exhibits plastoelastic properties bonding the aggregate permanently in position. This flexible surface is designed to be resistant to fuel, de-icers, oil, and impacts.

3.6.2 Safelane (Cargill)

The Safelane system consists of a combination of epoxy and proprietary domestic dolomite aggregate used to improve friction. This surface can be charged with standard anti-icing fluids that store the chemicals and release them automatically under snow conditions, preventing ice from forming on roadways and bridge decks (Cargill, 2008).

3.6.3 Tyregrip (Prismo - Ennis Paint)

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 offers color-coated chippings as well as pigmented and unpigmented binders (Tyregrip, 2008).

3.6.4 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 also 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 over short sections of roadway (Italgrip, 2008).

3.6.5 FlexoGrid (Polycarb)

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 (Polycarb, 2008). This product utilizes 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.

3.7 High Friction Surfaces Typical Application Procedure

The typically recommended locations for HFS installations include areas of high-friction demand like bridges, intersections, roundabouts, toll plazas, bus lanes, exit-entrance ramps, approaches to crosswalks, school crossings, corners, steep grades, horizontal curves, and other identified hazardous areas. The main benefit of HFS systems is that they save lives; application in the correct locations has been proven to result in accident reductions (Julian and Moler 2008). Other reported benefits of HFS are fast application, retro-reflection nighttime hazard-warning capabilities, and simple hand or machine application.

The general procedure for installing an HFS starts by preparing the road 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 road surface. This is accomplished using brooms, compressed air, and shot blasting on concrete surfaces. Then, the surface temperature should be measured to ensure it is above the resin installation standard. Subsequently drains and expansion devices must be covered with duct tape and plastic to prevent clogging with epoxy and aggregates.

The two components of the epoxy are usually delivered in 55-gallons drums that are laid down at the site and gravity fed into buckets of predetermined volume in a pre-established proportion. This 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.

Before the resin is spread manually, grids should be laid out with tape to control the application rate of the epoxy. Immediately after the epoxy is spread, workers use shovels and brooms to evenly spread the aggregates over the binder as presented in Figure 1. Finally the excess aggregate is removed and the system is left to cure for a period of two to four hours.

In a typical application, the epoxy is spread at an approximate rate of 2.6 to 3 square yards (27sq.ft) per gallon, and the aggregate is spread at a rate of 14-15 square yards per 200 pounds of aggregate. This is similar to the application rate of one epoxy gallon for each 25 sq. ft covered for Safelane application at the Virginia Tech Smart Road.

a) Mixing A-B Epoxy components

b) Binder is spread by crew

c) Aggregate is spread by crew

FIGURE 1. High-friction surface application (Adam and Gansen 2001).

3.8 High-Friction Surface Potential Sources of Failures

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

3.8.1 Epoxy Preparation - Composition

The two-part modified epoxy used on most of the HFS applications is to be mixed in a specific ratio, and sometimes due to construction errors this may not be the case.

This could affect the epoxy performance. The composition of the binder may also affect the adhesion with the aggregate particles and/or the pavement surface.

Some studies suggest that due to the decreasing use of creosol because of its strong odor and ability to burn the skin during application, new epoxy formulations exhibit worse performance than previously used combinations (Kelly 2008).

3.8.2 Epoxy Aggregate Placement

Epoxy should be spread homogeneously over the surface and at the correct rate to prevent the binder from covering the aggregate. There needs to be a complete coverage of the wet binder with aggregate to achieve a uniform friction surface, and no wet spots should be visible once the aggregate is placed. This could be difficult to accomplish at the moment of installation since most of these surfaces are applied at night for convenient traffic control and to reduce impact on traffic flow.

3.8.3 Existing Pavement - Existing Asphalt Compatibility

Some types of pavements are particularly difficult for the installation of an HFS. For example, the high permeability of porous asphalts poses a threat in accomplishing a uniform epoxy surface (Kelly 2008). It is also not recommended that an HFS be placed on pavements less than one month old. Also, sufficient cleaning is necessary for all pavements.

3.8.4 Humidity and Moisture (Surface and Aggregate)

Humidity and moisture are of great concern at the moment of HFS application. Surface humidity caused by condensation and fog impedes the full adhesion and performance of the epoxy over 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 is in service. For example, severe raveling may develop as the surface undergoes freeze-thaw action due to moisture trapped below the impermeable layer as shown in Figure 2.

FIGURE 2. High-Friction Surface Raveling (Adam and Gansen 2001)

3.8.5 Ambient Temperature

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

3.8.6 Curing Time

A curing time of two to three hours is required for most applications under convenient ambient temperatures. Curing will take longer at low temperatures, and optimum performance of the HFS may be compromised.

3.9 High-Friction Surfaces Field Evaluations

Several existing installations have been identified in the United States with products from Crafco, Safelane, Tyregrip, Italgrip, and Safe-T-Grip. The contact information for each supplier is presented in Table 2. The main experimental component of this thesis studies and analyzes the performance of these applications.

