Federal Highway Administration Pavement Friction Management (PFM) Support Program

LOCKED-WHEEL AND SIDEWAY-FORCE CONTINUOUS FRICTION MEASUREMENT EQUIPMENT COMPARISON AND EVALUATION REPORT

U.S. Department
of Transportation
Federal Highway
Administration

May 2019

FOREWORD

This report compares network-level friction measurements obtained with a continuous friction measurement system, Sideway-force Coefficient Routine Investigation Machine (SCRIM), and a traditional locked-wheel skid trailer (LWST). The report also describes the results of two “harmonization” experiments at the two national LWST testing calibration facilities and recommends equations for converting the SCRIM friction measurements to traditional LWST friction measurements. A strong correlation was found between LWST measurements using a ribbed tire and the SCRIM measurements, as both measurements are more sensitive to microtexture than macrotexture. The results show that harmonization is possible with reasonable confidence, as long as it is conducted with significant controls. Field or network-level harmonization resulted in higher variability than at the calibration facilities since the SCRIM and LWST did not test exactly the same surfaces. The report highlights the value of continuous friction measurement to assess the frictional characteristics of pavement surfaces.

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Cover Photos Source: Center for Sustainable Transportation Infrastructure (CSTI).

Technical Report Documentation Page

1. Report No.
FHWA-RC-19-001

2. Government Accession No.
N/A

3. Recipient's Catalog No.
N/A

4. Title and Subtitle
Locked-Wheel and Sideway-Force CFME Friction Testing Equipment Comparison and Evaluation Report

5. Report Date
May 2019

6. Performing Organization Code
N/A

7. Author(s)
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8. Performing Organization Report No.
N/A

9. Performing Organization Name and Address
Virginia Polytechnic Institute and State University
Applied Pavement Technology, Inc.

10. Work Unit No. (TRAIS)
N/A

11. Contract or Grant No.
DTFH61-14-C-00041

12. Sponsoring Agency Name and Address
Federal Highway Administration
Office of Infrastructure Research and Technology
6300 Georgetown Pike, HRDI-20
McLean, VA 22101-2296

13. Type of Report and Period Covered
April 2015–May 2019

14. Sponsoring Agency Code
N/A

15. Supplementary Notes
Andrew Mergenmeier, FHWA COTR

16. Abstract
This report compares network-level friction measurements obtained with a Sideway-force Coefficient Routine Investigation Machine (SCRIM) and traditional locked-wheel skid trailer (LWST). The report also describes the results of two “harmonization” experiments at the two national LWST testing calibration facilities and recommends equations for converting the SCRIM friction measurements to traditional friction measurements. A strong correlation was found between LWST measurements using a ribbed tire and the SCRIM measurements, as both measurements are more sensitive to microtexture than macrotexture. The results show that harmonization is possible with reasonable confidence, as long as it is conducted with significant controls. Field or network-level harmonization resulted in higher variability since the SCRIM and LWST did not test exactly the same surfaces. Since no high-speed friction measurement test can obtain both micro- and macrotexture, it is important to gather mean profile depth (MPD) data at the same time as the friction measurements. Incorporating equipment to obtain other geometric parameters normally used in safety/friction demand assessments, such as grade, cross-slope, and curvature, is also highly recommended.

17. Key Words
Friction, Microtexture, Macrotexture, Continuous Friction Measurement Equipment (CFME), Sideway-Force Coefficient Routine Investigatory Machine (SCRIM), Locked-wheel skid tester (LWST), Harmonization

18. Distribution Statement
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http://www.ntis.gov

19. Security Classification (of this report) **Unclassified**	20. Security Classification (of this page) **Unclassified**	21. No. of Pages **44**	22. Price

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ARFMS	Area Reference Friction Measurement System
BST	bituminous surface treatment
CFME	continuous friction measurement equipment
DFT	Dynamic Friction Tester
DGAC	dense graded asphalt
DOT	Department of Transportation
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FN	friction number
FTC	Field Test Center
HFST	high friction surface treatment
IFI	International Friction Index
IL	investigatory level
INDOT	Indiana Department of Transportation
LWST	locked-wheel skid trailer
MPD	mean profile depth
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
OGFC	open graded asphalt concrete
OR	orthogonal regression
PCCP	portland cement concrete
PFC	permeable friction course
PFMP	pavement friction management program
RMS	root mean square
SCRIM	Sideway-force Coefficient Routine Investigation Machine
SLR	simple linear regression
SMA	stone matrix asphalt
SR	slip ratio
TOM	thin overlay mix
TRC	Transportation Research Center (Ohio)

TTI	Texas Transportation Institute
TXDOT	Texas Department of Transportation
TY-D	type D mix
TZD	Toward Zero Deaths
VMT	vehicle miles traveled
WSDOT	Washington Department of Transportation

CHAPTER 1. INTRODUCTION

The United States has experienced gradual improvements in highway safety since the enactment of the Highway Safety Act of 1966. According to recent studies, the highway fatality rate on U.S. highways has decreased steadily from about 5.5 fatalities per 100 million vehicle miles traveled (VMT) in 1966 to about 1.16 fatalities per 100 million VMT in 2017 (NHTSA 2017). In addition, the total number of highway fatalities during the same time has decreased 27 percent from 50,894 to 37,133. However, over the last decade, several years of decreases in fatalities have been followed by increases, indicating that there is still much work to be done to achieve a highway system free of fatalities.

For pavement surfaces, efforts to decrease fatalities are focused on ensuring adequate friction/texture through the following:

- Proper design and construction of pavement surface mixes;
- Sufficient routine testing and monitoring of the friction/texture of in-service pavements;
- Application of corrective treatments in a cost-effective manner based on carefully established criteria linking friction/texture to crash risk.

Over the last 15 years, the methodology of crash prevention has evolved from making improvements based on crash events to a data-driven, risk-based, systemic approach to crash analysis. An effective pavement friction management program (PFMP) is a critical component in the effort to reduce pavement-related crashes and will assist in achieving the National Strategy on Highway Safety Toward Zero Deaths (TZD) effort.

OVERVIEW OF FEDERAL HIGHWAY ADMINISTRATION PAVEMENT FRICTION MANAGEMENT SUPPORT PROGRAM

In 2010, the Federal Highway Administration (FHWA) initiated a study to develop and promote PFMPs and investigate the benefits of using continuous friction measurement equipment (CFME) as compared to conventional locked-wheel skid trailer (LWST) testing. The overall goal of the study is to reduce highway crashes and related fatalities through the development and demonstration of PFMPs. Such programs, when properly devised and effectively implemented, have the potential to reduce the number and severity of crashes by decreasing crashes related to pavement friction and texture.

Phase I of a study titled “Development and Demonstration of Pavement Friction Management Programs” consisted of a theoretical analysis of vehicle, tire, and pavement interactions as they relate to skidding and resulting crashes, as well as a detailed evaluation of the pavement friction and texture measurement equipment used in managing pavement friction. One of the outcomes of this phase was an “Equipment Evaluation” report that rated the CFMEs that were available on a variety of factors. This report recommended the Sideway-force Coefficient Routine Investigation Machine (SCRIM) for testing in Phase II of the study.

The SCRIM allows continuous measurements of the following data:

- Sideway-force friction coefficient, using dynamic vertical load measurements with a free-rolling test wheel oriented at a 20-degree angle, in 1-, 2.5-, 5-, 10-, or 20-m averages, on the left wheel path;
- Mean profile depth (MPD) macrotexture with a 64-kHz, single-spot laser in 1- and 10- m averages on the left wheel path;
- Road geometry (grade, cross slope, and horizontal curvature) every 10 m;
- Temperature (pavement, tire, and air) in 1- and 10-m averages;
- Forward-facing video at a rate of one frame every 5- m.

The SCRIM has an operating speed between 15 and 55 mph, and a range of 150 miles per 2,200-gal tank of water. Data from the SCRIM are geolocated to enable integration with other data sets.

Phase II of the study, titled “Acceptance Testing and Demonstration of the Continuous Friction Measurement Equipment (CFME),” started in 2014. The following objectives were set for this phase:

- Assist four states in developing their PFMPs by considering pavement friction, texture, and crashes;
- Develop and demonstrate methods for establishing investigatory levels of friction and macrotexture for different friction demand categories in the four states;
- Demonstrate proven continuous friction and macrotexture measurement equipment for network-level data collection.

Phase II began with the purchase, training, and acceptance of the new SCRIM CFME (figure 1). Several candidate State Departments of Transportation (DOTs) were evaluated for participation in the study by considering a range of factors (e.g., friction/texture testing practices, safety and crash/fatality reporting practices, geographic diversity, availability and quality of historical friction and crash data). Based on the results of that evaluation, Indiana, Texas, Florida, and Washington were selected as participants in the study.

Source: VTTI.

Figure 1. Photo. SCRIM system.

In each of the four states, the research team met with DOT staff to identify a circuit of roads several hundred miles long for the joint SCRIM and LWST friction testing. The friction and texture data from the testing, together with historical friction, crash, and other data provided by the DOT, made up the data matrix for the analysis of the roads composing the circuit. The complete set of data analyzed using different methodologies established investigatory friction thresholds to identify road sections that should be reviewed for possible friction and/or texture enhancement.

REPORT OBJECTIVES

This report focuses on the following objectives:

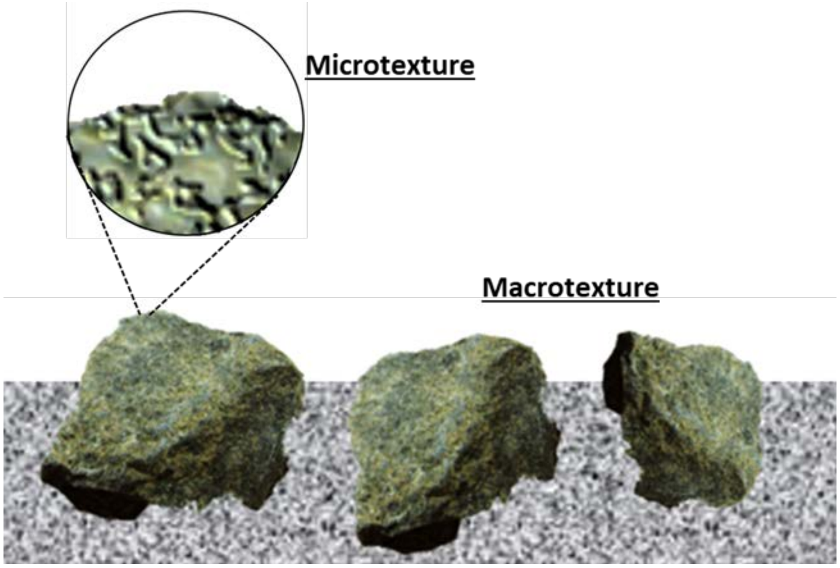
1. Compare the network-level friction measurements obtained with the SCRIM with measurements made with the traditional LWST (every 0.5 or 1.0 mi). This comparison includes data from the four states in the FHWA study and additional data collected in North Carolina.
2. Report the results of two "harmonization" experiments at the two national skid testing calibration facilities and compare them with the network-level results.
3. Assess, and if appropriate, recommend equations for converting the SCRIM friction measurements (SR30) at 30 mph to the traditional friction measurements used by most States, SN40R and SN40S at 40 mph, considering the use of macrotexture in the conversion.

CHAPTER 2. BACKGROUND

This section provides background on friction and macrotexture measurement methods and technologies, focusing on their application for network-level pavement safety evaluation.

PAVEMENT SURFACE TEXTURE

To maneuver a vehicle safely, a pavement surface should be able to provide adequate traction (also called skid resistance) to the vehicle tires in both dry and wet conditions. The pavement provides skid resistance through its surface texture. The texture of the pavement surface is separated into three categories according to texture wavelength, or the measureable distance from the peak of one asperity to another. In descending order of wavelength, the three categories are megatexture, macrotexture, and microtexture (Hall 2009). However, only macrotexture and microtexture are critical for influencing tire-pavement friction (figure 2).



Source: Adapted from Hall (2009).

Figure 2. Illustration. Pavement surface texture characteristics that influence pavement friction.

