PRACTICAL METHOD FOR LOCKED-WHEEL AND CFME FRICTION MEASUREMENT INTERCONVERSION

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State

University in partial fulfillment of the requirements for the degree of

Master of Science

In

Civil Engineering

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September 8, 2017

Blacksburg, Virginia

Keywords: International Friction Index, harmonization, friction measurements, friction testing devices

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ABSTRACT

As transportation agencies are adopting proactive pavement friction management using continuous friction measurement equipment (CFME), the need for a method that allows interconversion between the traditional locked-wheel skid testers (LWST) becomes important to assure continuity with past practices. This thesis evaluates several conversion methods based on the International Friction Index (IFI) approach and proposes and verifies an alternative method that allows predicting the measurements of the Locked Wheel Trailer (LWST) using the Sideway-Force Coefficient Routine Investigatory Machine (SCRIM). The investigation is based on data collected using a SCRIM and two LWSTs on a controlled pavement test facility. The results suggest that a conversion based only on the speed adjustments (FR60) is the most effective method to predict the LWST measurements from SCRIM measurements. The coefficient of determination and average absolute error are comparable to those using the full IFI F60 formula but do not require static reference measurements. The study also showed that the three tested devices produced appropriate repeatability as computed using the limit of agreement at the three tested speeds and on a wide range of surfaces.

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GENERAL AUDIENCE ABSTRACT

This thesis compares two devices that measure the friction of the pavement surface. One of the devices, the Locked Wheel Skid Tester (LWST) is the one that have traditionally used for the Departments of Transportation (DOT) in the US. The other one is a newer technology that is able to measure the friction in a continuous way (SCRIM). The comparison of measurement is difficult because there are many factors that affect the tire-pavement friction. The International Friction Index (IFI) provides a comparison approach but require taking static reference measurements that are time consuming and require road closures. This thesis proposes a simplified method to convert measurements with the LWST using only the SCRIM that do not require these reference measurements.

ACKNOWLEDGEMENTS

I would like to express my gratitude to my parents, my brothers and the rest of my family who have all been there for me in this process encouraging and supporting me.

Thank you to Dr. Flintsch, for gave me this great opportunity to grow as a professional, unconditional help, patience, and for the privilege of working with such an outstanding professional like you.

Thank you, Dr. de León for always being available to teach, explain, guide, and help throughout the process of this thesis.

Thank you, Dr. Katz, for being part of this and helped me in different ways to reach the goal.

The author would also like to express her gratitude to the Federal Highway Administration (FHWA) and the Texas and Virginia departments of transportation (DOTs) and the Texas Transportation Institute and Virginia Tech Transportation Institute for the support with the data collection and to Kevin McGhee from the Virginia Transportation Research Council for his guidance and feedback.

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CHAPTER 1 - INTRODUCTION

1.1 INTRODUCTION

Roads are designed, built and maintained to provide users with a comfortable and safe surface to drive. From the multiple factors involved in crashes --the driver, the vehicle, and the road-- transportation agencies can only influence the provision of a safer road. In this respect, pavement friction is a critical factor in road safety, especially under wet conditions. A pavement with good frictional properties can help reduce crashes by allowing vehicles to stop faster and maintain control of the vehicle in critical maneuvers (Julian and Moler 2008).

State's Departments of Transportation periodically monitor the pavement surface properties to ensure appropriate service conditions. The measurements taken are used to trigger surface restoration alternatives, investigate crashes, and support pavement management and winter road maintenance (Flintsch et al., 2008). Since various agencies use different devices and methods to measure friction and surface texture, there is a need to compare those measurements.

The World Road Association (PIARC) proposed one of the first approaches to harmonize friction measurements by conducting extensive equipment comparisons and developing the International Friction Index (IFI) (PIARC, 1995). The IFI method uses friction and macrotexture measurements to normalize measurements taken with different equipment and has been normalized in ASTM standard E1960 - 07(2015) (ASTM, 2016). However, this method has been tested and it does not always produce consistent results. Among other efforts, research at the Virginia Smart Road suggested that the coefficients needed to be adjusted (Flintsch et al., 2009).

1.2 PROBLEM STATEMENT

Since pavement frictional properties are critical for road safety, several companies and agencies have developed equipment to measure pavement friction. The comparison of measurements taken with different devices, in different types of pavement, and under different operational conditions is still a challenge for the pavement industry. It is often necessary to convert the measurements taken with one piece of equipment to a comparable scale used by another device. This thesis proposes and verifies an alternative method to the actual IFI standard, which uses the IFI basic concepts but require no static friction and macrotexture measurements. This thesis proposes an interconversion method between measurements from.

1.3 OBJECTIVES

The objective of the thesis is to propose a method to convert pavement friction measurements obtained with two different types of friction measuring equipment: a Locked Wheel Trailer (LWST) and a Continuous

Friction Measurement Equipment (CFME), the Side-force Coefficient Routine Investigatory Machine (SCRIM).

The following secondarily objectives were defined:

- Use data obtained on an experiment conducted on a test track at the Texas Transportation Institute (TTI runway) to determine a practical approach to predict the values measured by the LWST using friction and macrotexture data collected with a SCRIM.
- Verify the proposed approach using measurements taken on the Virginia Smart Road during the 2017 Surface Properties Consortium Annual Equipment Comparison.

1.4 CONTRIBUTION

The thesis proposed a practical approach to interconvert pavement friction measurements taken with the SCRIM and the LWST with a smooth tire using the pavement macrotexture. This method will allow transportation agencies to start using the continuous friction technology, without losing the historical information collected using LWSTs.

One advantage of the proposed method is that it allows comparing measurements without the need of conducting static measurements for texture or friction like in the case of the IFI with the Circular Test Meter (CT Meter) and the Dynamic Friction Tester (DFT). This will help to develop effective network-level pavement friction management programs that help provide acceptable levels of friction and enhance roads safety.

1.5 THESIS ORGANIZATION

This thesis follows a manuscript format and 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: Interconversion of locked-wheel and CFME friction measurements proposes a method to interconvert data collected with the LWST and the SCRIM. The chapter analyses data collected during an experiment at the Texas A&M RELLIS Campus (formerly known as the Riverside Campus). This experiment measured the pavement friction on the same sections with three different pieces of equipment (SCRIM and two LWST). Using the speed correction used for the IFI method, the data from the LWST was predicted using the data from the SCRIM. The results were compared to determine the effectiveness of the method using regression analysis. This paper has been accepted for presentation at the *2018 Annual Meeting Transportation Research Board*.

Chapter 3: *Verification of an interconversion procedure for locked-wheel and CFME friction measurements* evaluates the method proposed in the previous chapter using additional data collected on different surfaces. The effectiveness of the method on all types of surfaces was assessed using SCRIM and LWST measurements conducted on the Virginia Smart Road.

Chapter 4: *Findings, Conclusions, and Recommendations* summarizes of the main findings and conclusions of the research and provides recommendations for future research.

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CHAPTER 2 - INTERCONVERSION OF LOCKED-WHEEL AND CFME FRICTION MEASUREMENTS [1]

2.1 ABSTRACT

As transportation agencies are adopting proactive pavement friction management using continuous friction measurement equipment (CFME), the need for a method that allows interconversion between the traditional locked-wheel skid testers (LWST) becomes important to assure continuity with past practices. This paper evaluates several conversion methods based on the International Friction Index (IFI) approach and proposes an alternative method that allows predicting the measurements of the Locked Wheel Trailer (LWST) using the Sideway-Force Coefficient Routine Investigatory Machine (SCRIM). The investigation is based on data collected using a SCRIM and two LWSTs on a controlled pavement test facility. The results suggest that a conversion based only on the speed adjustments (FR60) is the most effective method to predict the LWST measurements from SCRIM measurements. The coefficient of determination and average absolute error are comparable to those using the full IFI F60 formula but do not require static reference measurements. The study also showed that the three tested devices produced appropriate repeatability as computed using the limit of agreement at the three tested speeds and on a wide range of surfaces.

2.2 INTRODUCTION

Pavement friction is a critical factor in road safety, especially under wet conditions. Towards Zero Deaths (TZD) is an international strategy to reduce fatalities and serious injuries that has the goal of reducing the number of fatalities due to car accidents around the world in half by 2020 *(*AASHTO, 2011). From the multiple factors involved in crashes, namely the driver, the vehicle, and the road, transportation agencies can only influence the provision of a safe road. In particular, pavement infrastructure with good friction can help reduce crashes by allowing vehicles to stop and maneuver with more control of the vehicle. Thus, it is important that a comprehensive TZD strategy include pavement friction management.

The friction between the pavement and a vehicle's tire is affected by temperature, seasonal changes, pavement condition, and the equipment used for the measurement. This surface characteristic should be taken into account in the design process and monitored during the service life of the road to assure good performance. One of the approaches to reducing crashes is to implement periodic network-level friction measurements. In the U.S., the equipment that has been traditionally used to monitor friction is the locked-wheel skid tester (LWST); however, other equipment has been considered. Several recent projects have experimented with continuous friction measurement equipment (CFME), such as fixed slip, sideway force,

[1] This paper has been accepted for presentation and publication in the proceedings of the *Transportation Research Board 97th Annual Meeting*. Co-authors include Gerardo W. Flintsch, Edgar de León Izeppi and Kevin K. McGhee.

and modified locked-wheel testers. However, understanding how to compare pavement surface friction measurements taken with different devices has been a challenge (Descornet, 2004 and Vos and Groenendijk, 2009). Globalization initiatives that require the use of common roads in adjacent countries (or states) have led to a desire for the harmonization of friction data with different equipment. One of the first attempts to do this by the World Road Association (PIARC) introduced the concept of the International Friction Index (IFI). The IFI is a method that uses texture and frictional properties to normalize measurements taken with different equipment. However, this method has been tested and the results have not always produced harmonious results among all devices *(*Flintsch et al., 2009*)*.

The need for a method that allows the comparison of measurements taken with different devices, in different types of pavement and different conditions, is still a challenge for the pavement industry. This paper proposes an alternative method to the IFI standard that uses measurements taken with a SCRIM to predict LWST values. This is important because it allows the experience gained through emerging pavement management friction programs that use CFME to be integrated with previous experience with measurements collected with the LWST.