TABLE 2. HFS Products Installed in the United States

Products Evaluated	Websites	Contacts
Crafco HFS (Crafco INC)	http://www.crafco.com/	Nick Nedas Office: (512) 432-5170 Mobile: (602) 228-1269 E-mail: nick.nedas@crafco.com
Italgrip (Italgrip USA)	http://www.italgrip.com/	Robert B. Schmiedlin Office: (608) 592-2725 Mobile: (608) 698-1712 E-mail: schmiedlin@italgrip.com
Flexogrid (Polycarb)	http://www.poly-carb.com/	Punit Zen Mobile: (678) 296-9910 Office: (440) 248-1223 E-mail: info@poly-carb.com
Safelane (Cargill)	http://www.cargillsafelane.com	Anthony Hensey Office: (866) 900-7258 Mobile: (423) 488-6884 E-mail: SafeLane@Cargill.com
Safe-T-Grip (Traffic Calming USA)	http://www.trafficcalmingusa.com	Glyn Owen Office: (770) 505-4044 Mobile: (404) 512-1792 E-mail: glyn@trafficcalmingusa.com
Tyregrip (Prismo USA) (Ennis Paint)	http://www.prismousa.com/	Richard J.Baker Office: (804) 213-0335 Fax: (804) 213-0337 Mobile: (804) 319-7456 E-mail: rbaker@ennispaint.net Dave Belanny Mobile: (678) 296-9910 E-mail: dave@ennispaint.net

4. DATA COLLECTION

4.1 Location of Studied High-Friction Surfaces

All of the testing was done in the states and at the locations presented in Table 3. The distinctness of testing sites and the uniqueness of each location provided the opportunity to obtain an encompassing idea of HFS performance.

TABLE 3. HFS Locations Investigated

HFS	State	Code	Location
Crafco HFS	Tennessee	TN-C	Spring Hill, Westbound End Southern parkway toward Columbia
Italgrip	Tennessee	TN-I-4	Spring Hill, Westbound End Southern parkway toward Columbia
Italgrip	Wisconsin	W-I-1	La Crosse Highway 35 N Wisconsin
Italgrip	Wisconsin	W-I-2	La Crosse Highway 16 W Wisconsin
Italgrip	Wisconsin	W-I-3	La Crosse Highway 16 E Wisconsin
FlexoGrid	Wisconsin	W-P	La Crosse Highway 35 S Wisconsin
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 VDOT; evaluated for comparison only.

Figure 3 shows examples of locations where the studied products have been applied. Picture **c** in this figure shows a bridge application by Italgrip where the HFS has been in place for nine years, and picture **d** presents a Polycarb HFS applied in the same year. A clear difference between the conditions of these products placed in the same year can be noticed.