Macrotexture is the average value of the mean 50-mm subsegment depth of a 100-mm segment. Wavelengths range from 0.5 mm to 50 mm. The spacing between the aggregates creates a channel for water to flow so that the peak of each aggregate is exposed to interaction with tire tread. At a wavelength of less than 0.5 mm, microtexture characterizes the surface texture of each aggregate (Hall 2009).

FRICTION

When the speed or direction of a vehicle is changed, frictional forces develop at each tire-pavement contact patch to resist the slipping of the rubber blocks of the tire tread. The frictional forces that develop at the tire-pavement interface have two components: adhesion and hysteresis (Hall 2009). The adhesion component results from the stretching, breaking, and reformation of molecular bonds between the rubber blocks of the tire tread and the pavement microtexture. At the same time, as the tire slides over the pavement surface, the tire tread immediately deforms as it strikes the macrotexture, and since the rubber is viscoelastic it does not immediately recover its original shape. This lagged recovery and the energy lost during the recovery results in the second component of friction, hysteresis (Michelin 2001).

In this report, friction is considered a function of the two surface texture components on the road: microtexture and macrotexture. The microtexture of the road surface is what contacts the rubber of the vehicle tire and allows friction from the first component, the adhesion between the two surfaces. The greater the microtexture, the greater the friction and the greater the stopping ability once the rubber of the tire encounters it. Microtexture is the finer texture that is not so easy to see but much easier to feel if one moves one's finger across a pavement's surface. It comes from the aggregate particles (and degree of polish on larger exposed aggregate surfaces), sand, portland cement paste, or bituminous components in the surface material mix.

Macrotexture is the texture you can easily see on the surface. It is the tining, grooving, or drag surface finish of a rigid concrete surface or the degree of "openness" of an asphalt concrete surface or, even perhaps, the "jaggedness" of a chip seal surface. When a road is wet and/or experiencing rainfall, macrotexture gives water a place to evacuate when the tire comes along such that the rubber of the tire and the microtexture of the surface can make contact. It does this by providing void channels or space for the water to move to and through. Macrotexture is increasingly important as travel speeds increase. Under wet conditions, it takes both plenty of macrotexture and plenty of tire tread to be safe[1]. Macrotexture is more closely associated with the hysteresis component of friction.

Longitudinal Friction Force

When a vehicle traveling along a straight path changes speed, the difference in the rolling velocity of the wheels (V_R) and the velocity of the vehicle (V_V) causes the rubber blocks of the tire tread to shear initially as they enter the tire-pavement contact patch and then slip as they leave. The stresses induced by the shearing of the rubber blocks produce the longitudinal friction force (F_L), which is expressed as the product of the wheel weight (W) and the longitudinal friction coefficient (μ) (Michelin 2001; figure 3).

Although the standard model for μ is expressed as the ratio of F_L to W, the majority of the variation in μ depends on the amount of tire slip at the tire-pavement contact patch (Michelin 2001). Figure 4 illustrates the relationship between μ and the percentage of slip or slip ratio (SR) (computed using equation 1) in the instance of braking (Hall 2009).

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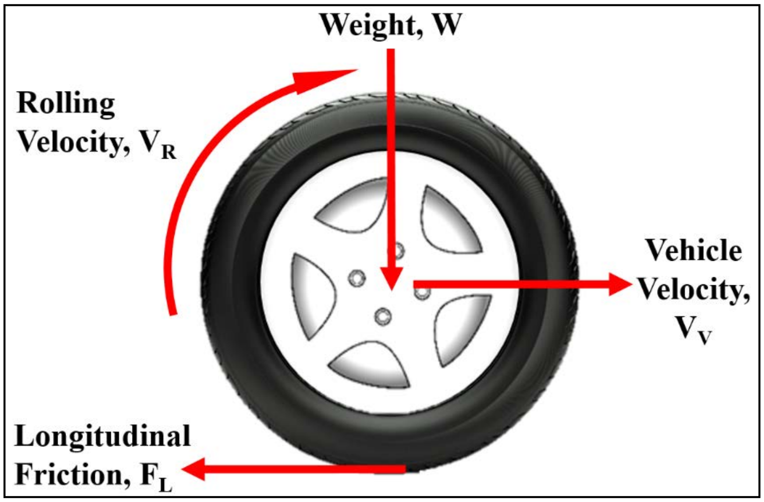
[1] Ohio Department of Transportation (Ohio DOT). 2016. Guide to Understanding Friction, Unpublished document, Office of Technical Services, Infrastructure Management Section, Columbus, Ohio.

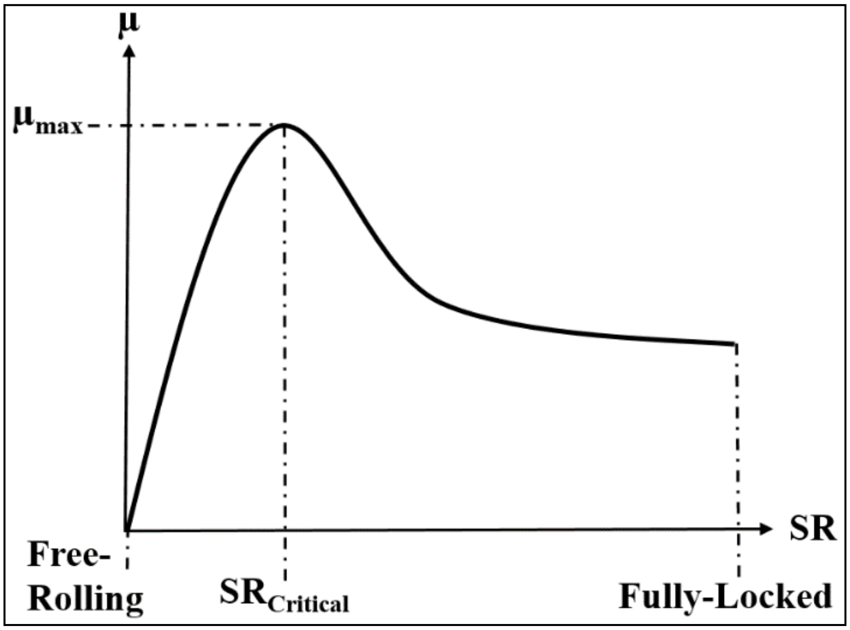
$$SR = \frac{V_V - R \times \omega}{V_V} \times 100 = \frac{V_V - V_R}{V_V} \times 100 \quad (1)$$

where SR = slip ratio (%), R = wheel radius, and ω = the angular velocity of the wheel.



Source: Adapted from Hall (2009).

Figure 3. Diagram. Forces influencing longitudinal friction.



Source: Adapted from Hall (2009).

Figure 4. Graph. Longitudinal friction coefficient versus percentage of slip.

Prior to applying the brakes, when the wheel is *free-rolling* ($V_R = V_V$), both μ and SR are approximately zero. At the instant the brakes are applied, μ quickly increases to a maximum value when SR is between 15 and 20 percent ($SR = SR_{Critical}$) (Do & Roe 2008). After passing the peak of the curve, μ begins to decrease with V_R until the wheels are fully locked ($V_R = 0$ and SR = 100%).

Transverse Friction Force

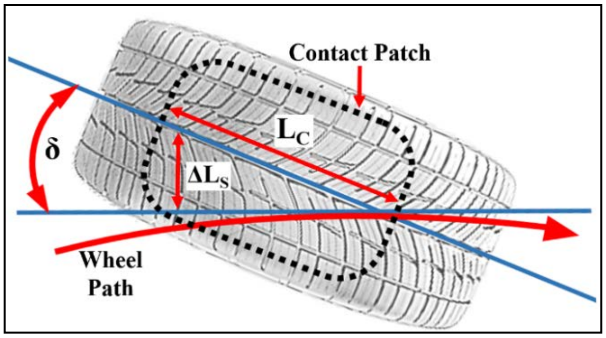
When a vehicle changes direction (e.g., traversing a curve) at a constant speed, the difference in the direction the vehicle is traveling and the direction the front wheels are pointed creates a slip angle (δ), which can be computed using equation 2 (Michelin 2001; figure 5-A).

$$\delta = \sin^{-1}\left(\frac{L_{Shear} + L_{Slip}}{L_C}\right) = \sin^{-1}\left(\frac{\Delta L_S}{L_C}\right) \tag{2}$$

where δ = slip angle of front wheel path;
L_{Shear} = length of sheared rubber tread;
L_{Slip} = length of rubber tread slippage;
ΔL_S = combined length of shearing and slippage;
L_C = total length of tire-pavement contact patch

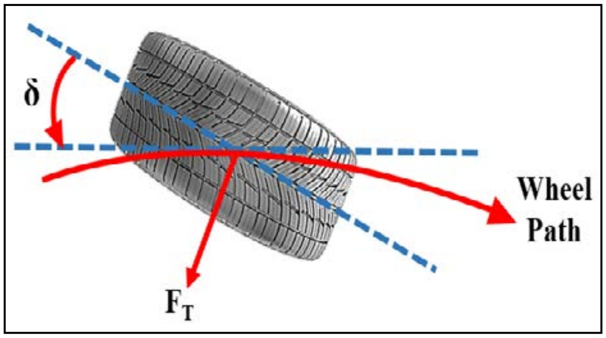
The slip angle δ causes the rubber blocks of the tire tread to shear as they enter the tire-pavement contact patch and then slip as they exit. The stresses induced by the shearing of the rubber blocks produce the transverse friction force (F_T) shown in figure 5-B.

Similar to μ, the transverse friction coefficient (η) is expressed as the ratio of F_T to W. Furthermore, the majority of the variation in η depends on δ in the same way that the majority of μ varies with SR. Figure 6 shows the relationship between η and δ. Prior to entering a curve, η and δ are approximately zero. As the vehicle enters a curve, η rapidly increases to a maximum value when δ equals $\delta_{Critical}$. The critical slip angle, $\delta_{Critical}$, can range from 4 degrees to 7 degrees for passenger cars, or 6 degrees to 10 degrees for trucks (Michelin 2001).



Source: Adapted from Michelin (2001).

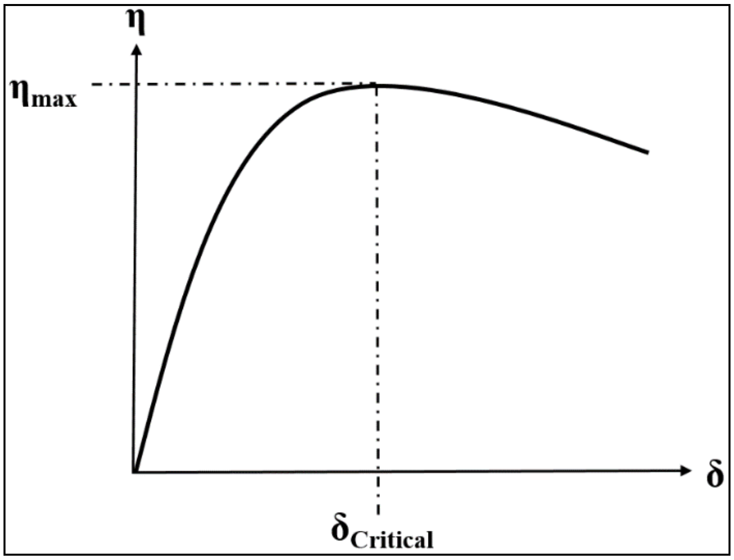
A. Shearing and slipping of the rubber tread.



Source: Adapted from Michelin (2001).

B. Generation of transverse friction force (F_T).

Figure 5. Illustrations. Influence of the front-wheel path slip angle on (A) the shearing and slipping of the rubber tread and (B) the generation of the transverse friction force (F_T).



Source: Adapted from Do & Roe (2008).

Figure 6. Graph. Side-force coefficient versus slip angle.

FRICTION AND MACROTEXTURE TESTING EQUIPMENT

Network-level testing requires high-speed measurement equipment. There are two categories of high-speed friction test methods, continuous and non-continuous. The locked-wheel (AASHTO T 242/ASTM E 274) is a non-continuous friction measurement test. There are three general types of continuous friction measurement equipment (CFME): fixed-slip (ASTM E 2340), sideway-force coefficient, and variable-slip (ASTM E 1859) (Henry 2000). These high-speed methods are operated at a fixed speed, generally between 30 and 50 mph, while they simultaneously wet the surface with a user-defined, uniform water film thickness on the pavement surface in front of the test wheel(s), usually 0.0197 inches (0.5 mm).