2.3 OBJECTIVE

The purpose of this study was to compare pavement friction measurements using LWST and CFME and propose an effective method for interconversion between the measures of both systems. The IFI approach was tested and simplified to propose a formula to predict the LWST friction numbers using SCRIM measurements. Data collected on a controlled facility (Texas Transportation Institute [TTI] RELLIS campus) were used to test the various approaches.

2.4 BACKGROUND

2.4.1 Pavement Friction

The friction in the pavement surface, also known as skid resistance, is defined as the force developed between the pavement surface and a tire when skidding or cornering on the pavement surface. The friction coefficient (μ) is obtained by dividing the frictional force by the vertical load on the testing tire. It represents the interaction between the vehicle tire and the pavement without considering the demand for friction due to the tangential and/or transversal accelerations. Friction is a significant safety issue that plays a critical role in the reduction of accidents on wet pavements *(*Noyce et al., 2005*)*.

2.4.2 Texture

Friction is influenced by several pavement surface characteristics, mainly microtexture and macrotexture. According to PIARC, pavement texture can be classified according to its wavelength in roughness/unevenness, megatexture, macrotexture, and microtexture *(*Flintsch, 2012*)*. Megatexture and roughness are not considered significant for safety. Macrotexture, on the other hand, gives the properties needed to allow the runoff of the water squeezed between the pavement surface and the tire, enhancing the contact between them. This characteristic affects the braking capacity in wet conditions and the sound emissions in the tire-pavement interface. Microtexture provides the direct contact and adhesion between the tire and the pavement, so it is directly related to the friction. It depends on the aggregate characteristics and their susceptibility to weathering produced by the contact with the tire.

2.4.3 Friction and Macrotexture Measuring Methods and Equipment

Most states in the U.S. use the locked-wheel trailer, with ribbed, smooth, or both tires, to determine a friction number. The measurement of the macrotexture is less common, but some agencies are starting to measure it. While most agencies report using the sand patch method, the use of the portable and high-speed laser devices is becoming popular *(*Smith et al, 2011*)*. Table 2**–1** describes the equipment used for the collection of the friction and macrotexture data for this paper.

Table 2–1 Equipment Used to Collect Data

Method	Description	Standard
Circular Texture Meter (CT Meter)	The CT Meter consists of a displacement laser on an arm that rotates, so the displacement sensor follows a circular trajectory with a diameter of 284 mm, where it collects a detailed pavement profile. The software of this equipment reports directly the mean profile depth (MPD) and root mean square (RMS).	ASTM E2157
Dynamic Friction Tester (DFT)	The DFT is composed of a 350-mm-diameter rotating disc with three sliders made of rubber. The disc is propelled by a motor while suspended over a pavement surface until the tangential speed gets to 90 km/h. Water is then applied by the equipment to the pavement surface and the disc is lowered to the surface (Choubane et al, 2012). The torque generated while the disc descends is used to calculate the friction as a function of the speed. The friction force and the speed as the disk slows to stop are saved in a file, and the results are reported at speeds of 20, 40, 60, and 80 km/h (Flintsch et al., 2008).	ASTM E1911
LWST	The LWST records the friction force when a trailer wheel is locked on the wet surface while the vehicle is moving at a constant speed. The equipment consist of a trailer with two wheels, and it blocks one at a time. The trailer includes a water distribution system connected to a water tank placed on the pulling vehicle. When the vehicle reaches the desired speed, the water system sprays water before the testing wheel and then the braking system is activated. The wheel is kept blocked for around 1 second and average Skid Number over that period is recorded (Flintsch et al., 2009). The LWST can use two different types of tires: smooth and ribbed. Ribbed tire measurements are known to be less sensitive to pavement macrotexture and water film depth than smooth tires (Flintsch et al, 2012).	ASTM E274
SCRIM	The SCRIM was originally developed by TRL in England, and it is one of the most used in Europe. It uses an oblique wheel system to determine the transversal friction coefficient in terms of sideway-force coefficient reported as a SCRIM reading. The equipment uses a smooth tire that is mounted at 20° to the direction of travel. A water tank on the vehicle wets the pavement just before the tire and the test tire has its own weight and suspension. The equipment measures the sideways force and computes sideway-force friction coefficient, which is typically reported as the average for each continuous 10 m section.	ASTM WK40015 (under development)

2.5 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. In 1992, Henry proposed a revised formula (known as the Penn State model), which relates friction with speed through the following formula *(*Henry, 2000*)*:

$$F(S) = F_o * e^{\frac{-S}{S_o}} \quad (1)$$

where,

$F(S)$ = friction measured with an equipment at speed "S,"

F_0 = non-dimensional constant that depends on microtexture and is the friction at skid speed of 0,

S = skid speed in km/h, and

S_o = constant with speed units that depends on macrotexture; its value varies between 20 and 600 km/h.

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

$$F(S) = F_{10} * e^{\frac{S-10}{S_0}} \quad (2)$$

where,

F_{10} = 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 and Astron, 2001*)*.

In the 1980's, 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 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 the following equation, the reference speed was changed to 60 km/h:

$$FR60 = FRS * e^{\frac{S-60}{S_p}} \quad (3)$$

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 and 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*)*.

2.6 RESEARCH METHODS

2.6.1 Data Collection

The data used for this study were collected as part of a Federal Highway Administration (FHWA) sponsored project managed by the National Pavement Surface Consortium led by the Virginia Transportation Research Council (VTRC). TTI and the Virginia Tech Transportation Institute (VTTI) collected friction measurements on a controlled facility at the TTI RELLIS Campus on September 2016 *(*Fernando et al, 2017*)*. The objective of this study was to compare the measurements from the SCRIM and the LWST. The facility consists of an old runway. Three lanes have been modified for testing friction equipment. It includes nine sections with different materials, as shown in Figure 2–1.

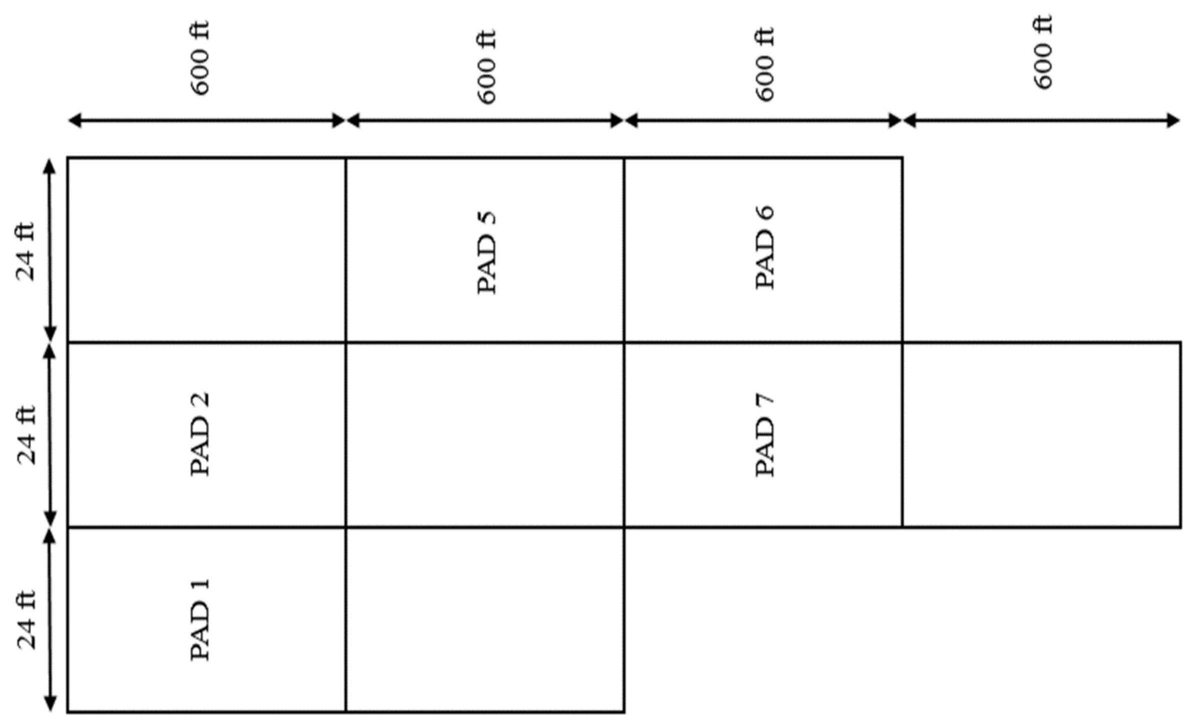


Figure 2–1. TTI Facility Layout.

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 the Texas Department of Transportation (TxDOT). Both devices used a smooth tire (ASTM E524). In summary, 24 measurements were done with each of the three different devices.

The CT Meter and DFT were used to take the reference measurements. Seven stations were defined along each PAD and three runs were done on each station. An average of the 21 measurements were obtained in each PAD to use as reference to calculate the S_p and the A and B constants.

2.6.2 Data Analysis Methods

Equipment Comparison using Limits of Agreement (LOA)

This method allows the comparison of two measurements taken with different devices or methodologies to show the agreement of the measurements (Bland and Altman, 1986). This method was first applied in 2012 to compare pavement friction measurements (Flintsch et al, 2012).

The first step in the LOA analysis is to compute the repeatability coefficient for each device. The data collected are used in an analysis of variance (ANOVA) to obtain the variance (or mean squares) needed as the variance factor to calculate the repeatability for each device. The repeatability, *r*, for each device is calculated using the following equation:

$$r = \sqrt{s_1^2} * \sqrt{2} * 1.96 \qquad (4)$$

where,

s_1^2 = mean square calculated with the ANOVA analysis for the first group of data.

The LOA method then compares the differences (*d*) between the mean of the measurements taken with one device and the mean measurement of other device. Simply put, LOA is a comparison that can be calculated as $d \pm 2s$, where *s* is the standard deviation (Bland and Altman, 1999). The equation used to calculate the LOA for each comparison was:

$$s_c = \sqrt{s_D{}^2 + f_1 * s_1{}^2 + f_2 * s_2{}^2} \qquad (5)$$

where ,

$s_D{}^2$ = variance of the difference between the measurements of each device,

$s_1{}^2$ and $s_2{}^2$ = variance corresponding to the data set for Device 1 and 2,

f_1 and f_2 = factors for each device that depends on the number of runs and are defined as follow:

$$f_i = \left(1 - \frac{1}{m_i}\right) \quad (6)$$

m_i = number of runs for the device *i*.