a) Crafco Tennessee

b) Cargill - EP-5 Smart-Road

c) Italgrip Wisconsin

d) Polycarb Wisconsin

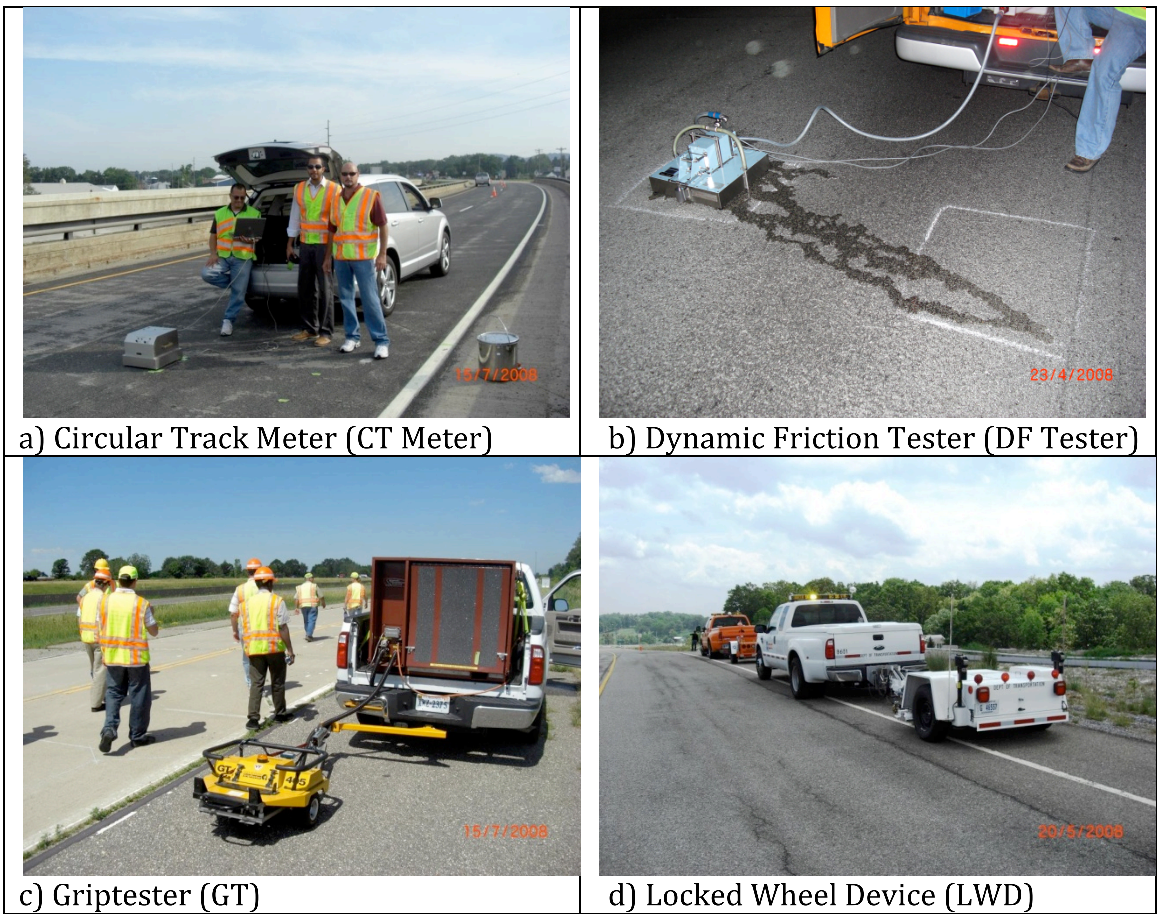
e) Safelane Virginia

f) Safelane Virginia

FIGURE 3. HFS Locations investigated.

4.2 Measurements of Friction and Texture Properties

Texture and friction properties for the selected HFS applications have been measured with the DF Tester (ASTM E1969), CT Meter (ASTM E2157), and GRIPTESTER (ASTM E1844); these devices (Figure 4) are further described in the following sections. All friction and texture measurements were collected in summer months to avoid seasonal variation effects on the recorded measurements.



a) Circular Track Meter (CT Meter)

b) Dynamic Friction Tester (DF Tester)

c) Griptester (GT)

d) Locked Wheel Device (LWD)

FIGURE 4. Data collection devices.

4.2.1 DF TESTER (ASTM E1969)

The DF Tester measures friction by spinning a horizontal disk fitted with three spring-loaded rubber sliders that contact the paved 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 measures the dynamic friction of the pavement continuously, and the results are typically recorded at speeds of 20, 40, 60, and 80 km/h. For this investigation, static friction measurements were taken at eight different locations: four on each wheel path along the HFS. Only the travel lane was measured because to record this measurement the lane had to be closed. The same friction pads were used for the entire section.

4.2.2 CT METER (ASTM E2157)

This equipment 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 having a diameter of 284 mm (11.2 in.). The CT Meter is designed to measure the same circular track that is measured by the DF Tester, and 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 standard. The CT Meter was used in this study to measure surface texture at the same eight spots used for the friction measurements with the DF Tester.

4.2.3 GRIPTESTER (ASTM E1844)

A Findlay Irvine Griptester was used to measure continuous skid resistance along the inside wheelpath of the travel lane of the test sections. This 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 constant slipping smooth tire at a 15.6 percent slip ratio.

Measurements are taken at speeds of 50 mph on interstates and 40 mph on other roadways, utilizing a constant water film thickness of 0.05 cm (8.9 gal/min at 80 km/h). The speed of the test tire is 15.6 percent of the speed of the vehicle because this device uses a constant slip ratio. Raw data for longitudinal friction forces and test wheel loads are by default recorded every 0.9 m, but the interval can be adjusted according to the needs of the experiment.

Due to the location of the test wheel when the Griptester is attached to the vehicle, only the outside wheel path friction is recorded (see Figure 4c). Several runs were made for each HFS section, and triggering points between each run were compared to account for possible errors.

4.2.4 LOCKED WHEEL DEVICE (ASTM E274)

This 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 device consists of a vehicle towing a trailer equipped with tests 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 100 percent slip ratio. The wheel remains locked for approximately 1 second, and the data is measured and averaged. The skid resistance of the paved surface is reported as skid number (SN) (ASTME-274), which is the force required to slide the locked test tire at a stated speed, divided by the effective wheel load and multiplied by 100 (ASTM E-274).

The locked wheel friction measurements used in this study were obtained from DOTs. Information was obtained only for a limited number of sections.

4.3 Cost Data

The companies responsible for the installation of the selected HFS systems were contacted to obtain a cost estimate for the application of each product. This information was used to further analyze and compare the cost of each product with its performance. HFS cost values presented in Table 4 do not include traffic control and other installation and supervision costs.

TABLE 4. Type of Aggregate and Price for Selected HFS

Product	Type of Aggregate	Total Price per ft^2
Crafco	Bauxite (China-Guyana) Granite	$ 3 $ 2.25
FlexoGrid	Basalt + granite Silica	$ 4.5 – 5 $ 2.2 -2.7
Italgrip	Steel slag (patented)	$ 2.2
Safelane (Cargill)	Dolomite	$ 6
Safe-T-Grip	Granite	$ 1.6
Tyregrip	Calcined bauxite (buff and grey)	$ 1.7

Monetary values assigned to accidents (Table 5), injuries, and property damage were obtained from the Minnesota Department of Transportation benefit-cost analysis (Mn/DOT 2005).