Friction Measurement Equipment

In the U.S., the locked-wheel technique is the most common method used by state highway agencies (Henry 2000). The locked-wheel equipment consists of a trailer equipped with two wheels with full-size tires (15 by 6 inch), one or both of which are used to test longitudinal friction. A test wheel on a locked-wheel device is fitted with either a standard smooth tire (AASHTO M 286/ASTM E 524) or a standard ribbed tire (AASHTO M 261/ASTM E 501). According to Hall (2009), the smooth tire is “sensitive to macrotexture,” while the ribbed tire is more “sensitive to microtexture.” A locked-wheel device measures friction by completely locking up the test wheel(s) and recording the average sliding force for a period of 3 s and reporting a 1-s average after reaching the fully locked state (100% slip). Thus, with a 40-mph test speed, a 1-s test time is equivalent to testing the pavement surface for approximately 59 ft. The full-lock requirement means that measurements can only be recorded periodically over short intervals of time. For example, one test per mile results in approximately 1.1% of the pavement surface being tested.

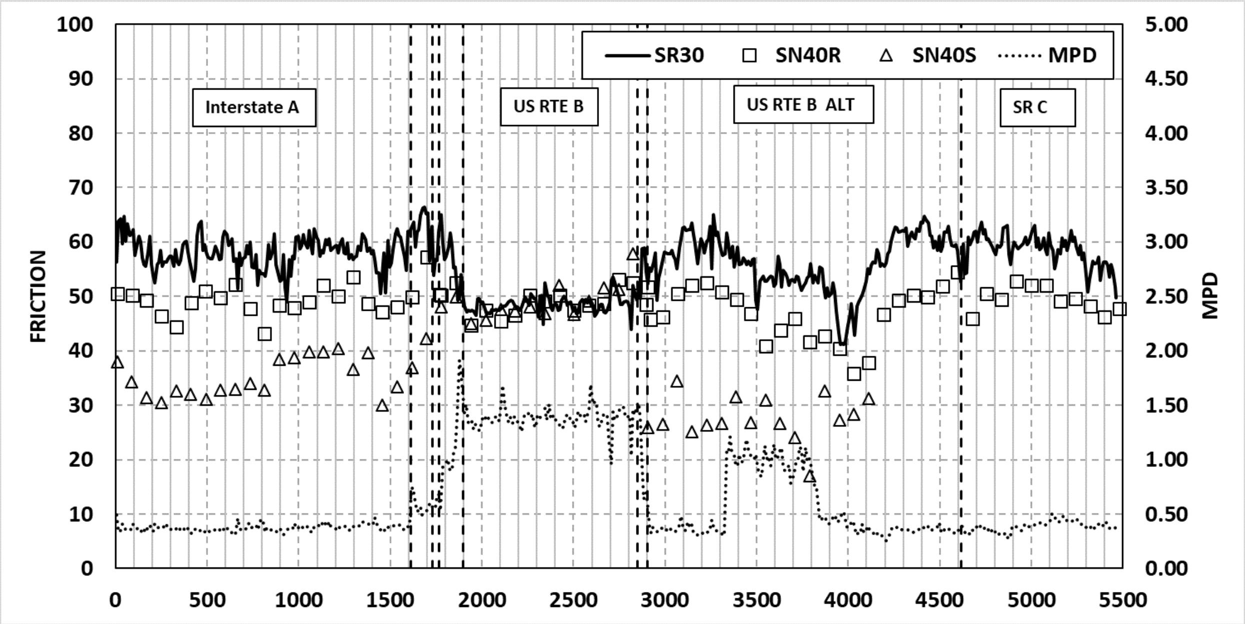
The SCRIM is more common internationally. It uses a free-rolling wheel, a treadless tire, and a fixed 20-degree slip angle to generate (and measure) a continuous frictional force. In contrast with the locked-wheel systems, the SCRIM tests 100 percent of the pavement surface, usually reporting at intervals as short as every 4 inches (0.1 m). The measured friction is usually reported as an SR30, or SCRIM reading at a standardized testing speed of 30 mph (50 km/h).

Surface Texture

For network-level measurements, the more practical alternative for testing macrotexture on in-service roads is to use high-speed equipment. High-speed, vehicle-mounted laser devices are used to obtain the profile of the pavement surface and a macrotexture parameter computed from this profile; typically, the MPD (ASTM E-1845) or the root mean square (RMS) is reported.

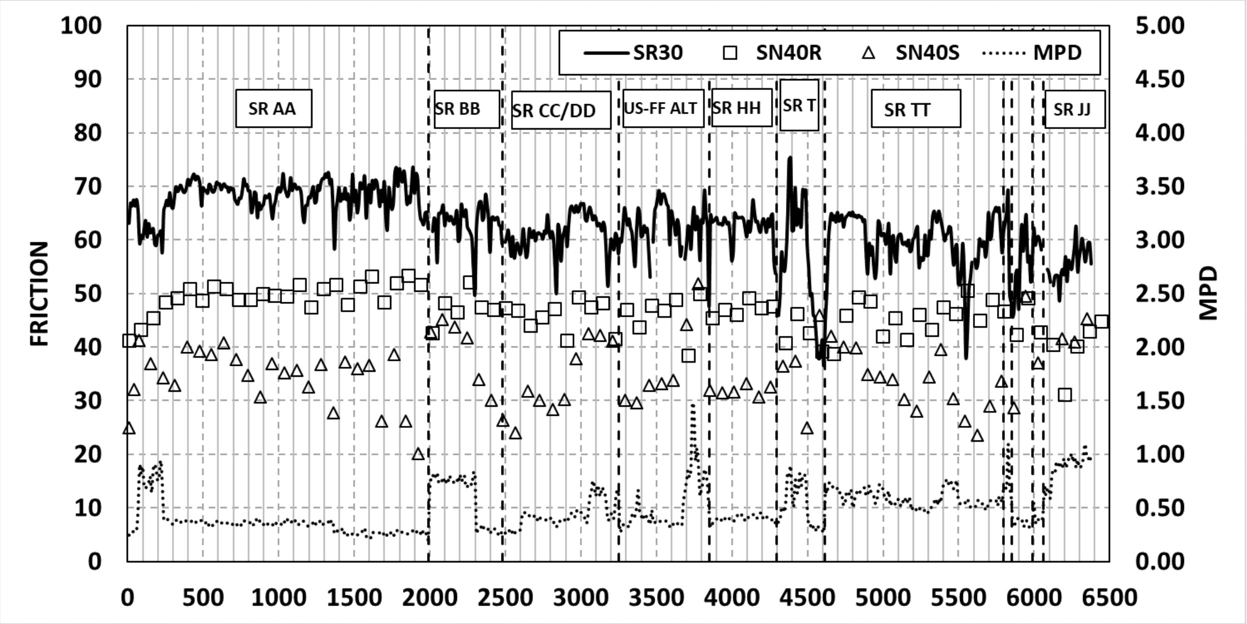
Differences in the design and configuration of friction testing equipment and their test tires create different sensitivities to speed and macrotexture (or MPD). According to Hall et al. (2009), the LWST standard ribbed tire is insensitive to MPD, whereas the standard smooth tire is very sensitive to MPD. Fuentes et al. (2014) explored this further by investigating the speed dependence of friction measured with a ribbed tire and a smooth tire on pavement surfaces with different levels of MPD. They showed that measurements made using both tires had similar speed dependence on pavement surfaces with high MPD. In contrast, the speed dependence was significantly different on pavement surfaces with lower MPD.

Figure 7 compares the friction along several sections of road as measured with an LWST using both the ribbed (SN40R) and the smooth (SN40S) tire. The figure also includes continuous friction (SR30) and MPD, which were measured with the SCRIM. The figure shows that where there are changes in MPD, there are also marked changes in the smooth-tire measurements (SN40S). However, there do not appear to be any significant changes in the ribbed-tire measurements (SN40R) for the same changes to MPD. In general, the figure appears to support Hall et al.'s (2009) statement that the LWST with a ribbed tire is relatively insensitive to changes in MPD. The figure also shows that the SCRIM SR30 and LWST SN40R measurements trend in a reasonably similar manner. Therefore, it is clear that the SCRIM measurements provide an indication of both microtexture from the SR30 results and macrotexture from the MPD results needed for complete friction evaluations, and continuously.



Source: CSTI

A. SR30, SN40S, SN40R, and MPD for Interstate A, US Route B, US Route B Alt, and State Route C.



Source: CSTI

B. SR30, SN40S, SN40R, and MPD for State Route AA, State Route BB, State Route CC/DD. State Route HH, State Route T, State Route TT, and State Route JJ.

Figure 7. Graphs. Example comparison illustrating equipment sensitivity to MPD.

FRICTION MODELS

The relationship between pavement friction, texture, and testing speed has been investigated for many years. Leu and Henry (1978) first predicted the relationship between friction and skid speed considering the micro- and macrotexture of pavement. Henry (2000) proposed a revised formula (known as the Penn State model), which relates friction with speed through the following formula (equation 3):

$$F(S) = F_o * e^{\frac{-S}{S_o}} \tag{3}$$

where $F(S)$ = friction measured with equipment at speed S;
F_0 = a nondimensional constant that depends on microtexture and represents the theoretical friction at skid speed of 0;
S = skid speed in km/h;
S_o = a constant with speed units that depends on macrotexture.

The model was subsequently modified so that the reference speed would be 10 km/h instead of 0, as follows in equation 4:

$$F(S) = F_{10} * e^{\frac{S-10}{S_0}} \tag{4}$$

where F_{10} = the friction value obtained for a skid speed of 10 km/h.

The values for F_{10} and S_0 were obtained based on measurements with different equipment using smooth and ribbed tires; however, the data did not present a good correlation in all cases (Wallman & Astrom 2001).

In the 1980s, PIARC conducted an international experiment to compare and harmonize the measurements of texture and skid resistance. The result of that experiment was what we know today as the International Friction Index (IFI). The experiment involved 16 countries and 47 measurement systems, and evaluated 54 different sections in Spain and Belgium (Wambold et al. 1995). The experiment also determined initial harmonization constants for the different equipment used in the experiment. As shown in equation 5, the reference speed was changed to 60 km/h:

$$FR60 = FRS * e^{\frac{s-60}{S_p}} \tag{5}$$

where FR60 = friction at the skid speed of 60 km/h;
FRS = friction value at S km/h;
s = slip speed;
s_p = speed constant, which has speed units and is related to macrotexture.

Other experiments, such as HERMES (Descornet 2004) and TYROSAFE (Vos & Groenendijk 2009) have also tried to harmonize measurements taken with the different friction measuring equipment to a common scale. However, a general harmonization has proven to be very challenging, although some organizations have had better results for their specific equipment (Flintsch et al. 2008).

CHAPTER 3. DATA COLLECTION

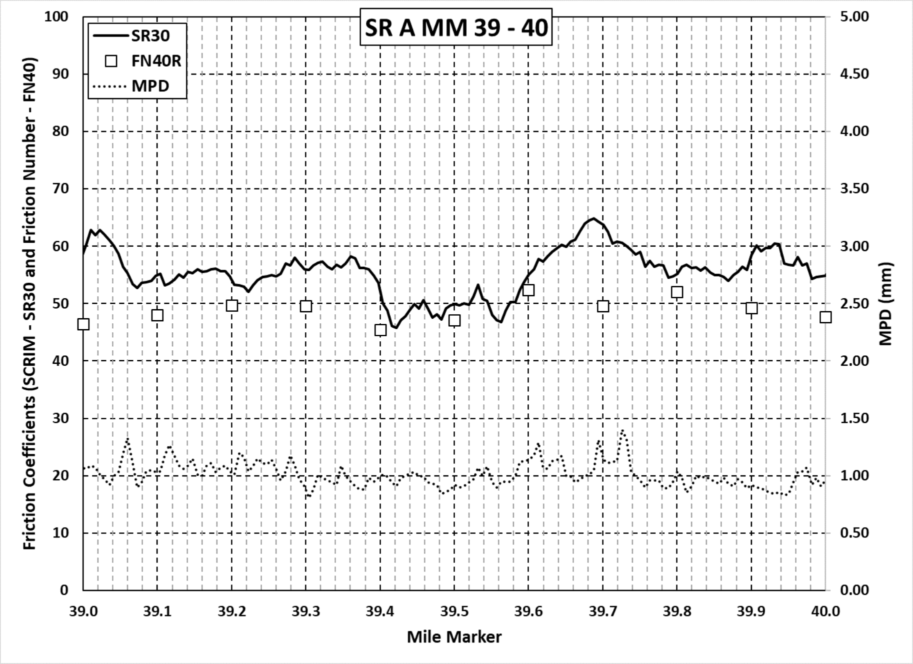
This section discusses the details of the data collection on the selected sample networks and at the two U.S. skid testing calibration facilities.