2.6.3 Data Pre-processing and Slipping Speed Adjustments

Three methods where investigated to convert data measured with the SCRIM to LWST friction number. All of them focus on bringing the measurements to a common reference slip speed to be able to compare the data. The first method is the direct application of the ASTM International Friction Index or IFI (ASTM 2016). The others are derivations (simplifications) of the IFI to adjust for speed. The following subsections describe data preprocessing and the three methods in more detail.

LWST Data Processing

The LWST measurements were filtered to remove the highest and lowest values, except for a few cases where either the 2 highest or the 2 lowest measurements were removed (Fernando et al., 2017).

SCRIM Data Processing

After data were exported using the equipment software to an Excel file, the measurements were adjusted to the target speed using the manufacturer-recommended equations and the data were filtered to remove outliers.

International Friction Index (IFI)

ASTM E 1960 "Standard Practice for Calculating International Friction Index of a Pavement Surface" normalizes how to obtain the IFI value from measurements of friction and macrotexture. The IFI is composed of two parameters, F60 and S_p. The first value is the friction of the wet pavement at 60 km/h, and the second is the speed parameter that describes the speed dependence of the friction.

IFI uses reference macrotexture (CT Meter) and friction (DFT) measurements to normalize the measurements done with different equipment. It was developed to provide a standard comparison of pavement friction measurements around the world *(*Flintsch et al, 2009*)*. Through this index, it is possible to compare measurements obtained with different equipment. The procedure followed to calculate the IFI is described as follows:

1. Calculate the constant S_p that is related to the macrotexture, which can be determined using linear regression as a function of the MPD in mm:

$$Sp = a + (b * MPD) \quad (7)$$

where,

a and b = constants that vary according to the equipment used to take the measurement of macrotexture (for this paper the equipment used was the CT meter, a = 14.2 and b = 89.7).

2. Calculate the F60 parameter for the equipment used to determine the friction (FRS), in this case the SCRIM and the LWST, the slipping speed (S), which is the testing speed for the LWST and 0.34 times the testing speed for the SCRIM ($sin(20^o) = 0.34$), and the S_p determined using the macrotexture measurements using equation 3:
3. Compute the value of F60 using the following equation:

$$F60 = A + B * FR60 \quad (8)$$

where,

A and B = constants that can be calculated using linear regression, where the independent variable is the F60 obtained with measurements taken using the DFT and the dependent variable is the FR60 using the FRS obtained from the equipment in question.

The IFI is expressed by the pair (F60, S_p). These two numbers were determined for the SCRIM and both LWSTs on each section of the TTI runway.

<u>Conversion using F60</u>

With the objective to simplify the comparison between the friction measurements, the F60 formulas for the SCRIM and the LWST were matched to obtain an equation to convert measurements taken with the SCRIM to values comparable to those obtained using the LWST.

$$F60_{SCRIM} = F60_{LWST} \quad (9)$$

$$A_{SCRIM} + B_{SCRIM} * FR60_{SCRIM} = A_{LWST} + B_{LWST} * FR60_{LWST} \quad (8)$$

$$A_{SCRIM} + B_{SCRIM} * FRS_{SCRIM} * e^{\frac{s_{SCRIM}-60}{Sp}} = A_{LWST} + B_{LWS} * FRS_{LWS} * e^{\frac{s_{LWST}-60}{Sp}} \quad (9)$$

$$FRS_{LWST} = \frac{A_{SCRIM} - A_{LWST} + B_{SCRIM} * FRS_{SCRIM} * e^{\frac{s_{SCRIM}-60}{Sp}}}{B_{LWST} * e^{\frac{s_{LWS}-60}{Sp}}} \quad (12)$$

Predicted LWST measurements were computed using Equation 12 and compared with the direct measured values.

Conversion Using FR60

Another comparison was made by matching FR60 instead of F60. The reason for using this formula was to avoid the need to take measurements with a third device, like the DFT, as it is needed for establishing *A* and *B* to compute the F60. The FR60 formulas for the SCRIM and the LWST were matched with the objective of obtaining an equation that would allow converting measurements taken with the SCRIM to values comparable to those obtained using the LWST.

$$FR60_{SCRIM} = FR60_{LWST} \quad (13)$$

$$FRS_{SCRIM} * e^{\frac{s_{SCRIM}-60}{Sp}} = FRS_{LWST} * e^{\frac{s_{LWST}-60}{Sp}} \quad (10)$$

$$FRS_{LWST} = \frac{FRS_{SCRIM} * e^{\frac{s_{SCRIM}-60}{Sp}}}{e^{\frac{s_{LWST}-60}{Sp}}} \quad (15)$$

Predicted LWST measurements were computed using Equation 15 and compared with the direct measured values.

2.6.4 Evaluation of Results

The evaluation used the FR60 and F60 formulas (Equations 13 and 16) to predict the FRS that would be measured by an LWST using the FRS measured with the SCRIM. The predicted values were then compared with the FRS actually determined with the LWST. The comparison was done using regression analysis, with the FRS measured as the independent variable and the FRS predicted as the dependent variable. In an ideal case, the regression will result in a 45° equality line with a coefficient of determination, R^2, of 1. The methods were compared based on goodness-of-fit statistics (R^2 and the average absolute error of the predictions) and considerations regarding the need to conduct reference measurements (which requires using additional devices).

2.7 RESULTS

2.7.1 Equipment Comparison (LOA)

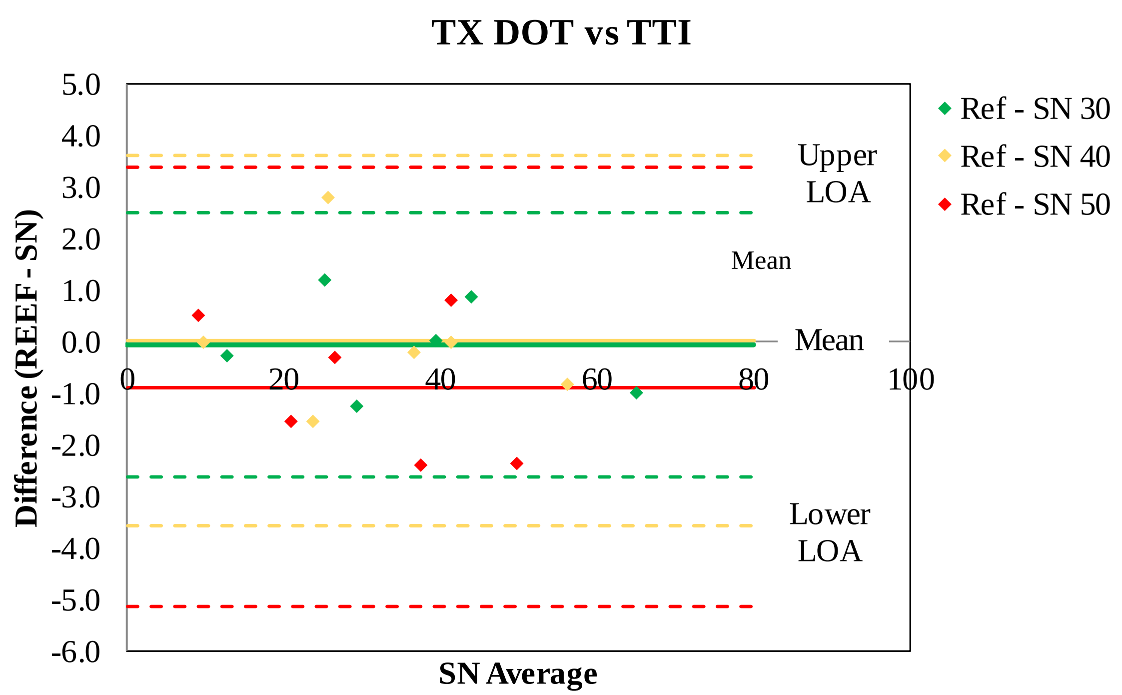
The repeatability of each device was determined as the LOA between the measurements. If the repeatability of a device is low, the agreement between that device and any other is going to be poor as well *(*Bland and Altman, 1986*)*. Table 2**–2** shows the repeatability of the three devices computed using the LOA calculated using Equation 4. The repeatability seems to be good and similar for all three devices.

The table also presents the results from the LOA for pairwise comparisons at the three tested speeds for the three devices studied. The reproducibility between the two LWSTs is good and close to the repeatability of each individual device. However, the measurements taken with both LWSTs are ±10 units approximately to the SCRIM measurements with a 95% level of confidence at the three speeds. This suggests that the measurements are different. This was expected because the two devices are measuring different frictional properties at very different slipping speeds. Although the testing speed is the same for the three devices, the actual slipping speed for the SCRIM is lower (approximately one-third) than the LWST. These results reinforce the need for speed corrections.

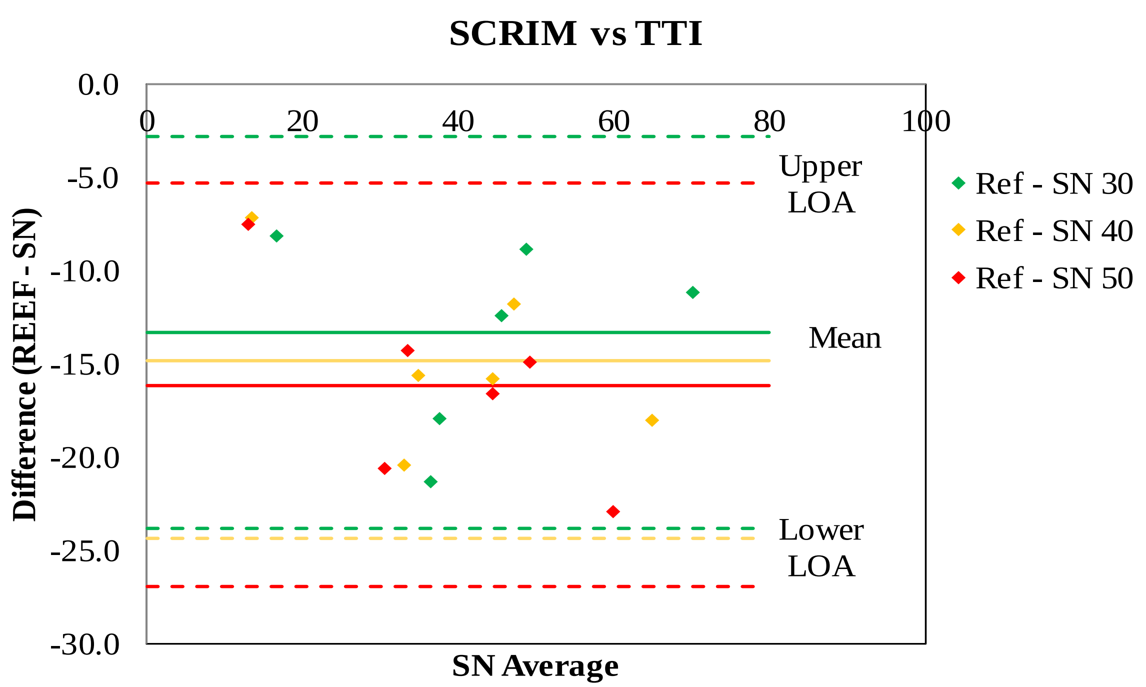
Table 2–2 Repeatability for Devices Used to Collect Data