TABLE 5. 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

4.4 Accident Data

Before-and-after accident data were obtained from only one location: the Wisconsin Department of Transportation. Accident data were collected for a period of three years prior to the installation of the HFS to three years afterward. It is possible that some accidents may have been overlooked in this data for several reasons, including: vehicle leaving the scene, accident not being reported, exact location being incorrectly documented on the accident report, or being missed by the database search (Bischoff 2008).

5. RESULTS

The locations shown in Table 3 were visited in 2008, and friction and macrotexture measurements were taken with the DF Tester, CT Meter and Griptester as discussed in the previous section. This section presents the main data collected.

5.1 Friction and Texture Data Processing

The average and standard deviation were computed for each of the collected friction properties. The values obtained from friction measurements with the Griptester at the beginning and end of each different pavement section were omitted from the data set to account for possible triggering error. In addition, engineering judgment was used when processing this data because joints caused the equipment to jump when measuring at high speeds, resulting in erroneous values close to the transitions between sections. In the case of the DFTester and CTMeter, the average and standard deviation of the eight measurements for each HFS application are presented in Tables 6 and 7. The values provide an indication of typical values of initial friction and texture that could be expected of an HFS system on highways. For comparison purposes the tables also include values of friction and texture for typical flexible and rigid pavement surfaces.

TABLE 6. Friction Measurements for Selected HFS

HFS	Code	Appl. Date	Friction (GN) at 40 mph*	Std. Dev.	Friction (DFT) at 20kph	Std. Dev.
Crafco	TN-C	2008	1.05	0.05	0.98	0.02
Italgrip	TN-I	2008	1.02	0.04	1.01	0.01
Italgrip	W-I-1	1999	0.67	0.07	0.78	0.04
Italgrip	W-I-2	1999	0.53	0.08	0.68	0.04
Italgrip	W-I-3	1999	0.63	0.07	0.68	0.02
Polycarb	W-P	1999	0.69	0.03	0.65	0.02
Safe-T-Grip	TN-G	2008	0.90	0.12	1.01	0.02
Safelane	VA-S-1	2005	0.50	0.05	0.48	0.04
Safelane	VA-S-2	2005	0.57	0.06	0.55	0.05
Tyregrip	VA-T	2005	0.90	0.14	1.00	0.02
EP-5	*Ref.*	*2005*	*0.65*	*0.11*	*0.62*	*0.03*
SM-9.5D	*Ref.*	*1999*	*0.77*	*0.01*	*0.82*	*0.03*
SMA-12.5	*Ref.*	*1999*	*0.74*	*0.01*	*0.72*	*0.04*
OGFC	*Ref.*	*1999*	*0.68*	*0.01*	*0.63*	*0.04*
Tinned CRCP	*Ref.*	*1999*	*0.82*	*0.02*	*0.77*	*0.01*

Pavements presented in italic are non-HFS used here as reference values and were collected on the Virginia Smart that has very only research traffic.

* This measurement corresponds to 10.14-12.48 km/h slip speed.

Table 6 shows that some of the HFS have considerably higher friction than the conventional surfaces. The difference in initial friction between these rigid and flexible pavements and the HFS systems emphasizes the need for HFS systems on black spots where wet-weather crashes or crashes caused by deficient surface properties occur frequently and where additional friction may be needed.

TABLE 7. Friction Texture Measurements for Selected HFS

HFS	Code	Application Date	Texture (MPD)	Std. Dev.
Crafco	TN-C	2008	1.46	0.09
Italgrip	TN-I	2008	1.61	0.12
Italgrip	W-I-1	1999	1.03	0.10
Italgrip	W-I-2	1999	1.07	0.06
Italgrip	W-I-3	1999	1.04	0.08
Polycarb	W-P	1999	1.07	0.24
Safelane	VA-S-1	2005	1.53	0.16
Safelane	VA-S-2	2005	1.56	0.20
Safe-T-Grip	TN-G	2008	1.57	0.23
Tyregrip	VA-T	2005	1.28	0.10
EP-5	*Ref.*	*2005*	*1.16*	*0.09*
SM-9.5D	*Ref.*	*1999*	*1.05*	*0.11*
SMA-12.5	*Ref.*	*1999*	*0.91*	*0.13*
OGFC	*Ref.*	*1999*	*1.58*	*0.09*
Tinned CRCP	*Ref.*	*1999*	*1.17*	*0.09*

Pavements presented in italic are Non-HFS used here as reference values.

Figure 6 Summarizes the data collected in whisker box plots for the friction and macrotexture on all of the HFS. Table 6 shows that the macrotexture values provided by the HFS are similar to those measured on OGFC and considerably higher than the typical flexible and rigid pavement surfaces.