CONTINUOUS FRICTION MEASUREMENT EQUIPMENT VERSUS TRADITIONAL LOCKED-WHEEL SKID TRAILER DATA COLLECTION

The high-resolution coverage provided by CFME like the SCRIM is particularly important when potential friction problems are relatively short road segments with locally high demand for friction, such as curves and intersections. Kummer and Meyer (1967) in National Cooperative Highway Research Program (NCHRP) Report 37 established that “because the intensity of the polishing process increases markedly with tread element slip, all other factors being equal, the lowest friction levels are found on high-speed roads, curves, and approaches to intersections; in short, in locations at which high friction values are needed most.” Due to the LWST standard practice of testing on a sampling basis and the challenge of testing in some curves and intersections, many times road sections with lower friction in areas with a higher friction demand are not tested.

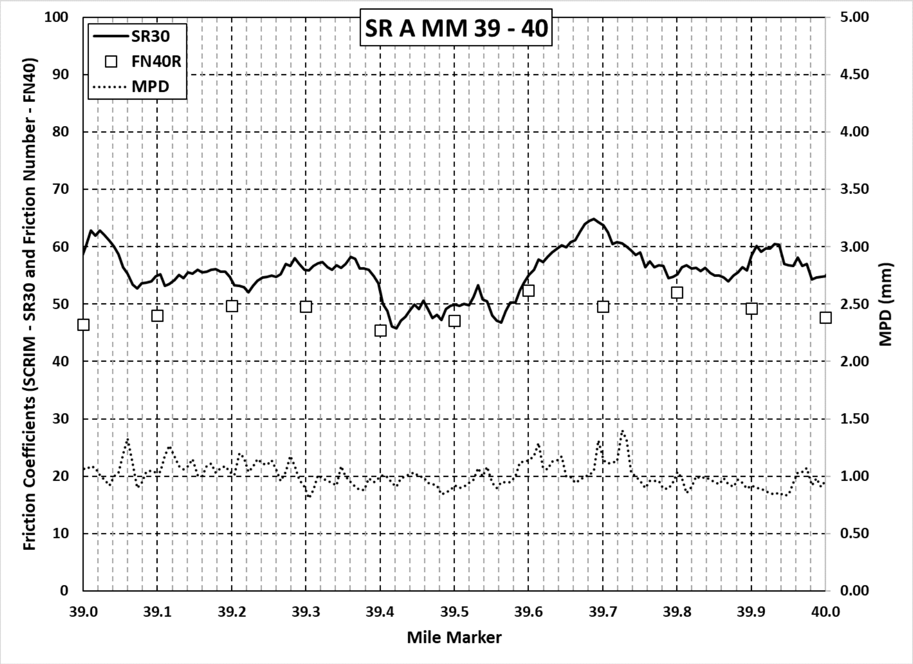
The importance of having a higher testing resolution is illustrated in the following example. Figure 8 compares the LWST and SCRIM measurements on one of the routes surveyed. In this section, LWST measurements were taken at two different testing frequencies. From mile 35 to mile 40, the LWST measurements were taken every 0.1 mi; across the rest of the route they were done at the usual 1.0-mi interval.

Figure 9 zooms in on the results of the measurements from mile 39 to mile 40. The figure highlights that the two sets of measurements in general follow the same trend, but the SCRIM measurements are more sensitive to spatial fluctuations in friction. For example, both systems identified relatively lower friction values near mile 39.4. However, the figure also shows several examples where the LWST is simply insensitive to short variations in friction. The higher granularity of the continuous friction measurement identified relatively higher values at mile 39.0 and mile 39.7, higher values that were not picked up by the LWST.



Source: CSTI

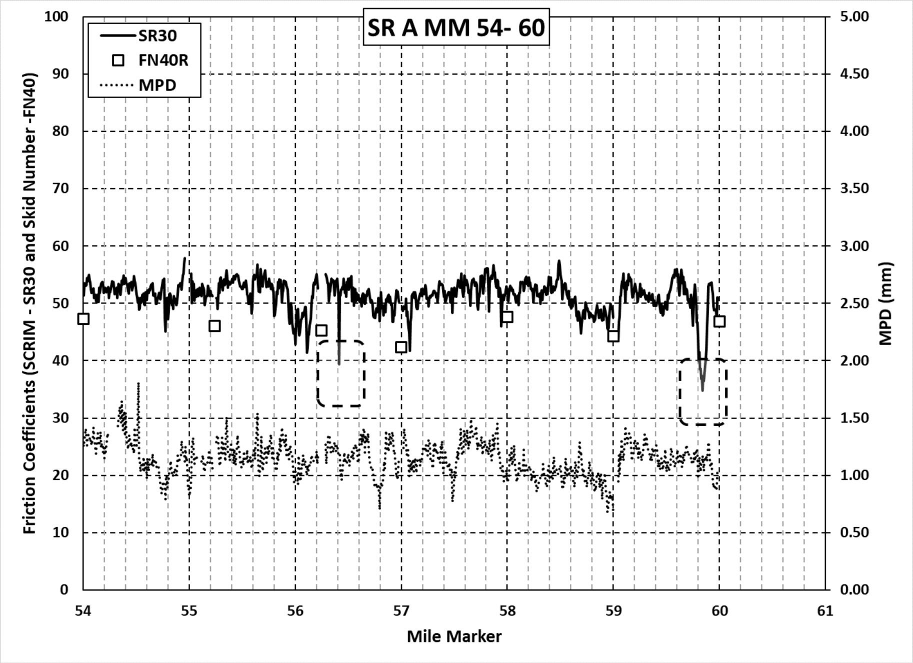
Figure 8. Graph. Example of friction and macrotexture along State Route A (milepost 33 to 60).



Source: CSTI

Figure 9. Graph. Detail of measurements on State Route A between mileposts 39 and 40 (with high LWST spatial frequency).

The discrepancy in resolution provided between the SCRIM and LWST is magnified when the LWST measurements are taken at the conventional frequency of one test every 1 mile. Figure 10 zooms in on the friction measurements from mile 54 to mile 60, where the LWST is only measuring one 59-ft segment every mile. In this plot, the data collected with the SCRIM detected two lower friction spots, including one at mile 59.8, which the LWST missed because it did not conduct any measurements in the 0.1-mi intervals between mile 59 and 60.



Source: CSTI

Figure 10. Graph. Detail of measurements on State Route A between mileposts 54 and 60 (low LWST spatial frequency).

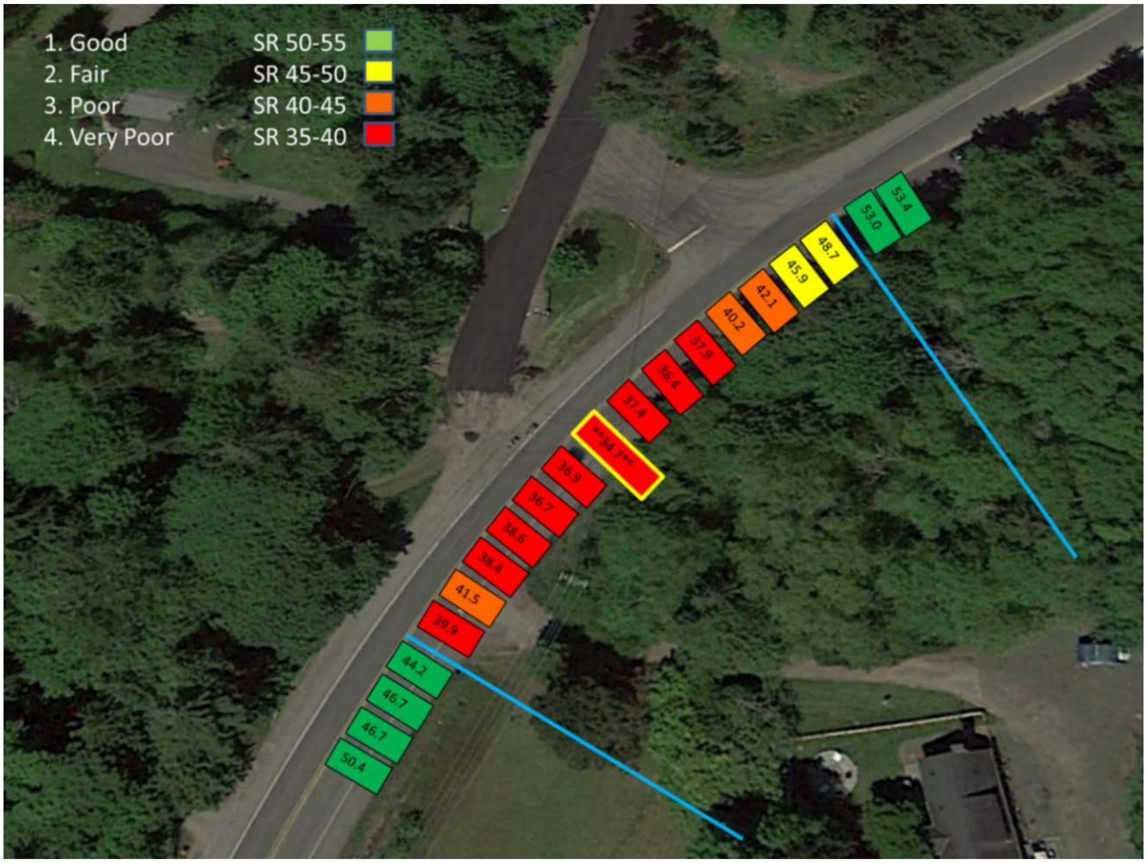
Source: CSTI

Figure 11. Photo. State Route A at mile marker 59.8.

Further investigation of the mile 59.8 location revealed that the cause of this lower friction section is probably exacerbated with the vehicle braking and turning at the intersection. This phenomenon, recognized some 50 years ago by Kummer and Meyer (1967), is typical of intersections where vehicles are braking and turning and thus polishing the pavement aggregates at a higher rate. It is also interesting to note that this is one of the locations with the highest number of crashes on that route. For the road segment from mile 33 to 60, the location with the second highest number of crashes is mile 59.9, with 25 reported crashes over the 3 years preceding this testing. Therefore, this section, which was identified using the SCRIM but missed with the lower-resolution testing of the LWST, is a good candidate to investigate for a localized friction enhancement treatment such as a high friction surface treatment (HFST). This information also illustrates the potential benefit of conducting continuous friction measurements before HFST installation to better identify the beginning and end points of the HFST for construction purposes.

Minimum threshold levels of friction, called investigatory levels (ILs), are used in pavement friction management to trigger an investigation to determine what is causing the deficiency in the skid resistance (Highways England 2015). Threshold levels are determined by relating the crash data to the friction measurements indicated by a significant increase in crashes below the threshold friction level.

Figure 12 presents an example of an alternative way to visualize continuous friction measurements done for one of the states in the study. Using geospatial tools, a colored scale indicating the friction level relative to the IL is overlain on map data. Figure 12 provides a rough sketch of what can be done with this tool to better appreciate the interplay of geometry, traffic maneuvering/friction demand, and available friction.



Original Photo: © 2018 Google.

Figure 12. Map. SCRIM measurements on State Route A from milepost 59.8 to 59.9.