Equipment	**Speed (mph)**	**Repeatability**	**LOA ±**	
			SCRIM	**TxDOT**
TTI LWST (reference)	30	1.4	10.5	2.6
	40	1.3	9.5	3.6
	50	3.5	10.8	4.2
TxDOT LWST	30	1.1	10.9	-
	40	2.5	9.3	-
	50	4.5	9.0	-
SCRIM	30	3.3	-	-
	40	2.9	-	-
	50	1.3	-	-

Figure 2–2 shows the results of the LOA comparison between the TxDOT LWST and SCRIM with the reference to the TTI LWST. The plot shows the LOA for individual measurements, and individual points represent the difference between the average measurements for each device, at each speed, on each pad. The plot shows no bias for the TXDOT device, except at 50 mph, probably due to difficulties in maintaining the high speed over the short sections. It is also interesting to note that the LOA band gets wider as speed increases. The figure also shows an average negative bias of 15 friction numbers of the SCRIM and that the bias is dependent on the Skid Number (SN), as in general measurements (and the LOA bands) show a downward trend. This supports the necessity of converting all the measurements to a reference sliding speed as presented in the following sections.



(a) TxDOT vs. TTI LWST comparison.



(b) SCRIM vs. TTI LWST comparison.

Figure 2–2. Results of LOA analysis of comparison between devices.

2.7.2 Equipment Interconversion using the IFI (F60)

To calculate the speed constant (S_p), the MPD was measured using a CT Meter. Note that the values for different speeds are slightly different because they were computed over the skidding length of the LWST, which varies with speed. Table 2–3 shows the results obtained for each section and speed. For the calibration of the friction testers, a DFT was used as the friction reference. The FR60 and F60 shown in the first part of Table 2–4 were calculated as discussed in the Methods section.

Table 2–3 Average Macrotexture (MPD) and Computed Speed Constants (after Fernando et al., 2017)

Speed	30 km/h		40 km/h		50 km/h	
Section	Avg. MPD (mm)	*S*p	Avg. MPD (mm)	*S*p	Avg. MPD (mm)	*S*p
Pad 1	0.64	71.81	0.65	72.36	0.66	73.28
Pad 2	1.37	137.29	1.42	141.80	1.29	129.79
Pad 2A	0.82	87.85	0.84	89.17	0.84	89.13
Pad 5	2.35	225.39	2.47	235.46	2.76	261.53
Pad 6	1.91	185.63	1.98	192.18	1.92	186.54
Pad 7	1.36	136.09	1.40	139.71	1.46	145.52

The IFI constants A and B (presented in Table 2–4) were determined using linear regression of the values of FR60 of the equipment in question and the F60 calculated for the DFT. They were then used to calculate the F60 for each equipment using Equation 9 (Fernando et al, 2017).

2.7.3 Direct Comparisons Using F60

After the calculation of the IFI values for each device, and the calculation of the constants A and B, the next step was to use Equation 12 to predict the values of friction that would be measured by the LWSTs using the SCRIM SR values. The results are presented in the second part of Table 2**–4** for the comparison of the SCRIM with reference to the TTI LWST.

2.7.4 Prediction of LWST Measurement Using FR60

Trying to further simplify the prediction of the measurements and reduce the number of variables, the next step was to predict the friction values from the LWST using Equation 15. The results for the TTI LWST are presented in the third part of Table 2–4. That same table shows the difference between the predicted and the measured data. In Pad 2 there is a significantly greater difference than for the other sections, which could be due to the irregularities in that specific pavement section.

Table 2–4 Average Friction Values Measured, IFI Calculations, and Analysis Results

Speed (mph)	Section	IFI Calculation												Comparison of TTI LWST SN40 Using F60 formula			Comparison Using FR60 formula and CT Meter Macrotecture			Comparison using FR60 formula and SCRIM Macrotexture		
		DFT			TTI LWST			TxDOT LWST			SCRIM											
					A = 0.085, B= 0.615			A = 0.089, B= 0.598			A = 0.077, B= 0.599											
		Avg. SN20	FR60	F60	Avg. SN40	FR60	F60	Avg. SN40	FR60	F60	AVG SR(50)	FR60	F60	Avg. SN meas.	SN pred.	Diffe-rence	Avg. SN meas.	SN pred.	Diffe-rence	Avg. SN meas.	SN pred.	Diffe-rence
30	Pad 1	0.36	0.21	23	29	0.24	23	30	0.25	24	47	0.25	23	28.7	29.2	-0.5	28.7	30.0	-1.3	29.9	25.6	4.4
	Pad 2	0.32	0.24	25	26	0.24	23	25	0.23	22	47	0.34	28	25.8	36.4	-10.6	25.8	37.4	-11.6	24.6	37.9	-13.3
	Pad 2A	0.2	0.12	17	13	0.11	15	13	0.11	16	21	0.13	15	12.6	14.1	-1.5	12.6	14.5	-1.9	12.9	14.9	-2.0
	Pad 5	0.35	0.3	30	44	0.42	34	43	0.41	33	53	0.44	34	44.3	44.9	-0.6	44.3	46.1	-1.9	43.4	45.2	-1.8
	Pad 6	0.34	0.27	28	39	0.37	31	39	0.37	31	52	0.41	32	39.4	42.5	-3.1	39.4	43.7	-4.3	39.4	42.5	-3.1
	Pad 7	0.71	0.53	47	64	0.59	45	65	0.6	45	76	0.55	41	64.4	58.3	6.1	64.4	59.9	4.5	65.4	60.4	5.0
40	Pad 1	0.36	0.2	23	23	0.24	23	24	0.26	24	43	0.26	23	22.9	23.5	-0.7	22.9	24.2	-1.3	24.4	19.7	4.7
	Pad 2	0.33	0.25	26	27	0.28	26	24	0.25	24	43	0.33	27	27.1	30.9	-3.8	27.1	31.7	-4.6	24.3	31.7	-7.4
	Pad 2A	0.21	0.13	18	10	0.1	15	10	0.1	15	17	0.11	14	9.8	10.2	-0.5	9.8	10.5	-0.8	9.8	9.8	-0.1
	Pad 5	0.36	0.31	30	41	0.42	34	41	0.42	34	53	0.45	35	41.2	43.1	-1.9	41.2	44.3	-3.1	41.2	43.4	-2.2
	Pad 6	0.37	0.3	30	36	0.37	31	37	0.37	31	52	0.43	33	36.5	40.9	-4.4	36.5	42.0	-5.5	36.7	39.6	-3.0
	Pad 7	0.76	0.57	50	56	0.57	44	57	0.58	44	74	0.56	41	55.8	53.1	2.7	55.8	54.5	1.2	56.6	54.1	2.5
50	Pad 1	0.34	0.19	22	20	0.26	25	22	0.28	26	41	0.26	23	20.2	19.3	0.9	20.2	19.8	0.4	21.7	16.0	5.7
	Pad 2	0.33	0.24	26	26	0.31	27	27	0.31	27	41	0.32	27	26.3	26.3	0.0	26.3	27.0	-0.7	26.6	27.9	-1.3
	Pad 2A	0.23	0.14	19	9	0.12	16	9	0.11	15	17	0.12	15	9.2	9.0	0.2	9.2	9.2	0.0	8.7	9.3	-0.6
	Pad 5	0.37	0.32	31	42	0.45	36	41	0.44	35	57	0.5	38	41.6	45.0	-3.3	41.6	46.2	-4.5	40.8	45.1	-4.3
	Pad 6	0.37	0.3	30	36	0.4	33	39	0.43	35	53	0.44	34	36.2	38.7	-2.5	36.2	39.8	-3.6	38.6	36.8	1.8
	Pad 7	0.75	0.57	50	49	0.56	43	51	0.58	44	71	0.57	42	48.5	48.4	0.1	48.5	49.7	-1.2	50.9	48.0	2.9
Average of Absolute Differences																2.41			2.9			2.82

2.7.5 Prediction of LWST Measurement Using FR60 and Texture from SCRIM

To take advantage of the capacity of the SCRIM to measure macrotexture and simplify the prediction of the LWST measurements, the prediction of the LWST measurements was done using the FR60 formula and the texture measured with the SCRIM. This way the prediction would require only one device, the SCRIM. The third part of Table 2**–4** shows the results of the prediction for the TTI LWST.

2.8 ANALYSIS AND DISCUSSION

2.8.1 Comparison of the Predictions

Figure 2–3 compares the SN measured with the LWST from TTI and the one predicted based on the SCRIM measurements using the two methods discussed. Using the FR60 or the F60, the coefficient of determination, R^2, is the same; this is expected because of the linear nature of the IFI relationships. It should be noted that each dot in the figure represents the average of several measurements in the same section and differences among individual measurements will certainly have a higher variability. Very similar results were obtained when comparing the SCRIM with the TxDOT LWST.