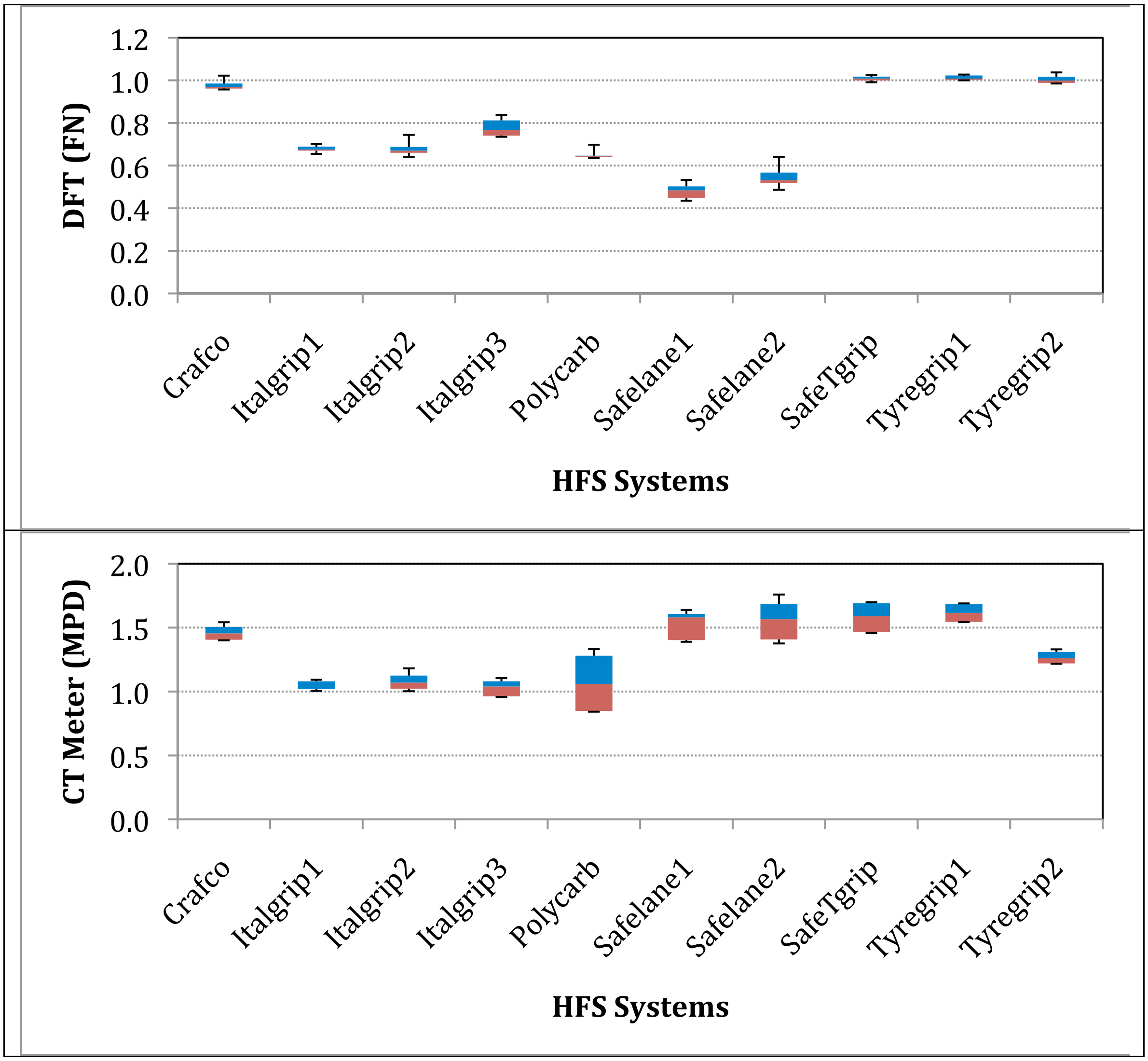


FIGURE 5. Texture and friction whisker box plot for all HFS systems.

To illustrate the influence of the friction coefficients on a real-life situation, the following scenario is proposed. A 2,500-lb vehicle traveling at 65 mph on a 2 percent downhill grade with a brake efficiency of 100 percent requires 210.2 ft of minimum stopping distance on a pavement with a friction of 0.735 DFT (average initial friction of non-HFS pavements from Table 6). On the other hand, 158.4 ft is the minimum stopping distance for the same vehicle on an HFS surface with a coefficient of friction of 0.963 DFT (average initial friction of HFS from Table 5).

5.2 Initial Friction – Cost

Table 7 summarizes the cost, initial friction, and texture values associated with each HFS product for which enough information was obtained. The source of these cost values is explained in Section 4.2. The purpose of Table 8 is to help agencies identify which HFS would better fulfill their specific need and at the same time adjust to their budget.

TABLE 8. Price and Initial Friction and Macrotexture for Selected HFS

HFS	Type of Aggregate	Initial Friction (GN) at 40 mph	Friction (DFT) at 20 km/h	Texture (MPD)	Total Price per ft^2
Crafco	Bauxite	1.05	0.98	1.46	$3
Italgrip	Steel slag (patented)	0.98	1.01	1.61	$2.2-2.7
Safe-T-Grip *	Granite	0.90	1.01	1.52	$2.2
Tyregrip	Calcined Bauxite	0.90	1.01	1.28	$1.7
Safelane - Cargill**	Dolomite	0.86	1.02	1.21	$6

* When measurements were recorded, the system was not completely cured.