The color scale is set to reflect a recommended IL of 50–55 (SR30) for the curve section, with each colored section representing 30 ft of roadway. For this illustration, the conventional LWST testing frequency would have missed the concerning dip in friction, while the SCRIM data clearly show that friction is a consideration that should be investigated further.

NETWORK-LEVEL DATA COLLECTION

The data for this comparison were collected in collaboration with four state DOTs, Florida (FDOT), Indiana (INDOT), Texas (TXDOT), and Washington (WSDOT), under the FHWA Pavement Friction Management Support Program Project. The friction data were obtained in a separate data collection effort for each individual state highway agency using a SCRIM and the various ASTM E274 LWSTs equipped with either a standard ribbed tire (ASTM E501) or smooth tire (ASTM E524). Similarly, skid resistance was also collected in North Carolina through a contract with the North Carolina Department of Transportation (NCDOT) in an effort to compare data measured with an LWST, a Grip Tester (a fixed-slip CFME), and a SCRIM.

Table 1 shows the approximate total centerline length, in one direction of travel, of the roads tested in each state with the SCRIM. Skid resistance was tested on the travel lane of each roadway.

Table 1. Length of all roads tested per state.

State	**Miles Tested**
Florida (Ribbed Tire)	875
Indiana (Smooth Tire)	875
North Carolina (Ribbed Tire)	560
Texas (Smooth Tire)	900
Washington (Ribbed tire)	570

Data Pre-Processing

The SCRIM collects friction data continuously every 100 mm; however, the SCRIM software can average that data into 1-, 2.5-, 5-, 10-, or 20-m segments. Macrotexture is also collected continuously and averaged in either 1- or 10-m segments. All other data are collected and then reported every 10 m. For consistency, all raw data are averaged in 10-m segments for network-level analysis of 0.1-mi sections.

When network-level testing is conducted, because of different roadway conditions (e.g., traffic, geometric design, etc.), it is not always possible to operate the equipment at constant speeds. Therefore, the measured friction is later standardized for speed. For the SCRIM, the British standard for skidding resistance (HD 28/15) corrects to a speed of 50 km/h (31 mph) all friction measured from 25 to 85 km/h using equation 6 (Highways England, 2015). In this study, if the testing speed for any 10-m segment fell outside of this range, then the segment was not reported.

$$\mathrm{SR}(30) = \mathrm{SR}(\mathrm{S}) \times \ (-0.015 \times \mathrm{S}^2 + 4.77 \times \mathrm{S} + 799)/1000 \tag{6}$$

where *SR(30)* = friction corrected to 30 mph (50 km/h);
SR(S) = uncorrected SCRIM reading friction measurement;
S = speed at which the friction is measured in mph.

Segments with potentially wrong macrotexture measurements were also removed in the cases when (1) the macrotexture was measured on a wet (or reflective) pavement surface, which was recorded as “abort,” or (2) the file showed a large percentage of dropouts (>10%).

Friction characterization of the 10-m segment data into meaningful averages for each 0.1-mi pavement site was accomplished using the minimum value of a three-point moving-average filter (20 m ≈ 60 ft) for the entire 0.1 mi. The filter length was selected to align with the locked-wheel tester, which reports friction from an average of 1 s of measurement at 40 mph (a distance of 59 ft). The analysis then selected the lowest value in that 0.1-mi moving-average data, which represents the lowest measurement that any LWST could find if it knew exactly where the lowest 1-s average test result would happen in every 0.1 mi. The three-point moving-average filter is a more conservative estimation of a possible low-friction area in the entire 0.1-mi section instead of using the lowest point value. The average friction value of the entire 0.1-mi section is not considered appropriate because the objective of using continuous measurements is to remove the possibility of missing low-friction spots.

In all the network-level pilots, the data collected with the LWST and the SCRIM devices were paired using Global Position System (GPS) coordinates to effect a pairing as close as possible with both devices. Table 2 lists the total number of miles tested with the SCRIM in each State, and considering how many tests were done per mile with the LWST, the total number of paired measurements is listed. In general, the States collected LWST measurements between a 0.5- and 1-mi intervals. Sometimes, on very short segments, measurements were made at higher frequency (generally every 0.1 mi).

Table 2. Paired LWST and SCRIM sample size.

Network	Miles Tested	LWST/mile	Data Points Paired	Data Points SCRIM
Florida	875	2-3	1,173	6,437
Indiana	875	2-3	1,743	7,885
North Carolina	560	2	1,180	1,180
Texas	900	2	1,788	8,911
Washington	570	1	519	4,855

Descriptive Statistics

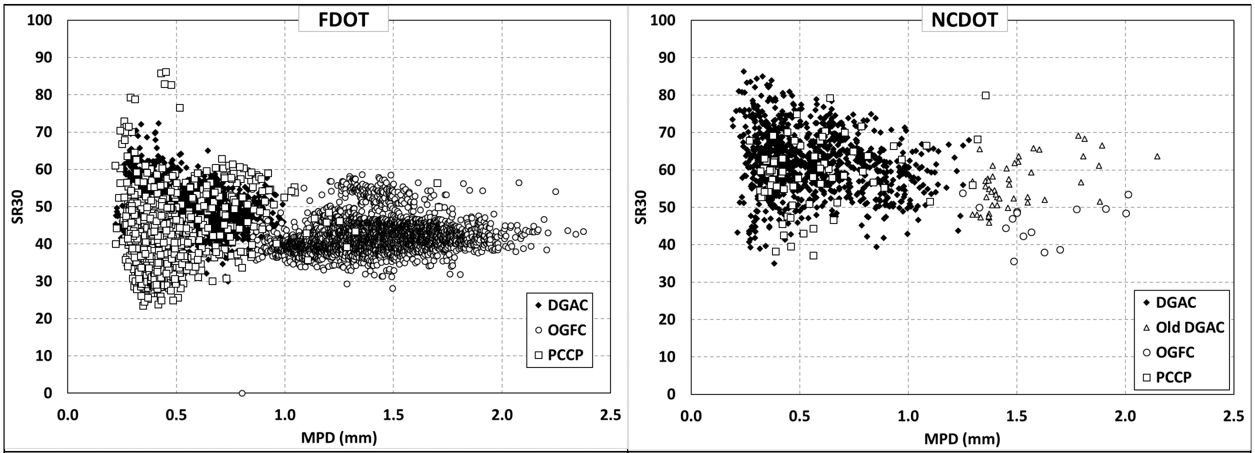
In every state, the skid resistance measured with the LWST was compared to the SCRIM measurement (SR30) averages in the closest 0.1-mi segment. At all of the locations, the LWST was either equipped with a ribbed tire (ASTM E501) or smooth tire (ASTM E524). FDOT and WSDOT use a ribbed tire, while INDOT and TXDOT use a smooth tire. Unlike the others, NCDOT uses both a ribbed and a smooth tire. However, since the number of NCDOT test results with the smooth tire were very limited, only the results for the NCDOT ribbed tire were used in these comparisons.

The plots shown in figure 13 and figure 14 show the comparisons of the MPD and skid resistance measured with the SCRIM and LWST, respectively. Because of the vast difference in the number of data points for each device, it is very difficult to make a direct comparison between the two devices by looking at these plots.

However, it is interesting to note that these results and the results shown in figure 7 show that the SCRIM plots more closely align with those of the LWST with a ribbed tire than those of the LWST with a smooth tire. This has already been corroborated by previous studies that have found that the SCRIM friction measurements are “independent of their macrotexture” because of “very little correlation between SR and MPD” (Roe et al., 1991 and Roe et al., 1998).

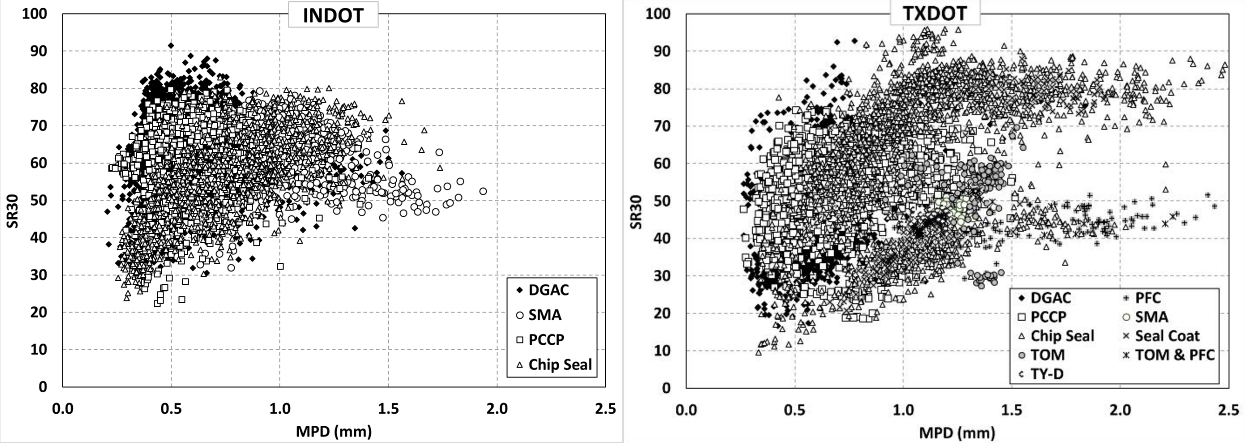
The figures compare the friction of the two devices measured on different pavement surfaces. The majority of the pavement surfaces in each state were either dense graded asphalt (DGAC) or portland cement concrete (PCC). Other less common surfaces included bituminous surface treatment (BST) or chip seals, open graded asphalt concrete (OGFC) or permeable friction course (PFC), seal coats, stone matrix asphalt (SMA), thin overlay mix (TOM), and type D mix (TY-D).

As stated before, differences in the design and configuration of testing equipment and their test tires create different sensitivities to speed and MPD. Fuentes et al. (2014) explored this further by investigating the speed dependence of friction measured with a ribbed and the smooth tire on pavement surfaces with different levels of MPD. They showed that measurements made using both tires had similar speed dependence on pavement surfaces with high MPD. In contrast, the speed dependence was significantly different on pavement surfaces with lower MPD.