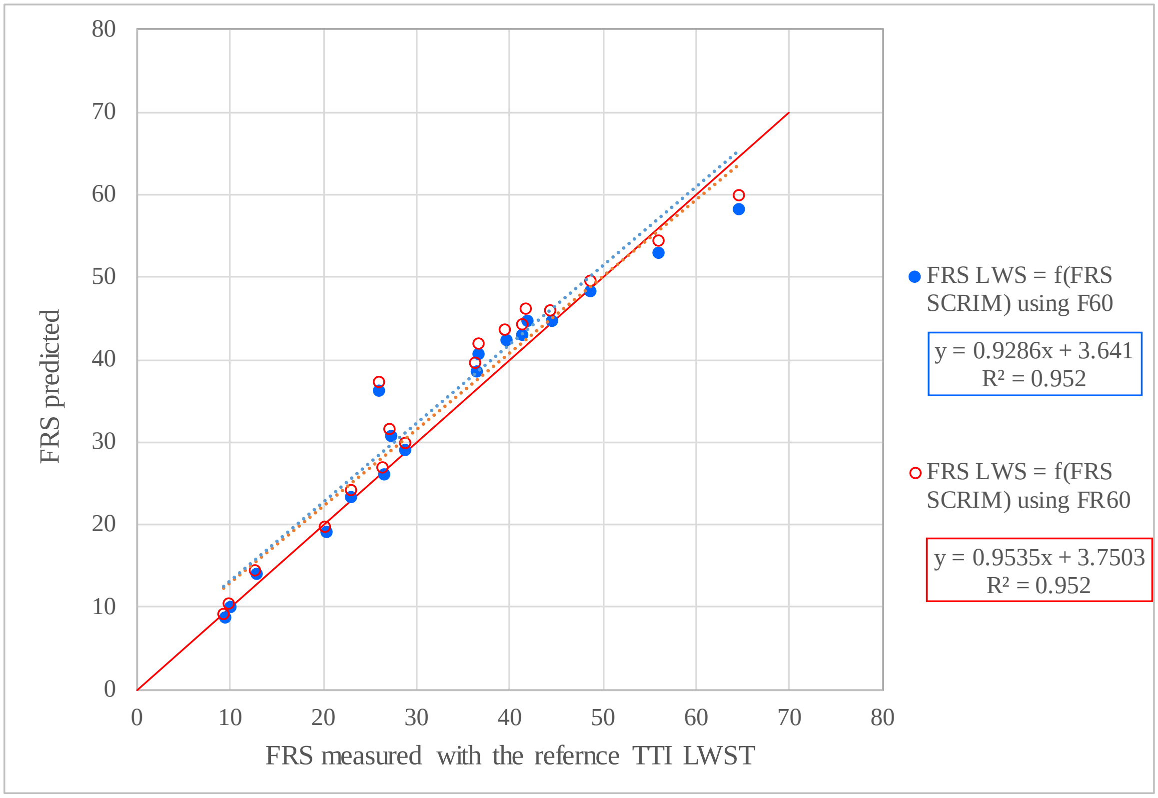


Figure 2–3. Comparison of measured and predicted friction measurements for TTI LWST.

Both prediction methods have good prediction ability, with a coefficient of determination, R^2, greater than 90%. However, the F60 formula involves an intermediate step that requires measurements with the reference DFT and CT Meter. On the other hand, the FR60 formula does not require taking reference friction measurements using the DFT measurements, thus offering a practical alternative.

To simplify the interconversion even further, one additional approach was tested: replacing the CT Meter macrotexture measurements with those taken using the SCRIM texture sensor. Figure 2–4 shows the comparison of the prediction of the LWST measurements using the FR60 formula and the texture measured with the SCRIM. As shown, the R^2 is very close to the one obtained in the previous cases using the texture measured with the CT meter, suggesting very little change in predicting ability.

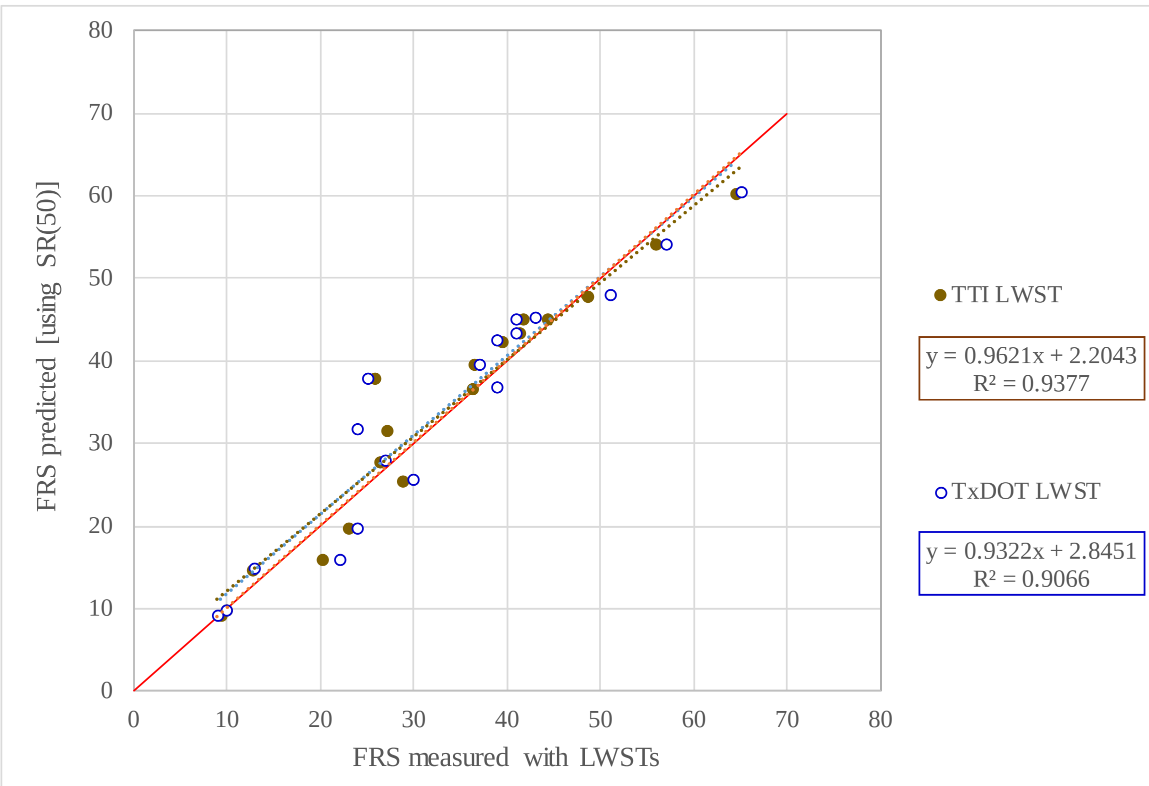


Figure 2–4. Comparison of predicted FRS using FR60 formula and texture from the SCRIM with measured one.

2.8.2 Discussion

The repeatability of the three devices is in the same order of magnitude, ranging between 1.8 and 3.7 for the three speeds evaluated. The LOA analysis shows that the measurements of the SCRIM are consistently higher than the measurements of the LWST. On average, the SCRIM has a difference of 15 friction numbers from the mean when compared with the LWSTs.

To use Equations 13 and 16 to predict the friction that would be measured with the LWST using the SCRIM measurements, it was necessary to calculate the S_p using the CT meter and the F60 from the DFT to complete the standard procedure for the IFI. According to ASTM E1960, the pavements should have profile depths for the range 0.25 mm < MPD < 1.5 mm and friction values for the range $0.3 < DFT_{20} < 0.90$. Some of the sections of pavement used for this study have macrotexture and friction characteristics that are out of these ranges. However, all the values measured include a wider range of friction and macrotexture values and improve the relationship.

The results obtained with the methods proposed are encouraging in the search for a way to convert friction measurements. In order to recommend a specific method, several variables were considered: the number of devices required to get the measurements needed to apply the method, the number of variables in the formula applied, and goodness-of-fit statistics (R^2 and the average of the absolute value of the differences between the FRS measured and predicted).

Table 2**–5** presents a summary of the results for the methods tested for the prediction of the friction measured with the LWST. The table shows that the four combinations result in similar average absolute errors. Furthermore, the average absolute error is in the same order of magnitude as the equipment's repeatability. Since the conversion based only on the speed adjustments (FR60) using the SCRIM macrotexture values does not require reference measurements with static equipment, it is recommended for implementation.

Table 2–5 Summary of Comparison of Methods Used

Equipment used for texture	**Method**	**Number of devices required**	**Variables**	**Average of absolute value of the difference**	
				TTI	**TX DOT**
CT meter	F60	3	Macrotexture, speed, SR measured with the SCRIM, previous comparison with DFT (A and B)	2.41	2.93
	FR60	2	Macrotexture, speed, SR measured with the SCRIM	2.90	3.13
Texture of SCRIM	F60	2	Macrotexture, speed, SR measured with the SCRIM, previous comparison with DFT (A and B)	2.71	3.60
	FR60	1	Macrotexture, speed, SR measured with the SCRIM	2.82	3.66

2.9 CONCLUSIONS

After the comparison done between the measurements of friction taken with the LWST (TTI and TxDOT) and the SCRIM on the same road sections, it can be concluded that:

- All three tested devices produced appropriate repeatability as computed using the LOA, producing measurements within less than ± 1.1 to 4.5 friction numbers with a 95% level of confidence at the three tested speeds and on a wide range of surfaces.
- The conversion based only on the speed adjustments (FR60) seems to provide the most effective method to predict the LWST measurements from SCRIM measurements. The coefficient of determination and average absolute error are comparable to those using the IFI F60 formula but static reference measurements are not required.

Although the range of surface fiction and texture is rather wide, these conclusions were based on a limited number of tests on a few experimental sections under controlled conditions; thus, it is recommended that the approach be verified using production data collected on a variety of road and surface types.

2.10 ACKNOWLEDGMENTS

The data used for this paper were collected by TTI and VTTI in a collaborative effort under a study funded by the FHWA. E. Fernando, D. Arrington, R. and Zimmer (from TTI) and B. Hobbs (of VTTI) participated in the experiment design and data collection. Dr. James Wambold oversaw the field experiment and provided guidance during the testing.

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CHAPTER 3 - VERIFICATION OF AN INTERCONVERSION PROCEDURE FOR LOCKED-WHEEL AND CFME FRICTION MEASUREMENTS [2]

3.1 ABSTRACT

Transportation agencies are adopting proactive pavement friction management using Continuous Friction Measurement Equipment (CFME). Thus, a method to convert the traditional Locked-Wheel Skid Testers (LWST) becomes important to assure continuity with past practices. This paper evaluates a conversion method based on the International Friction Index (IFI) approach. The evaluation used data collected in the Virginia Smart Road using the Side-force Coefficient Routine Investigatory Machine (SCRIM) and the LWST from VDOT. The results confirm that, in general, a conversion based only on the speed adjustments (FR60) can be used to estimate LWST friction measurements (with a smooth tire) a using SCRIM friction and texture measurements.