** Measurements were recorded from Smart Road and traffic was assumed to be zero.

6. ANALYSIS

6.1 Economic Analysis

A benefit-cost study is an economic evaluation of the advantages and disadvantages on a set of investment alternatives, where if the ratio of the benefit-cost is greater than one the alternative is said to be economically justifiable.

In this case the base scenario is a roadway section without an HFS application (roadway with rigid or flexible pavement) and the alternative is an HFS system. A simplified cost-benefit analysis is used to compare an HFS alternative with a non-HFS pavement to determine the most cost effective alternative. This method considers in its analysis the costs associated with the initial construction of surface treatment; it does not include future maintenance because on these systems rehabilitation means overlay. The benefits used in the analysis are safety performance improvements; such as reductions in deaths, injuries, and property damage before and after the system was placed. The objective of this economic analysis is to illustrate a methodology that can be used to analyze the feasibility of HFS applications.

6.1.1 Estimated High-Friction Surface Service Lives

Four Italgrip HFS sections placed in the state of Wisconsin were studied. This product and location were selected because historical friction measurements and accident data were only found for this installation. Figure 7 shows measurements of friction over time for two of the selected surface samples (estimation for other considered locations can be found in Appendix I). After trials with different models, a power regression model was selected because it exhibited the best behavior of all HFS and also represented the physical wearing process typically observed.

The power trend fitted to the data showed that the various materials do not reach unaccepted friction values within the analysis period. However, based on engineering judgment and the observation of the sections evaluated in Wisconsin, a HFS service life of 10 years was considered appropriate. According to the data in Tables 6 and 7 it may be expected for the system to maintain acceptable friction levels after 10 years; however, the raveling process would be very advanced as shown in Figure 3, picture c. Applications W-I-1, W-I-2, W-I-3, and W-P have been in service for nine years and still exhibit good friction and macrotexture levels but the first three also show significant raveling.