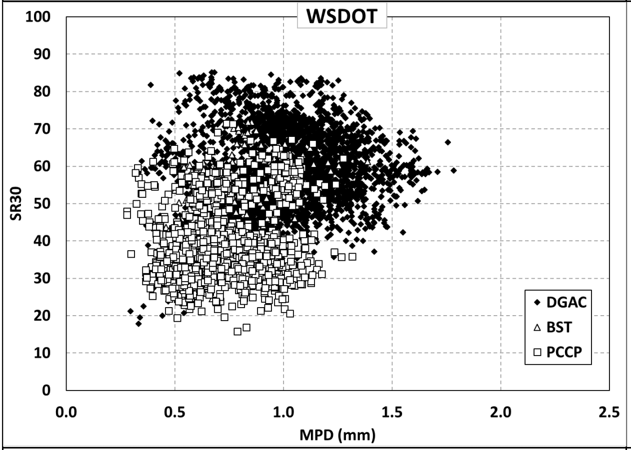
A. SR30 vs. MPD for Florida

B. SR30 vs. MPD for North Carolina



C. SR30 vs. MPD for Indiana

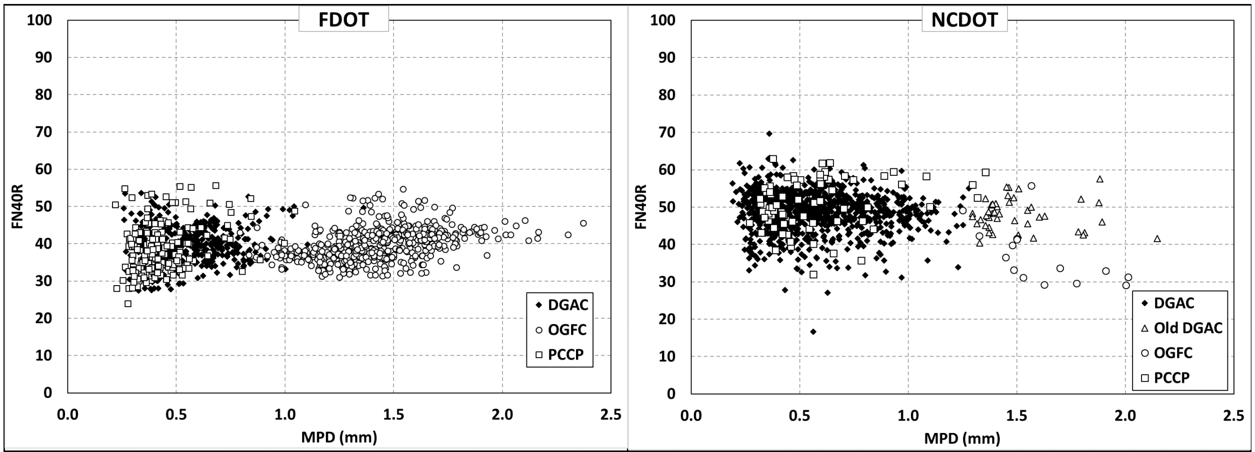
D. SR30 vs. MPD for Texas



E. SR30 vs. MPD for Washington

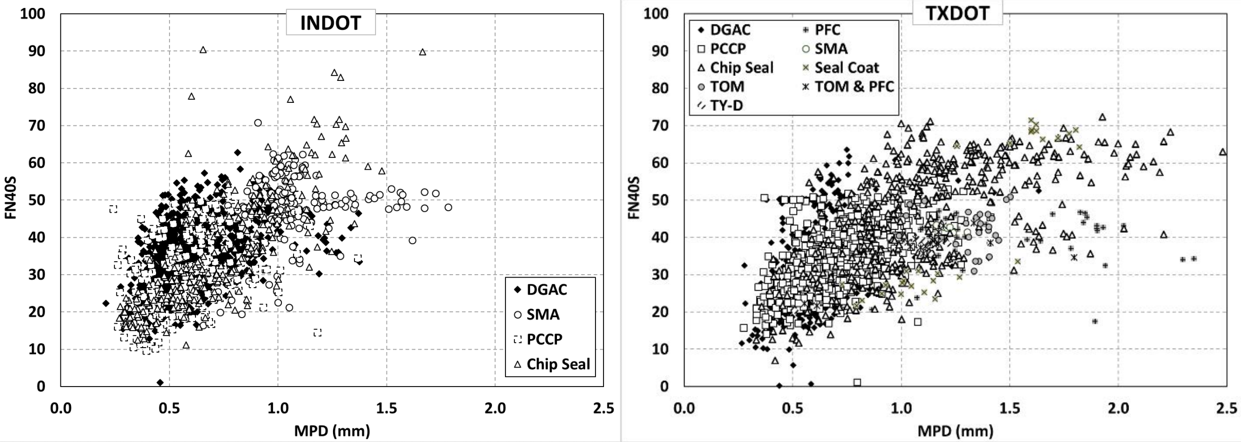
Source: CSTI

Figure 13. Charts. SCRIM and MPD network-level comparisons.



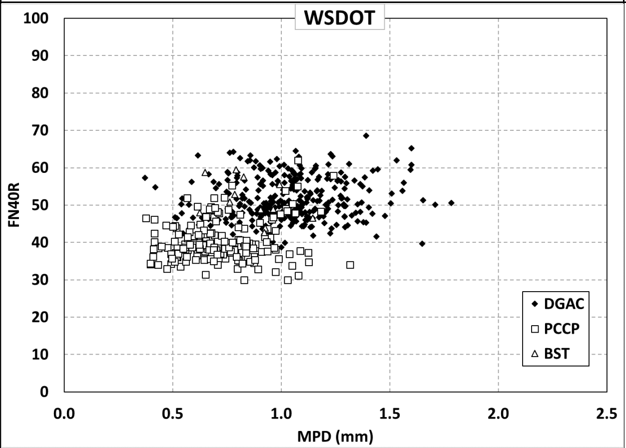
A. FN40R vs. MPD for Florida

B. FN40R vs. MPD for North Carolina



C. FN40S vs. MPD for Indiana

D. FN40S vs. MPD for Texas



E. FN40R vs. MPD for Washington

Source: CSTI

Figure 14. Charts. LWST (ribbed and smooth tires) and MPD network-level comparisons.

HARMONIZATION TESTING

Friction comparisons were made with measurements done at the Ohio Transportation Research Center (TRC) and at the Texas Transportation Institute (TTI) RELLIS campus facility for the purpose of comparing the SCRIM with both reference LWSTs (Tech Memo, Fernando et al., and Bilbee, DOT Pooled Fund TPF-5(345), TRC report). These two sites are the Field Test Centers (FTCs) used to calibrate all LWSTs in the United States. Each FTC has an Area Reference Friction Measurement System (ARFMS) that serves as the reference for all calibrations at each site (ASTM E-2793).

These experiments were done in controlled conditions to assure that the pavement sections tested with the two pieces of equipment coincided accurately. In many previous efforts to compare friction testing systems, clearly pairing the test result data sets to ensure that the pavement surface tested was the same for both systems has been challenging and was a significant source of analysis variability.

For the measurements made at both FTCs, average values over the lengths tested with the LWST within the section were compared. In these locations, the average length used to obtain the SCRIM averages depended on the length of the LWST section being measured, which varied depending on the speed of the devices in each particular test. For example, at 40 mph the distance of the LWST test section is 59 ft, at 50 mph it is 73 ft, etc., and so data were obtained using the 1-m option and approximated to the required distance to compare.

Because of this, the variability for the network analysis is much higher because it can be stated with confidence that the two tests (SCRIM and LWST) were not testing the exact same pavement surface, as was achieved at the both FTC test facilities. In the two FTC locations, the SCRIM and LWST tests were matched (paired) to the same pavement surface, and with a finer granularity.

Ohio Transportation Research Center

The TRC was the center originally contracted by the FHWA in the 1970s as part of a program to reduce interstate variation in the locked-wheel skid measurements of pavement surfaces (Bilbee 2018). In June 2018, the annual equipment comparison, organized by the pooled fund TPF-3(345) Surface Properties Consortium – Managing the Pavement Properties for Improved Safety, was held at the TRC (figure 15).

Correlation performed at the TRC consisted of 12 skids on a Low Mu Pad, 12 skids on a Mid Mu Pad, and 12 skids on a High Mu Pad at speeds of 40 mph and 60 mph. The pads were tested in the following order: Low Mu on the first pass (Pad 0), and then Mid and High Mu together on the second pass (Pad 2 and 1). Note: “Low Mu” is intended to represent relatively low skid resistance, “Mid Mu” moderate skid resistance, and “High Mu” relatively high skid resistance.

During the correlation, all LWST systems were operated simultaneously, both with the E501 ribbed tire and the E524 smooth tire. The SCRIM used its regular tire for both correlations and all speeds.

Source: Mike Bilbee, TRC.

Figure 15. Photo. Equipment used in the experiment from the Friction Pooled Fund.

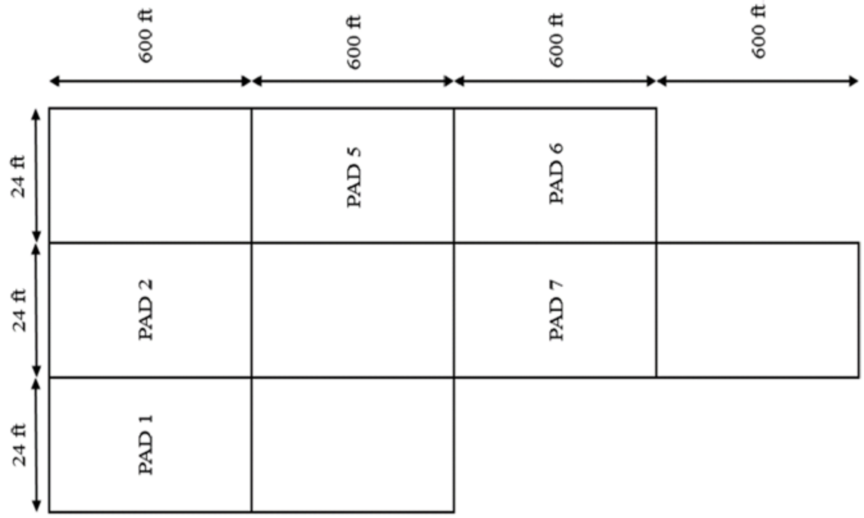
The TRC's standard E-274 locked-wheel tester (figure 16) was used as the reference device. Testing on all three surfaces was conducted as described above, but only the results of this LWST using the ribbed tire were used to determine a conversion equation for the SCRIM measurements.

Source: Mike Bilbee, TRC.

Figure 16. Photo. TRC standard E-274 locked-wheel tester.

Texas Transportation Institute RELLIS Facility

The other LWST calibration center is located at the TTI RELLIS campus. The facility consists of an abandoned runway, of which three lanes have been modified for testing friction equipment. The section tested covered nine segments with different surfaces, as shown in figure 17. Friction measurements were collected in September 2016 using the TTI "reference" LWST with a smooth tire (figure 18) and the SCRIM (Fernando et al. 2017).



Source: Fernando 2017.

Figure 17. Diagram. Sections used on TTI runway.

Source: CSTI.

Figure 18. Photo. TTI reference E-274 locked-wheel tester.

Measurements were taken on PAD 1 (portland cement concrete), PAD 2 (Jennite flush seal), PAD 5 (rounded gravel hot mix), PAD 6 (rounded gravel chip seal), and PAD 7 (lightweight aggregate chip seal). A second set of measurements was taken on the second wheel path of PAD 2, providing as a result, measurements on six sections. On each section, eight runs were conducted at 30, 40, and 50 mph using the SCRIM and two LWSTs, a reference unit owned by TTI and another unit provided by TXDOT. Both devices used a smooth tire (ASTM E524). In summary, 24 measurements were done with each of the three different devices. Only the TTI LWST data are used in this report.

In addition to the high-speed measurements, a CT meter and Dynamic Friction Tester (DFT) were used to take reference macrotexture and friction measurements, respectively. Seven stations were defined along each PAD and three tests were done at each station. An average of the 21 measurements was obtained in each PAD to use as reference to calculate S_p and the A and B constants (Barrantes et al. 2018), which are required for harmonizing friction measurements using the IFI (ASTM E 1960).

CHAPTER 4. ANALYSIS

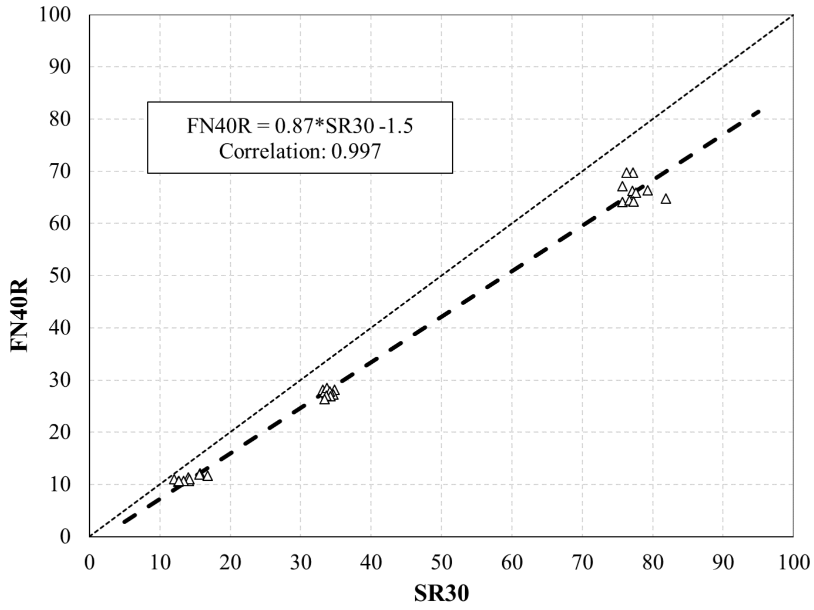
This section first presents the results of the comparisons under controlled conditions at the skid calibration centers and then compares them with the results of analyzing all the network-level data collected.

HARMONIZATION COMPARISONS

This section summarizes the results obtained from the two controlled experiments at the ASTM E-274 locked-wheel skid calibration centers, which have been reported in Fernando et al. (2017) and Bilbee (2018), and expands the analysis to recommend interconversion equations.