3.2 INTRODUCTION

Pavement friction is receiving increased attention in the pavement management process. This attention has increased the need of a method to compare between different friction measuring equipment used by various Highway Agencies. Barrantes et al. (2018) compared several methods and proposed a practical approach to interconvert LWST and SCRIM measurements. Three methods were evaluated using data collected in a controlled track in Texas. The results showed a very good correlation between the prediction and the measurement. The most practical method was selected based on the goodness-of-fit statistics and the number of devices required.

3.3 OBJECTIVE

This paper presents a study to verify the method proposed by Barrantes et al. (2018) to interconvert LWST and CFME pavement friction measurements. Data collected on a different controlled facility, the Virginia Smart Road, were used for the evaluation.

3.4 BACKGROUND

There have been several efforts to harmonize the friction measurements from different devices. Those efforts have tried to understand the relationship between the different devices and the influence of texture and speed on the measurements.

[2] Co-authors include Gerardo W. Flintsch, Edgar de León Izeppi and Kevin K. McGhee

3.4.1 International Equipment Comparisons

The method evaluated on this paper uses the speed correction formula from the International Friction Index (IFI). The IFI method (ASTM, Standard E 1960-07) was developed after an international experiment directed by the World Road Association (PIARC) (Wambold et al, 1995). The method uses texture and friction measurements to normalize the measurements done with different equipment (Flintsch et al., 2009). The IFI uses the following equation to adjust the friction for different slip speeds:

$$FR60 = FRS * e^{\frac{S-60}{Sp}} \quad (11)$$

where,

FR60 = friction at the skid speed of 60 km/h,

FRS = friction value at S km/h,

S = slip speed,

Sp = the speed constant, related to macrotexture (km/h). (For this case, as shown in the equation, the reference speed was changed to 60 km/h).

Other equipment comparisons include those conducted by the Joint Winter Runway Friction Measurement Program (JWRFMP), led by Transport Canada (Balkwill, 2003) and NASA (Wambold et al, 2000), which included the Annual NASA Tire/Runway Friction Workshop (Wambold et al, 2004). These efforts offered different approaches as an attempt to harmonize and compare measurements from different devices.

More recent efforts, such as HERMES (Descornet, 2004) and Tyrosafe (Vos and Groenendijk, 2009), have tried to improve the interconversion between the measurements with mixed results. Roa (2008) showed that the relationships appear to be equipment-dependent and recommended that agencies develop specific relationships for their own equipment.

3.4.2 Annual Equipment Comparisons at the Virginia Smart Road

The Virginia Transportation Research Council (VTRC) and the Virginia Tech Transportation Institute (VTTI) lead a transportation pooled-fund project, known as the Pavement Surface Properties Consortium. The main objective of this initiative is to improve the level of service provided by the roadway transportation system optimizing pavement surface texture. Every year since its inception in 2006, consortium members have met at the beginning of summer at the Virginia Smart Road to compare their profile, friction, and macrotexture measuring equipment under controlled conditions. This exercise is a collaborative research effort to verify the operation, reliability and accuracy of the equipment. The data used for this study were collected as part of the 2017 experiment, conducted in June of this year.

3.5 RESEARCH METHODS

3.5.1 Data Collection

The objective of this study was to compare the measurements from the SCRIM and the different LWST that participated in the 2017 Pavement Surface Properties Rodeo. For this paper only one of the LWST was considered because is the only one using smooth tire (ASTM E524). The measurements were taken in 7 sections of the Smart Road (Table 3–1), at three different speeds (30, 40 and 50 mph) and doing 5 runs on each direction (uphill and downhill).

Table 3–1. Surfaces Tested at The Virginia Smart Road.

Section	Surface Type
A	SM-12.5D
B	SM-9.5D
C	SM-9.5E
D	SM-9.5A
J	SM-9.5D
L	SMA-12.5D
PCC	Transversally Tined Concrete

3.5.2 Data Analysis Methods

<u>SCRIM Data Processing</u>

After data were exported using the equipment software to an Excel file, resulting in 42 files with each run information, the measurements were adjusted to the target speed using the manufacturer-recommended equations and the data were filtered to remove outliers. Following, the different runs were synchronized. First, using as reference the nodes determined by the operator of the truck and then using the trend of the measurements in the different sections. Figure 3–1 shows the data after the synchronization for the case of 40 mph in downhill direction.

The figure shows that there is not a perfect match of the individual measurements (every meter) but the general trends on the different pavement sections in general agree. The red lines indicate the beginning of each of the sections that were part of the study. For the different speeds, the distance used to calculate the average of the friction measurement that would be compared to the measurement of the LWST is different. This is because the LWST averages the measurements over 1 second and thus, the length (d) measured by the LWST at the different speeds varies. At 30 mph the distance measured with the LWST is approximately 13.4 m, at 40 mph is 17.9 m and 50 mph is 22.3 m.

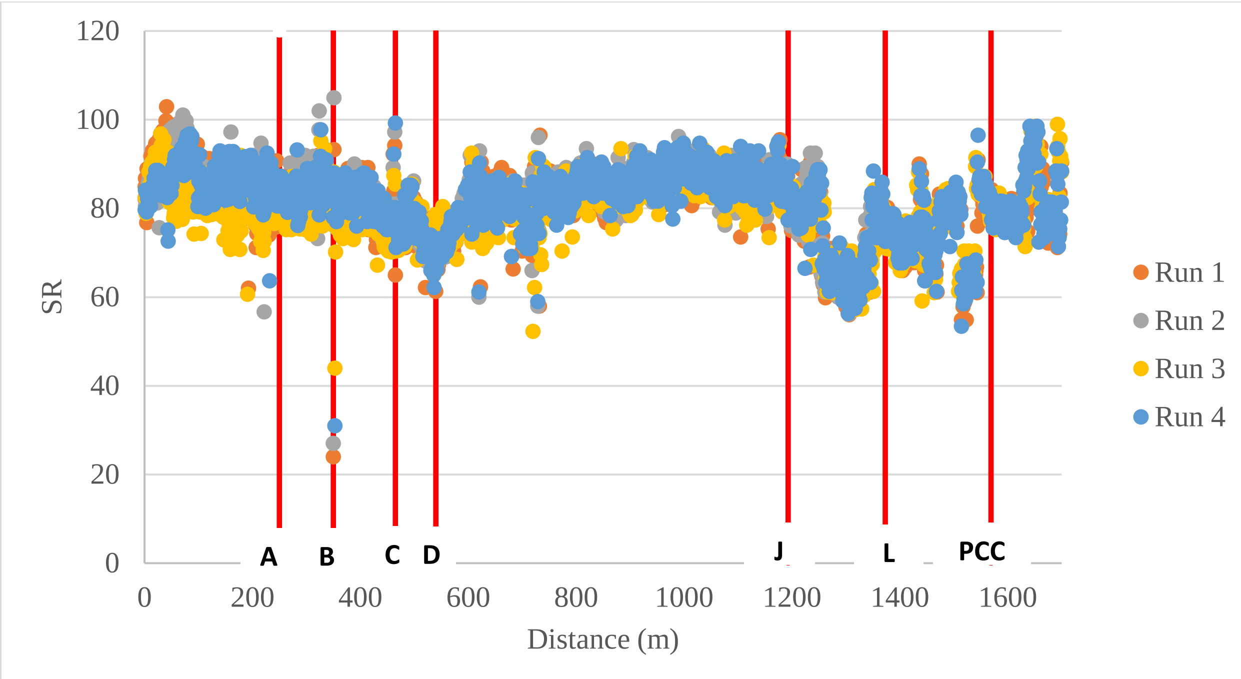


Figure 3-1..

Figure 3–1. SCRIM Runs at 40 mph, downhill synchronized

Figure 3–2 illustrates the distance “d”. The cones show the beginning and ending of each section and the “d” is the distance measured by the LWST.

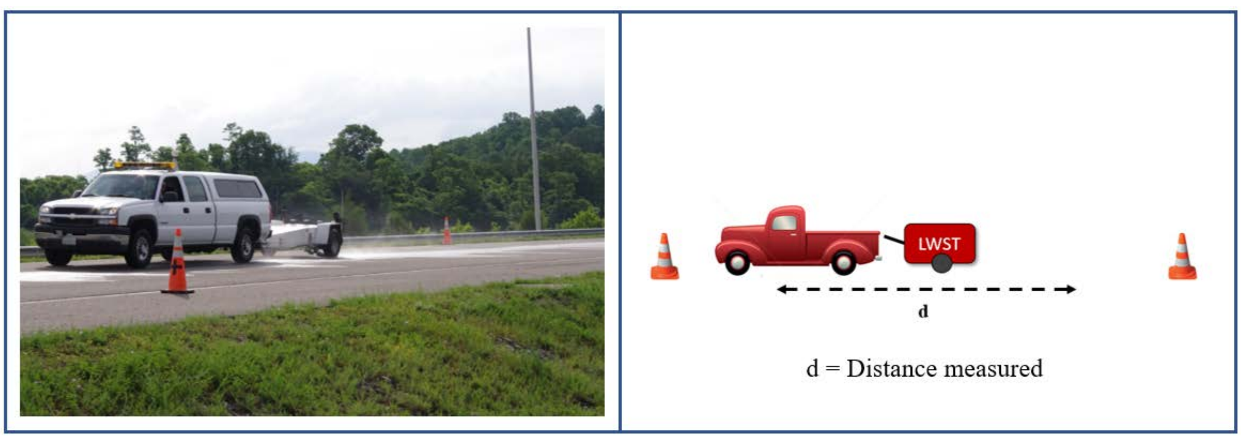


Figure 3–2. Determination of the distance used for each speed.

Conversion Using FR60

The evaluation was made by matching FR60, as described in Barrantes et al. (2018). This formula was selected to avoid the need to take reference static measurements, e.g., the DFT needed for establishing *A* and *B* to compute the F60. The FR60 formula was use to obtain the following conversion equation.

$$FRS_{LWST} = \frac{FRS_{SCRIM} * e^{\frac{s_{SCRIM}-60}{Sp}}}{e^{\frac{s_{LWST}-60}{Sp}}} \tag{12}$$

where,

FRS_{LWST} = friction value at *S* km/h from the LWST,

FRS_{SCRIM} = friction value at *S* km/h from the SCRIM,

s_{SCRIM} = slip speed of the SCRIM (a fraction of the testing speed),

s_{LWST} = slip speed of the LWST (testing speed),

s_p = speed constant, which has speed units and is related to macrotexture.