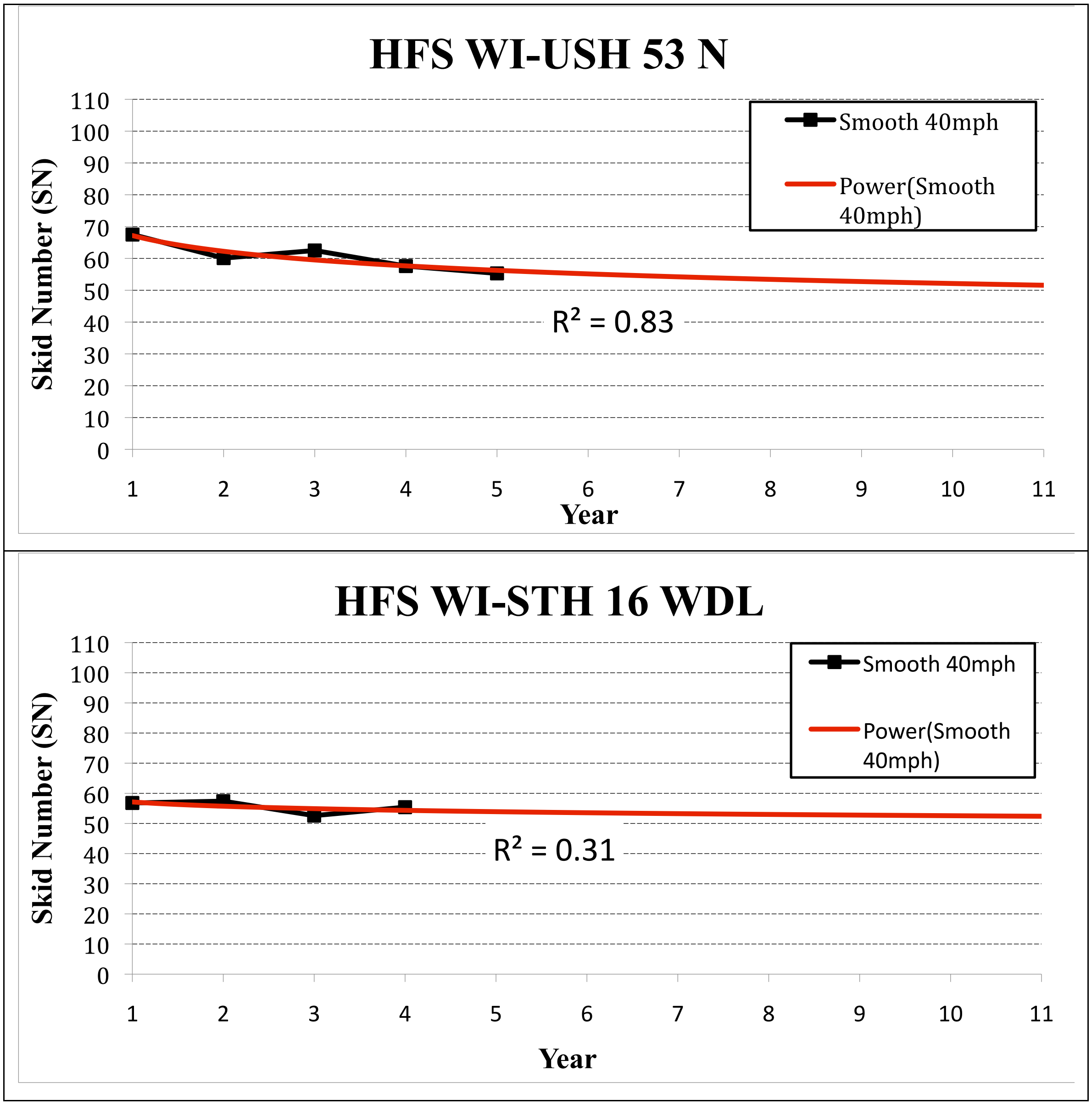


FIGURE 6. HFS wear and scuffing rate.

6.1.2 Values for Transportation Economic Study

Reduction in the number of skid-related accidents is the principal benefit from the application of HFS. Benefits occur when severity or number of crashes is reduced in a system due to roadway surface properties improvement. For the analysis presented in this thesis, the least severe injuries (type C) for highway users were assumed and only property damage was considered for vehicles involved in these accidents to evaluate HFS under a conservative scenario.

6.1.3 Benefit-Cost

The benefit of the project is derived from comparing the "before" base case highway accidents that occur within the study area to those of the "after" alternative scenarios. The study area includes two roadway sections in the towns of LaCrosse and Waukesha, Wisconsin. The base case scenarios are defined for this thesis as the existing conditions before the application of the HFS, whereas the proposed alternative scenarios are the conditions after the application of the HFS. The analysis period is 10 years, the base year is 2008, and the discount rate is 4 percent.

The benefit is measured as the reduction of annual number of crashes, injuries, and deaths from the base case to the alternative case. The economic values of the crash events were obtained from Table 5. The total present cost of accidents for the base and alternative cases are calculated as the sum of the discounted annual cost found for each year in the 10-year analysis period. The difference in crash costs between the base and alternative are reported as the present worth of benefits.

Typical construction costs were obtained from the material suppliers and were reported in Table 5. Routine maintenance costs were assumed to be the same for the base and alternative scenarios since the alternative does not have a significantly different effect on maintenance and they both require plowing, debris removal, etc.

The results of the benefit-cost analyzes for the two studied areas are presented in Table 9 and Table 10. The table also shows the benefit-cost ratio computed as the ratio between the savings in crash cost and the cost of applying the HFS. These results show that in all four of the studied sections the alternative is economically justified compared to the base scenario, with benefit cost ratios ranging between 4 and 20.

TABLE 9. Benefit-Cost Analysis for HFS Locations in Waukesha, Wisconsin

Waukesha County STH 16		LaCrosse County STH 16 - NB and SB	
Accidents		**Accidents**	
Before Italgrip (per Year)		*Before Italgrip (per Year)*	
incidents	1.6	Incidents	3.66
vehicles	2.3	Vehicles	10
injured / 0 killed	0.67	injured / 0 killed	2
After Italgrip (per Year)		*After Italgrip (per Year)*	
incidents	0	Incidents	0.33
vehicles	0	Vehicles	1.33
injured / 0 killed	0	injured / 0 killed	0
Accidents Benefits		**Accidents Benefits**	
Vehicles-Property Benefit*	$85,366	Vehicles-Property Benefit*	$321,791
Injuries-Death Benefit **	$169,550	Injuries-Death Benefit **	$506,120
Present Worth Benefit	**$254,916**	**Present Worth Benefit**	**$827,911**
Cost of HFS		**Cost of HFS**	
# of Lanes	2	# of lanes	4
lane width	12	lane width	12
Typical section length	400	Typical section length	400
price/ft^2	$2.20	price/ft^2	$2.20
Total HFS Cost	**$21,120**	**Total HFS Cost**	**$42,240**
B/C	**12.07**	**B/C**	**19.60**

TABLE 10. Benefit-Cost Analysis for HFS Locations in LaCrosse, Wisconsin

LaCrosse County STH 35 NB		LaCrosse County STH 53 NB and SB	
Accidents		**Accidents**	
Before Italgrip (per year)		*Before Italgrip (per year)*	
incidents	1	incidents	3
vehicles	5.33	vehicles	3.33
injured / 0 killed	1	injured / 0 killed	1
After Italgrip (Nov 99 - Oct 02)		*After Italgrip (Nov 99 - Oct 02)*	
incidents	0	incidents	0.33
vehicles	0	vehicles	1
injured / 0 killed	0	injured / 0 killed	0.66
Benefits		**Benefits**	
Vehicles–Property Benefit*	$191,986	Vehicles-Property Benefit*	$83,926
Injuries-Death Benefit **	$245,590	Injuries-Death Benefit **	$83,501
Present Worth Benefit	**$437,576**	**Present Worth Benefit**	**$167,427**
Cost		**Cost**	
# of lanes	2	# of lanes	4
lane width	12	lane width	12
Typical section length	400	Typical section length	400
price/ft^2	$2.20	price/ft^2	$2.20
HFS Cost	**$21,120**	**HFS Cost**	**$42,240**
B/C	**20.72**	**B/C**	**3.96**

6.2 International Friction Index for High-Friction Surfaces.

In order to provide standard reference values for the different products evaluated, the International Friction Index parameters, F(60) and S_p, were computed using ASTM 1960 with small modifications.