Ribbed Tire Friction Number

The comparison for the friction number (FN) measured with the ribbed tire used the measurements obtained at the TRC facility in Ohio. Figure 19 presents the FN normalized to 40 mph (FN40R) versus the SCRIM reading normalized to 30 mph (SR30). The figure shows that the relationship is not exactly along the equality line, but the two are very highly correlated for this controlled field test.



Source: CSTI.

Figure 19. Graph. Comparison of FN40R and SR30 at TRC.

The predicted FN40R values are approximately 87% of the SR30 measurements. The difference is expected as the SCRIM should measure a higher FN because it operates at a lower slipping ratio and its measurements are normalized to a lower reference speed (30 vs. 40 mph). As explained in the section on surface texture, it seems like the SCRIM measurements are more closely related to the ribbed tire measurements because both tires are more sensitive to the microtexture on the road and do not exhibit much sensitivity to changes in MPD (figure 7).

Equation 7, obtained using orthogonal regression, as discussed later in the report, can be used to convert between the two measurements:

$$FN40R = 0.87 * SR30 - 1.5 \tag{7}$$

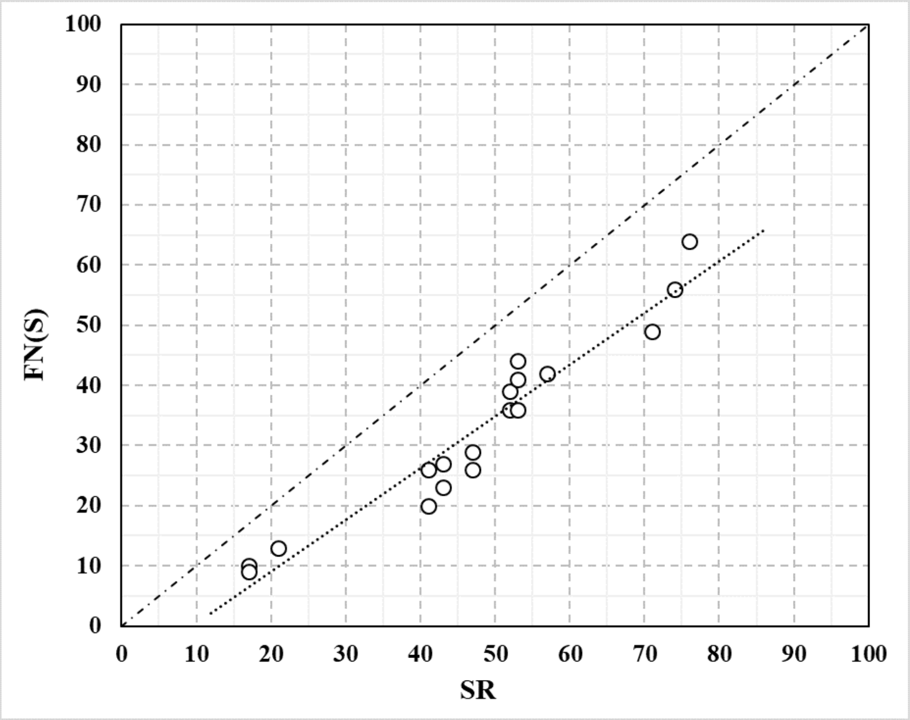
Smooth Tire Friction Number

The comparison for the FN measured with the smooth tire was based on the results of the testing conducted at the TTI RELLIS facility (Fernando et al. 2017). Figure 20-A compares the average results from each of the sections tested at speeds of 30, 40, and 50 mph. Figure 20-B shows the relationship between the measurements after normalizing the FNs and SRs to 40 and 30 mph, respectively. In this case, FN40S is even lower when compared with the SR30 measurements, as the slope coefficient is similar but in this case the intercept is almost 10 points.

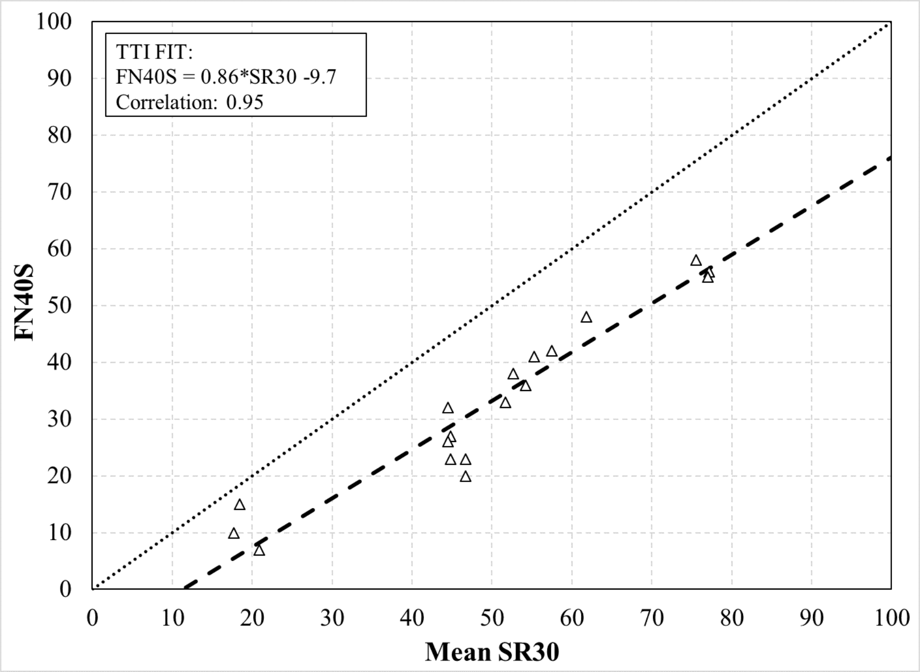
The experiment determined the IFI parameters for the SCRIM (A = 0.085, B = 0.615), but further studies recommended using the simplified procedure shown in equation 8 to convert from SCRIM to LWST measurements using the smooth tire (Barrantes et al. 2018). The equation uses the IFI speed corrections (s_p) to bring the measurements to a common slip speed, but does not require determination of an estimated friction value at 60 km/h (F60), thus eliminating the need to make reference skid measurements using the DFT.

$$FNS = \mathrm{SR} * e^{\frac{s_{SCRIM} - s_{LWST}}{Sp}} \tag{8}$$

where FNS = LWST friction number at a speed s_{LWST};
$S_p = a + (b * \mathrm{MPD})$
a and b = ASTM constants (a = 14.2 and b = 89.7);
MPD = macrotexture mean profile depth (mm);
s_{SCRIM} = 0.34 × SCRIM testing speed (km/h);
s_{LWST} = LWST testing speed (km/h standard = 64.37 m/h or 40 km/h);



A. FNS vs. SR.



B. FN40S vs. mean SR30.

Source: CSTI.

Figure 20. Graphs. Comparison of FN40S and SR30.

COMPARISON OF LOCKED-WHEEL SKID TRAILER AND SIDEWAY-FORCE COEFFICIENT ROUTINE INVESTIGATION MACHINE NETWORK-LEVEL MEASUREMENTS

This section compares all the network-level LWST and SCRIM measurements. These comparisons were separated based on the LWST tire used. The term *in-service* refers to the measurements collected in the field under roadway conditions that an operator conducting routine testing would experience. In contrast, the TRC and TTI comparisons previously discussed were conducted under controlled conditions in which many of the variables that affect measured skid resistance have at least been mitigated, if not eliminated, thus improving the likelihood of conducting a rigorous comparison between the LWST and the SCRIM.

Methodology

This study compares the LWST and SCRIM using orthogonal regression (OR). This method of regression assumes that both x and y have unobserved measurement error, in the form of “noise” in the data. This is in contrast to simple linear regression (SLR), which assumes that only y has unobserved measurement error while the measurement error of x is minimal. Therefore, while SLR treats x and y as fixed and random variables, respectively, OR treats both x and y as random variables. Since both x and y are random variables in OR, another term, called the variance ratio (θ) is introduced, that divides the variance of y by the variance of x. The SCRIM and LWST equipment used in this study were not tested for repeatability, and therefore, the analysis assumes that both x and y have equal measurement error (θ is set to 1).

The slope (β_1) and intercept (β_0) of the OR line are estimated using equations 9 and 10, where $\bar{x}$ and $\bar{y}$ are averages of x and y. Finally, the degree to which x and y are related (i.e., the strength of the fitted OR line) is measured using simple correlation, which is a value from 0 to 1. Correlation values closer to 1 indicate a strong association between x and y.

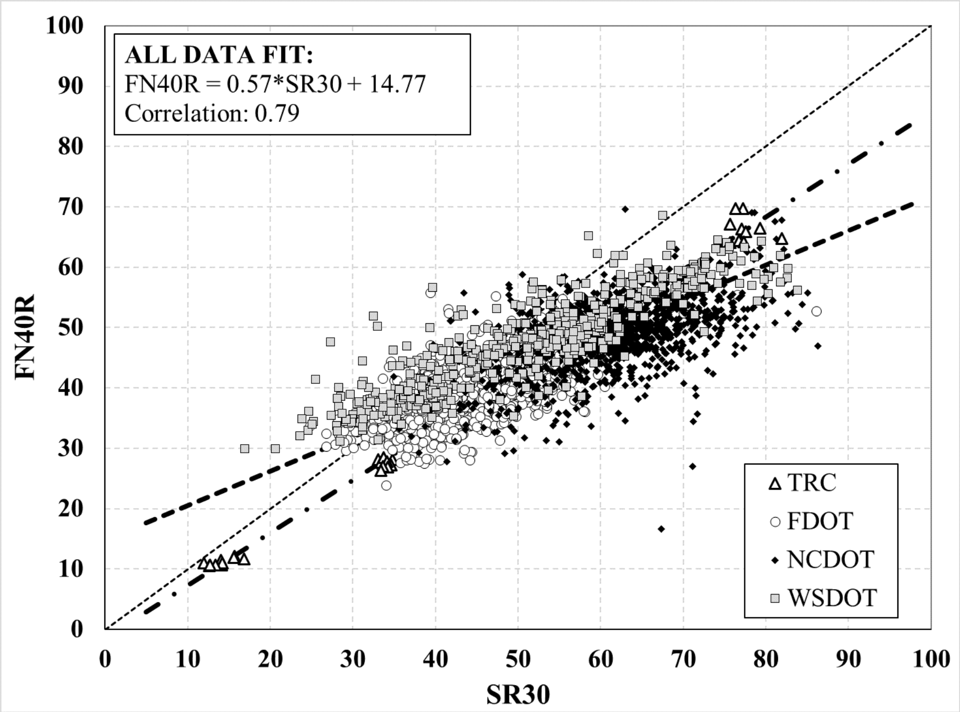
$$\hat{\beta}_1 = \frac{S_{yy} - \theta S_{xx} + \sqrt{\left(S_{yy} - \theta S_{xx}\right)^2 + 4\theta {S_{xy}}^2}}{2S_{xy}} \tag{9}$$

$$\hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x} \tag{10}$$

Ribbed Tire Comparison

Figure 21 compares the LWST ribbed tire and SCRIM measurements, differentiated by source. In this comparison, the results of the OR fitting indicate a high correlation (0.79) between the two devices. Both testing systems are more sensitive to microtexture than macrotexture. Although the relationship is strong, the correlation considering all the network-based data is lower than that found using only the TRC data (superimposed as a red dashed line and triangle data points). It is expected the TRC correlation would be higher due to the efforts to ensure the paired data points came from the two testing devices testing the same section of pavement surface. This cannot readily be duplicated in network testing data.

For the TRC fit, the correlation is nearly perfect (figure 19), and thus, equation 7 is recommended for converting between SR30 and FN40R.