Predicted LWST measurements were computed using Equation 1 and compared with the direct measured values. The macrotexture values measured with the SCRIM instead of the reference CT Meter were used to compute the s_p as recommended in Barrantes et al. (2018).

3.6 RESULTS

3.6.1 Prediction of LWST Measurement Using FR60

The results are presented in Table 3–2, which also presents the difference between the predicted and the measured data. Table 3–2 shows how the differences are larger for the higher speeds. This could be caused because is harder to measure in the exact same spot driving faster as it is harder to maintain the wheel path and trigger the measurement at the same exact location.

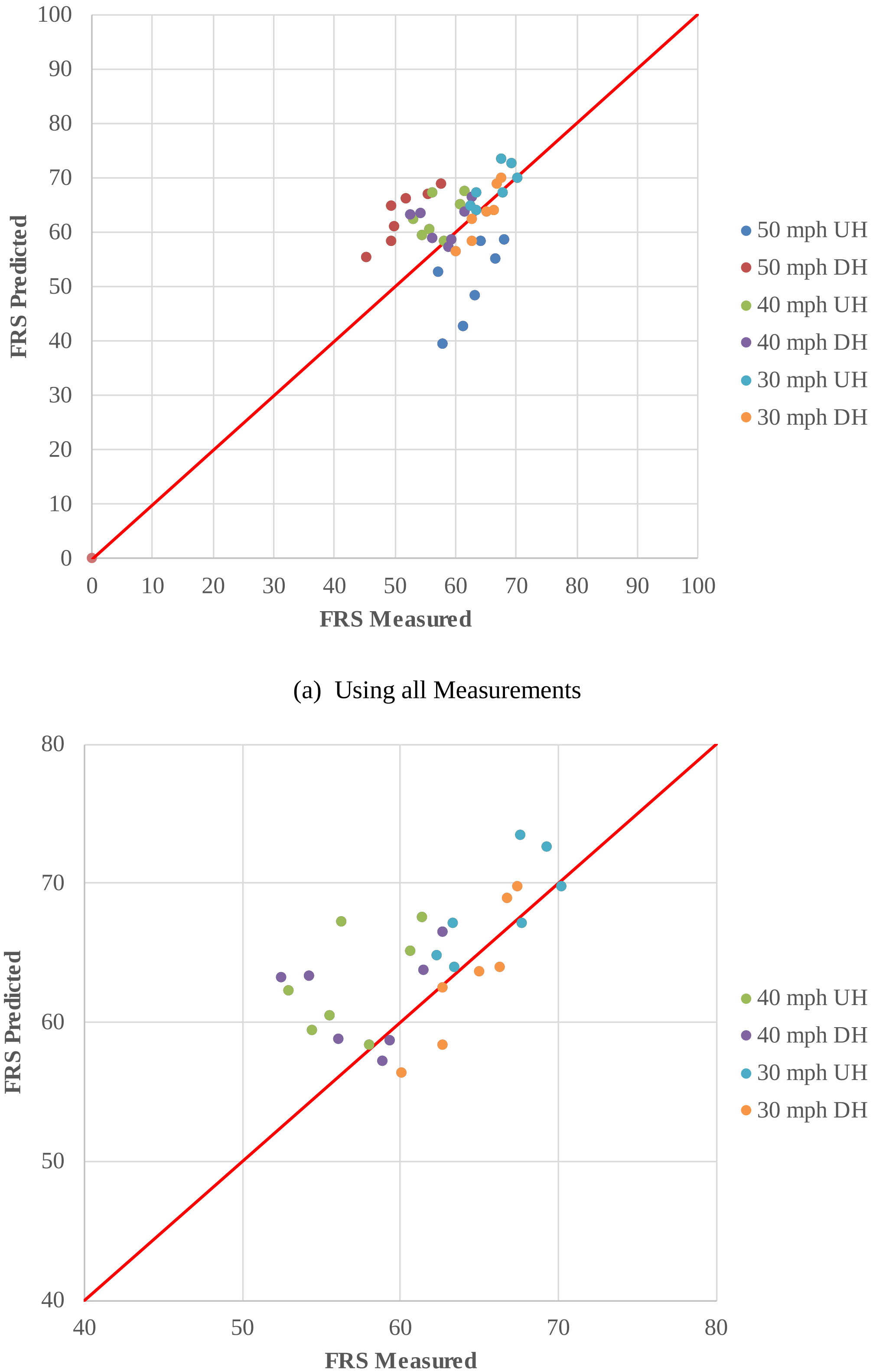
3.7 ANALYSIS

3.7.1 Comparisons

Figure 3**–3**(a) compares the measured and predicted FRSs and confirms that the conversions are better for the lower speeds (e.g., 30 mph). The points for the highest speed (50 mph) are further from the equality red line. In addition, the plot shows that the friction range is quite narrow and does not allow for a comprehensive verification. Figure 3**–3**(b) compare the predicted and measured Sn after removing the 50 mph measurements, and in this case, all the points are relatively close to the equality line.

Table 3–2. Average Friction Values Measured and predicted.

Uphill							***Downhill***						
Speed (mph)	Section	Avg. SR from SCRIM	Average MPD	Avg. SN from LWST	SN predicted	Diffe-rence	Speed (mph)	Section	Avg. SN from SCRIM	Average MPD	Avg. SN from LWST	SN predicted	Diffe-rence
30	**A**	91.9	0.91	67.6	67.2	0.4	30	**A**	82.9	1.92	67.4	69.9	2.5
	B	85.1	1.51	70.2	69.9	0.3		**B**	81.4	1.96	66.8	68.9	2.2
	C	75.4	1.87	63.4	64.0	0.6		**C**	76.4	1.17	62.7	58.4	4.3
	D	88.3	1.55	69.3	72.6	3.45		**D**	72.2	1.27	60.1	56.4	3.6
	J	78.0	1.63	62.3	64.8	2.5		**J**	79.5	1.42	65.0	64.1	0.9
	L	81.5	1.55	63.4	67.2	3.8		**L**	74.55	1.81	62.6	62.5	0.1
	PCC	84.8	2.14	67.6	73.5	5.9		**PCC**	82.7	1.19	66.3	64.1	2.2
40	**A**	88.9	1.39	60.6	65.2	4.6	40	**A**	81.5	1.80	61.5	63.8	2.4
	B	81.6	2.41	61.4	67.6	6.3		**B**	80.4	2.37	62.7	66.6	3.9
	C	76.1	1.74	58.0	58.4	0.4		**C**	74.9	1.81	56.1	58.8	2.7
	D	85.7	1.34	52.9	62.4	9.4		**D**	70.9	2.10	58.9	57.2	1.6
	J	71.9	2.66	55.5	60.5	5.0		**J**	80.7	1.83	52.4	63.3	10.8
	L	78.0	1.60	54.4	59.4	5.0		**L**	74.8	2.76	54.2	63.4	9.3
	PCC	83.2	2.12	56.2	67.3	11.1		**PCC**	78.8	1.45	59.4	58.7	0.6
50	**A**	88.7	1.25	52.6	57.1	4.5	50	**A**	84.0	2.97	57.5	68.9	11.4
	B	80.8	2.54	58.5	64.2	5.8		**B**	81.4	2.97	55.5	67.1	11.7
	C	70.5	2.93	39.4	57.8	18.4		**C**	74.2	3.00	49.8	61.2	11.4
	D	81.9	3.14	58.8	68.0	9.2		**D**	65.8	3.44	45.2	55.5	10.3
	J	70.5	4.09	42.8	61.2	18.4		**J**	78.5	3.36	51.7	66.2	14.5
	L	76.3	3.13	48.4	63.3	14.9		**L**	74.5	4.18	49.2	64.9	15.7
	PCC	78.0	3.54	55.3	66.4	11.2		**PCC**	78.0	1.88	49.4	58.3	8.9



(a) Using all Measurements

(b) After Removing the 50 mph Measurements

Figure 3–3. Comparison of measured and predicted friction measurements.

3.7.2 *Discussion*

The results obtained with the method proposed are encouraging in the search for a way to convert friction measurements. Although the agreement is not as good as in Barrantes et al. (2018), it was still considered acceptable. There are two potential reasons to explain the larger differences: (1) the equipment used may not have been calibrated as carefully as the reference LWST used in the previous comparison, and (2) the range of friction values is much narrower than in the previous study and this makes it difficult to observe general trends.

3.8 CONCLUSIONS

The comparison done between the measurements of friction taken with the LWST (VDOT) and the SCRIM on the a variety of pavement surfaces showed that, in general, the FR60 formula proposed by Barrantes et al. (2018) can be used to estimate LWST smooth tire friction values using SCRIM measurement. There were significant different at 50 mph but these are suspected to be due to the difficulties of the operators to maintain consistent lateral position and to test the exact same location because of the geometry of the road. These conclusions are based on a limited number of tests on a few experimental sections within a narrow range of friction values; therefore, additional verifications are recommended.

3.9 ACKNOWLEDGMENTS

The data used for this paper were collected during the 2017 Equipment Comparison at the Virginia Smart Road. The LWST data used for this evaluation was from VDOT. This experiment has been made possible thanks to the contributions of the Virginia Transportation Research Council (VTRC), the Federal Highway Administration (FHWA), the Virginia Departments of Transportation and the Virginia Tech Transportation Institute (VTTI).

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CHAPTER 4 - SUMMARY, FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

It is important that highway agencies provide drivers with safe and smooth rides throughout the year. It is for this reason that friction, macrotexture and other surface properties are monitored periodically. In particular, friction measurements are important to provide a safe road but different friction measurement equipment produce different results. The thesis proposed a method to convert pavement friction measurements obtained with two different types of friction measuring equipment: a Locked Wheel Trailer (LWST) and a Continuous Friction Measurement Equipment (CFME), the Side-force Coefficient Routine Investigatory Machine (SCRIM).

Chapter 2 evaluated two conversion approaches based on the International Friction Index equations and proposed a simplified method for adjusting the measurements to a common slip speed using macrotexture measurements from the SCRIM. Chapter 3 verified that the approach worked for data collected on a different facility. Although the results were not as good as for the first case, in general they were considered acceptable.