Table 12 presents the results based on the DFTester and CTMeter measurements and using the original coefficients developed by PIARC and the revised coefficient presented in Chapter 2 and Equations (1) through (3). In addition the table also includes the measured Gripnumber (GN) and the values “estimated” using the original and revised IFI coefficients. Unfortunately, none of the set of confidents can be used to accurately harmonize the DFTester and Griptester measurements, since the estimated Gripnumbers do not match the actual field measurements. This suggests that more data on a wider range of pavement surfaces, including positively-textured surfaces such as HFS, may be needed to accurate determine the harmonization confidents.

TABLE 12. HFS Friction Measurements using the International Friction Index.

				PIARC COEF.	REVISED COEF.	
CODE	TX	**Sp**	F(60)	FR(S)	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

7. FINDINGS AND RECOMMENDATIONS

High-friction surfaces (HFS) are increasingly being considered for areas where additional friction may be needed because they provide high levels of friction without negatively affecting other pavement qualities, like noise or durability. The review conducted showed that the products available in the United States market include Crafco HFS, Italgrip, FlexoGrid, Safelane, SafeTGrip, and Tyregrip. Some of the available applications for these products were evaluated and a cost-benefits methodology was proposed.

The field evaluations showed that most of these products provide very high initial levels of friction and macrotexture. The limited historical data also show that at least some of the systems can maintain high friction values after 9 years of service.

Furthermore, in the few applications where before and after crash data were recorded, a benefit-cost analysis showed that the use of HFS is economically justified. The reduction in crash cost is 4 to 20 times the cost of the treatments for these locations. Similar analyzes should be conducted for other products and installation locations and/or conditions before strong conclusions can be drawn.

Comparisons between friction data collected with the DFtester and the Griptester showed that the available harmonization models cannot be accurately applied to HFS. More harmonization experiments are recommended with a wider range of pavement surfaces, including HFS and other types of surface treatments, to determine the IFI coefficients recommended by ASTM 1960.

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CHAPTER IV
SUMMARY, FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

It is important that highway agencies provide drivers with safe, smooth rides throughout the year. It is for this reason that friction, texture and other surface properties must be monitored periodically. Roadway sections with deficient friction must be treated to improve safety and HFS are starting to be considered as a viable treatment in areas with high number of skidding-related accidents.

The thesis presented a detailed evaluation of the main HFS products available in the United States market; by measuring their performance on different applications, under different weather conditions, and in various locations (states).
In addition, it also presented efforts to compare and harmonize texture and skid resistance measurements taken with various devices.

1. FINDINGS

In the process of evaluating the IFI coefficients, discrepancies were found in the IFI values calculated for the different devices:

- The data collected for this project showed that the model developed by PIARC does not produce harmonious results among the devices used by the consortium members in the Virginia Smart Road Rodeo for the surfaces tested.
- This suggests that the original coefficients determined during the PIARC experiment may need to be adjusted for the devices evaluated before the IFI can be implemented in the U.S.

- Furthermore, it was not possible to harmonize the measurements obtained with the various devices used in this thesis on all the studied HFS.

The evaluation of the various identified HFS products and applications permitted to draw the following findings:

- There are various HFS products available in the U.S. market, which have been used by different agencies.
- The data collected for this project showed that HFS can maintain good levels of friction and macrotexture texture for at least 9 years of service.
- However, some of the evaluated applications developed significant level of raveling after 10 years.
- The benefit-cost study found that at least in areas with high number of skidding-related crashes , HFS can be economically justifiable treatments.
- Some of the applications evaluated resulted in present benefit-cost ratios of 4 to 20.

2. CONCLUSIONS

The results of the evaluation of the various identified HFS products and applications suggested that HFS are an appealing alternative for areas with frequent wet weather and/or run-off-the-road crashes. Therefore, HFS systems should continue to be considered in the pool of available safety improvement alternates. Additional application and before and after crash studies for different application conditions may provide additional understanding of the benefits of the various available systems.

3. RECOMMENDATIONS FOR FUTURE RESEARCH

The use of recorded accident data on black spots where friction is being monitored frequently is recommended to determine required threshold levels for surface properties' maintenance and rehabilitation.

It is necessary to study, monitor and correlate texture, friction and accident data to predict minimum acceptable surface friction values according to safety standards.

The existing correlation between accidents, skid resistance and geometric design parameters, like radius of curvature, could be further studied, for the reason that a high percentage of accidents occur on curves.

More experiments are recommended with different types of pavement surfaces, including HFS and other types of surface treatments, to demonstrate the validity of the Sp coefficients recommended by ASTM and also the validity of using the DF Tester as the standard device to gather friction measurements for the IFI calculations.