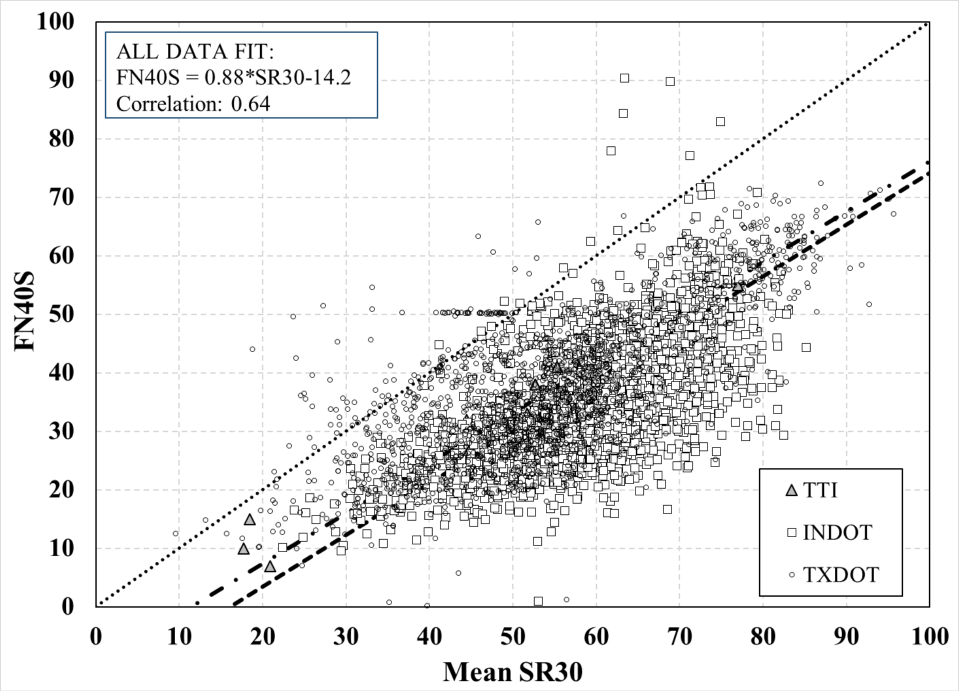
Source: CSTI.

Figure 21. Graph. Comparison of LWST ribbed tire (FN40R) and SCRIM (SR30).

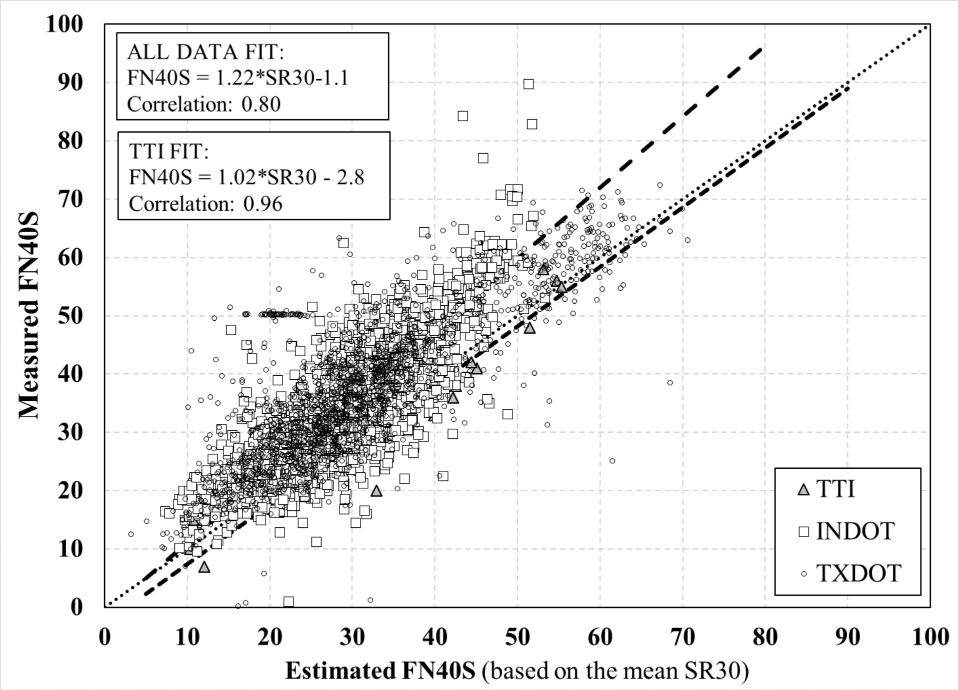
Smooth Tire Comparison

Figure 22-A compares the SR30 and SN40S measurements. Similar to the comparison with the LWST ribbed tire, the controlled conditions at TTI provided a much better association than the network-oriented data set. However, this should be expected because (1) each point in the case of the TTI facility represents the average of several measurements, and (2) the effort to ensure the paired data points came from the two testing devices testing the same section of pavement surface. For the network-level measurements, the correlation (0.64) was significantly lower than for the controlled experiment (0.95) and also lower than for the case for the ribbed tire (0.79). It is reasonable to expect the correlation between the LWST smooth tire, which is more sensitive to macrotexture, and the SCRIM, which is more sensitive to microtexture, to be weaker than the correlation between the LWST ribbed tire and SCRIM.

The conversion presented in equation 5 was applied and the resulting "predicted" FN40S are compared with measured values in figure 22 -B. Although the match still departs from the 1-to-1 line, it is closer to the equality line and almost perfect when pairing the data when the conditions were controlled (TTI). For this reason, equation 5 is recommended to convert between SR30 and FN40S, using the macrotexture value corresponding to the friction measurement.



A. FN40S vs. mean SR30.



B. Measured FN40S vs. estimated FN40S.

Source: CSTI.

Figure 22. Graphs. Comparison of LWST smooth tire (FN40S) and SCRIM (SR30).

CHAPTER 5. CONCLUSIONS

Based on the overall network-level comparisons and the harmonization studies, the following conclusions can be drawn:

1. The collection of continuous friction and macrotexture data through the adoption of CFME instead of the traditional sampling approach using an LWST provides higher resolution data for assessing the frictional characteristics of the pavement surface. The frictional characteristics can be used with safety analysis procedures to identify pavement sections for investigation of possible friction enhancement.

2. There is strong correlation between the LWST measurements using a ribbed tire and the SCRIM measurements, as both measurements are more sensitive to microtexture than macrotexture. As expected, FN40R values are approximately 87% of the SR30 values. If warranted, the following equation is recommended for the interconversion between FN40R and SR30:

$$FN40R = 0.87 * SR30 - 1.5 \tag{7}$$

3. The correlation is weaker between the LWST measurements using a smooth tire and the SCRIM measurements, but the interconversion equation using macrotexture measurements (MPD) produced acceptable results. The following equation is recommended for the interconversion between FN40S and SR30, after normalizing the speeds for each device:

$$FN40S = \mathrm{SR30} \; * \; e^{\frac{-48.0}{Sp}} \tag{8}$$

   where $S_p = 14.2 + 89.7 * \mathrm{MPD}$, and MPD = macrotexture mean profile depth (mm).

4. Harmonization is possible with reasonable confidence, but it needs to be conducted with significant controls, such as the TTI and TRC comparisons (to ensure that the pavement surface measured is the same for each paired test). Field or network-level harmonization results in higher variability due to the fact that the testing rarely aligns perfectly (i.e., exactly the same surfaces are tested with both devices).

5. SCRIM rubber tire friction measurements are more sensitive to microtexture. Since no high-speed friction measurement test can obtain both micro- and macrotexture, it is important to gather macrotexture MPD data at the same time that the friction measurements are done. There are several high-speed, non-contact systems that can be used to collect macrotexture MPD data (e.g., high-speed laser). Incorporating equipment that can simultaneously obtain other geometric parameters normally used in safety/friction demand assessments such as grade, cross-slope, and curvature, is also highly recommended.

REFERENCES

Barrantes, S., Flintsch, G.W., de León Izeppi, E., and McGhee, K.K. (2018). "Interconversion of Locked-Wheel and Continuous Friction Measurement Equipment (CFME) Friction Measurements." *Transportation Research Record*, Transportation Research Board of the National Academies, Washington, DC. doi:10.1177/0361198118797455

Bilbee, M. (2018). DOT Pooled Funds TPF-345, Consortium for Pavement Surface Properties Twelfth Annual Equipment Roundup (Rodeo 2018*)*.

Descornet, G. (2004). "The HERMES Project." Presented at the *5th Symposium on Pavement Surface Characteristics Conference*, SURF 2004 (CD-ROM), World Road Association, Paris.

Do, M.-T., and Roe, P.G. (2008). *Deliverable 04: Report on State-of-the-art of Test Methods*. TYROSAFE. Retrieved August 17, 2016, from http://tyrosafe.fehrl.org/?m=49&id_directory=977/_TYROSAFE_T2.1_DeliverableD04_v4_20081205_final.pdf

Fernando, E., Arrington, D., and Zimmer, R. (2017). *Technical Memorandum, Task Report: Comparative Evaluation of Locked-Wheel and SCRIM Testers*, Presented by the Texas Transportation Institute to the Virginia Transportation Research Council, April 3, 2017.

Flintsch, G.W., de León Izeppi, E., Roa, J., McGhee, K.K., and Swanlund, M. (2008). "Evaluation of the International Friction Index Coefficients for Various Devices." Presented at *SURF 2008, 6th Symposium on Pavement Surface Characteristics*, Oct 20-22, 2008, Portoroz, Slovenia.

Flintsch, G.W., de León Izeppi, E., McGhee, K.K. and Najafi, S. (2012). *The Little Book of Tire Pavement Friction*. Retrieved from https://www.apps.vtti.vt.edu/1-pagers/CSTI_Flintsch/The%20Little%20Book%20of%20Tire%20Pavement%20Friction.pdf

Fuentes, L., Flintsch, G., and de León Izeppi, E. (2014). "Evaluation of the Use of Ribbed Tires for the Characterization of Skid Resistance Using Friction Models." *Journal of Testing and Evaluation*, Vol. 42, No. 6, pp. 1479-1485. doi:10.1520/JTE20130063

Hall, J.W., Smith, K.L., Titus-Glover, L., Wambold, J.C., Yager, T.J., and Rado, Z. (2009). *Guide for Pavement Friction*, Web-Only Document 108, National Cooperative Highway Research Program (NCHRP), Washington, DC. Retrieved July 26, 2016, from http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w108.pdf

Henry, J. (2000). *Evaluation of Pavement Friction Characteristics*, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC.

Highways England. (2015). *Design Manual for Roads and Bridges*, HD 28/15, Volume 7, Section 3, Part 1, Skidding Resistance, Crown, United Kingdom.

Kummer, H.W. and Meyer, W.E. (1967). *NCHRP Report 37: Tentative Skid-Resistance Requirements for Main Rural Highways*, Transportation Research Board (TRB), Washington, DC.

Leu, M., and Henry, J. (1978). “Prediction of Skid Resistance as a Function of Speed from Pavement Texture Measurements.” *Transportation Research Record*, Vol. 666, pp. 7-13.

Michelin. (2001). “The Tire Grip.” Clermont-Ferrand, France: Société de Technologie Michelin. Retrieved July 11, 2016, from http://www.dimnp.unipi.it/guiggiani-m/Michelin_Tire_Grip.pdf

National Center for Statistics and Analysis. (2017, October). *Traffic Safety Facts*, Report No. DOT HS 812 456, National Highway Traffic Safety Administration, Washington, DC.

Roe, P.G., Webster, D.C., and West, G., (1991). *The Relation between the Surface Texture of Roads and Accidents*, TRRL Research Report 296, Transport and Road Research Laboratory.

Roe, P.G., Parry, A.R., and Viner, H.E. (1998). *High and Low Speed Skidding Resistance: The Influence of Texture Depth*, TRL Report 367, Transport Research Laboratory.

Vos, E., and Groenendijk, J. (2009). *EU Project TYROSAFE, Deliverable D05: Report on Analysis of Previous Skid Resistance Harmonization Research Projects*, FEHRL, Brussels, Belgium. Retrieved from http://tyrosafe.fehrl.org

Wallman, C., and Astrom, H. (2001). *Friction Measurement Methods and the Correlation between Road Friction and Traffic Safety*. Swedish National Road and Transport Research Institute.

Wambold, J., Antle, C., Henry, J., Rado, Z., Descornet, G., Sandberg, U., Gothié, M., and Huschek, S. (1995). *International PIARC Experiment to Compare and Harmonize Skid Resistance and Texture Measurements*, Publication 01.04, PIARC, Paris, France.

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1200 New Jersey Avenue, SE
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July 2019
Publication Number: FHWA-RC-19-001