4.1 FINDINGS

The following findings emerged during the process of finding a method that allows interconvert measurements from different friction measuring devices:

- The LOA method proved to be an effective tool to compare measurements taken with different devices and to evaluate the repeatability of the individual devices. This is consistent with previously reported results (de Leon, 2012).
- The three devices compared in Chapter 2 produced appropriate repeatability as computed using the LOA, producing measurements within less than ± 1.1 to 4.5 friction numbers with a 95% level of confidence at the three tested speeds and on a wide range of surfaces.
- The conversion based only on the speed adjustments (FR60) seems to provide the most effective method to predict the LWST measurements from SCRIM measurements. The coefficient of determination and average absolute error are comparable to those using the IFI F60 formula but static reference measurements are not required.
- The verification of proposed method using data collected on a separate experiment on the Virginia Smart Road, produced results that do not show the same level of agreement in comparison with the results from the original experiment. This may be due to lack of calibration of the LWST or is because the range of friction values measured on these sections is very narrow.

4.2 CONCLUSIONS

The overall results of the thesis showed that it is possible to interconvert smooth-tire LWST and SCRIM friction measurements based only on the International Friction Index speed adjustments (FR60). The coefficient of determination and average absolute error are comparable to those using the IFI F60 formula but static reference measurements are not required. Since the verification results showed some discrepancies for the measurements collected at high speeds, it is recommended that the proposed method continue to be evaluated with additional data.

4.3 RECOMMENDATIONS FOR FUTURE RESEARCH

Given the very limited verification conducted as part of the Thesis, it is recommended that future research further evaluate the proposed method under the following operating conditions:

- Using LWST devices that have been recently calibrated,
- Measuring on a wide range of pavement texture, and
- Taking the measurement on straight and flat pavement sections

Furthermore, it may be recommendable to clean the pavement surfaces to be tested before starting the measurements to make sure that the measurements are repeatable as possible.

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APPENDIX I – COMPLEMENTARY LITERATURE REVIEW

I-1. IMPACT OF FRICTION ON SAFETY, CRASHES, AND ASSOCIATED FATALITIES.

In 2010, just in the US, almost 33,000 people died in car crashes and in 2015 that number went down just a little to over 32,000 (NHTSA, 2015). Towards Zero Deaths (TZD) is an international strategy to reduce fatalities and serious injuries that has the goal of reducing the number of fatalities due to car accidents around the world in half by 2020 *(*AASHTO, 2011). This requires making our roads safer.

Although there are different factors involved in a crash --the vehicle, the driver and the road conditions, transportation agencies can only influence the provision of a safe road. In particular, pavement infrastructure with good friction can help reduce crashes by allowing vehicles to stop and maneuver with more control of the vehicle. Thus, it is important that a comprehensive TZD strategy include pavement friction management.

All pavements have as main objective to provide the user with a comfortable and safe ride. Thus, they need to provide adequate friction. Some of the issues produced by lack of friction include: loss of control, braking associated problems, and steering difficulties, among others (Smith et al., 2011). Thus the fiction and macrotexture of the surface play a key role on the ability of the user to prevent crashes. It has been demonstrated the contribution of friction and macrotexture to reducing vehicle crashes specially at horizontal curves, intersection approaches, congested areas and merging/weaving areas of freeways, and work zones (Julian and Moler 2008).

In the U.S., the AASHTO Green Book states that the stopping distance provided in a roadway "should be sufficiently long to enable a vehicle traveling at or near the design speed to stop before reaching a stationary object in its path". In order to accomplish this, the level of friction in the roadway should be enough to accommodate the braking and steering maneuvers needed (Noyce et al., 2005).

Furthermore, studies indicate that approximately 80 percent of all crashes and fatalities on slippery pavements are associated with wet conditions and that up to 70 percent of wet-pavement crashes can be prevented or minimized by improved pavement friction and texture. (Smith et al., 2011). Thus, improvements on the friction of the pavement is a countermeasure to reduce the risk of crashes that has a low cost and could have a significant impact in the reduction of fatalities and injuries in specific parts of the road.

The friction between the pavement and a vehicle's tire is affected by temperature, seasonal changes, pavement condition, and the equipment used for the measurement. This surface characteristic should be taken into account in the design process and monitored during the service life of the road to assure good performance. One of the approaches to reducing crashes is to implement periodic network-level friction measurements. In the U.S., the equipment that has been traditionally used to monitor friction is the locked-wheel skid tester (LWST); however, other equipment has been considered. Several recent projects have experimented with continuous friction measurement equipment (CFME), such as fixed slip, sideway force, and modified locked-wheel testers. However, understanding how to compare pavement surface friction measurements taken with different devices has been a challenge (Descornet, 2004 and Vos and Groenendijk, 2009). Globalization initiatives that require the use of common roads in adjacent countries (or states) have led to a desire for the harmonization of friction data with different equipment. One of the first attempts to do this by the World Road Association (PIARC) introduced the concept of the International Friction Index (IFI). The IFI is a method that uses texture and frictional properties to normalize measurements taken with different equipment. However, this method has been tested and the results have not always produced harmonious results among all devices *(*Flintsch et al., 2009*)*.

I-2. FRICTION MEASUREMENTS

The friction in the pavement surface is defined as the force developed between the pavement surface and the tire. Figure I–1 shows the force body diagram explaining the friction (μ) concept. It represents the interaction between the vehicle tire and the pavement, no considering the demand of friction due to the tangential and/or transversal accelerations. It describes the phenomenon in a local level.

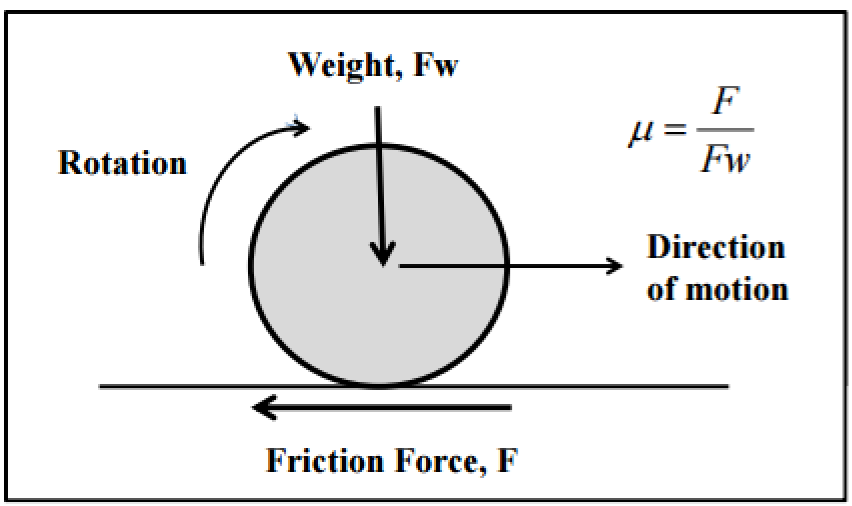

Figure I–1. Force body diagram for rotating wheel.
Source: Flintsch et al., 2012.

The friction between the pavement and a vehicle's tire is affected not only by the surface texture but also by temperature, seasonal changes, pavement condition, and the equipment used for the measurement.

Texture

Noyce, et al. (2005) defined surface texture as the roughness in the surface measured as the deviation of the surface compared to a flat surface. According to the World Road Association (PIARC) pavement texture can be classified according to it wave length in roughness, megatexture, macrotexture and microtexture. Figure I–2 shows the scale defined by PIARC.

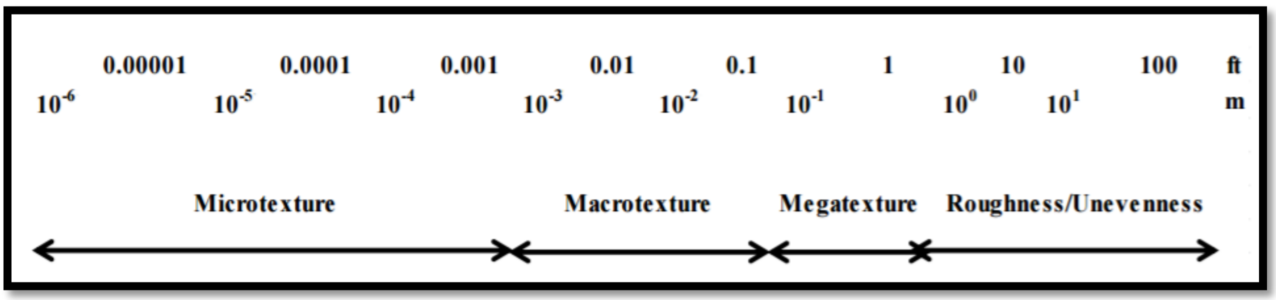

Figure I–2. Texture wavelength scale defined by PIARC.

Source: Flintsch et al., 2012.

Megatexture and roughness are not consider as significant for safety. Macrotexture, in the other hand, gives the properties needed to the runoff of the water in the pavement surface to maintain contact between the tire and the pavement. Macrotexture affects the braking capacity in wet conditions and the noise generated in the tire-pavement interface. Microtexture gives the direct contact between the tire and the pavement, and thus, it is directly related to the skid resistance. It depends mostly on the aggregate characteristics and it susceptibility to polishing produce by the contact with the tire. Microtexture is very important at low speeds as it provided adherence between the tires and the pavement, macrotexture contributes to increase wet friction at high speed and reducing hydroplaning potential (Noyce, et al., 2005).

Other Factors

Friction changes through the service life or design of a pavement. There are many factors that affect tire-pavement friction and they can be classified in four group: surface characteristics of the pavement, vehicle operation, tire properties and environmental factors (Table I–1). Some of those factors are not directly related to the pavement and is one of the reasons that makes difficult to control the variations on the measurements, even when are done with same device.

Table I–1. Factors that affects the friction between the tire and the pavement surface.

Surface characteristics	**Vehicle operation**	**Tire properties**	**Environmental**
• Microtexture • Macrotexture • Irregularities • Material properties • Temperature	• Skid speed • Vehicle speed • Braking action • Driver maneuver • Turns • Overtaking	• Trace • Design and conditions of the tread • Composition of the rubber • Pressure • Skid speed • Load • Temperature • Specific heat	• Weather • Wind • Temperature • Rain • Ice, snow • Contamination (fluids) • Nonskid material • Dirt • Viscosity • Density • Thickness of the water film • Specific heat

Source: (Wallman and Astrom, 2001).

It is specially a concern in wet conditions because friction is reduced because a water film is developed between the vehicle tire and the surface thus decreasing friction and potentially causing hydroplaning, even when friction levels are adequate. (Noyce et al., 2005)

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