RESEARCH & DEVELOPMENT

Evaluation of Methods for Pavement Surface Friction, Testing on Non-Tangent Roadways and Segments

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16. Abstract

This report presents the research effort to explore the use of continuous friction measurement equipment (CFME) as a tool for pavement friction management to be incorporated into the NCDOT Pavement Management Program to produce a strong Safety Improvement Program. The new tool and processes could supplement and/or replace the traditional locked-wheel tangential friction measurements and provide critical details to better understand road departures, wet crashes, and overall traffic performance and safety along ramps, loops, curves, and super-elevated sections that have traditionally been difficult to assess friction on. Testing included measurements with the locked-wheel trailer currently used by NCDOT, a Grip Tester, and a SCRIM (Side-Force Coefficient Routine Investigation Machine). The researchers took measurements with the three devices on common pavement types, overlays, and surface treatments on various highways in the state. The results from the three different equipment and methodologies were compared, and guidance for future implementation is provided.

The research products include: (1) A comparison of friction obtained from the three different equipment and methodologies, including continuous average friction values by pavement type for all the roadway geometries tested (curve/ramp/loop/super elevated section/section on grade); and (2) Recommendation and guidance with regards to the feasibility of collecting continuous friction and macrotexture data to define investigatory friction and macrotexture levels to support the state's pavement friction management program.

The main conclusions of the review of practice and analysis of the data collected as part of the study are the following: (1) The direct results of the comparison showed that it is possible to interconvert GN and SR measurements with LWST measurements but the correlations are not very strong; (2) Macrotexture is a very important parameter to obtain the full pavement frictional properties, especially for those devices that are insensitive to it (such as the LWST with a ribbed tire); and (3) The development and implementation of a PFM program would benefit from the collection of continues friction and macrotexture data.

Based on the stated conclusions the following recommendations are provided: (1) It is recommended that NCDOT start collecting macrotexture data to complement the agency's friction data collection; and (2) NCDOT should investigate the feasibility of implementing a pro-active friction management program that uses CFME with macrotexture measurement capabilities.

17. Key Words Continuous Friction Measurement Equipment (CFME), Locked-Wheel Skid Tester, Ribbed and Smooth Tires, Orthogonal Regression, Pavement Friction Management	18. Distribution Statement		
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EXECUTIVE SUMMARY

This report presents the research effort to explore the use of continuous friction measurement equipment (CFME) as a tool for pavement friction management to be incorporated into the North Carolina Department of Transportation (NCDOT) Pavement Management Program to produce a stronger Safety Improvement Program. CFME data could supplement and/or replace the existing locked-wheel tangential friction measurements and provide critical details to better understand road departures, wet crashes, and overall traffic performance and safety along ramps, loops, curves, and super-elevated sections where assessing friction using traditional methods is difficult. The more-detailed data that result from such efforts could help to better identify the most appropriate and effective treatments and better define the limits of the needed treatment.

Testing included measurements with the locked-wheel trailer currently used by NCDOT, a Grip Tester, and a Side-Force Coefficient Routine Investigation Machine (SCRIM). The researchers took measurements with the three devices on common pavement types, overlays, and surface treatments on various highways in the state. The results from the three different machines and methodologies were compared, and guidance for future implementation is provided.

The research products include:

1. A comparison of friction obtained from the three different machines and methodologies, including continuous average friction values by pavement type for all the roadway geometries tested (curve/ramp/loop/super-elevated section/section on grade).

2. Recommendation and guidance with regard to the feasibility of collecting continuous friction and macrotexture data to define investigatory friction and macrotexture levels to support the state's pavement friction management program.

The main conclusions of the review of practice and analysis of the data collected as part of the study are the following:

- The direct results of the comparison showed that it is possible to interconvert Grip Number (GN) and SCRIM Reading (SR) measurements with locked-wheel skid tester (LWST) measurements but the correlations are not very strong. This is consistent with the results of several reviewed international efforts.

- Macrotexture is a very important parameter for understanding the pavement's full frictional properties, especially for those devices that are insensitive to it (such as the LWST with a ribbed tire). There is significant consensus on the impact of macrotexture on total crashes.

- The development and implementation of a Pavement Friction Management program would benefit from the collection of continuous friction and macrotexture data. This can facilitate the definition of investigatory friction levels that can be used to flag sections with marginal friction levels based on crash trends. In addition, the cost of data collection

per mile is lower than the traditional approach and provides a better characterization of the pavement frictional properties.

Based on the stated conclusions the following recommendations are provided:

- NCDOT should investigate the feasibility of collecting macrotexture data to complement the agency's friction data collection. This will allow areas with potentially deficient macrotexture to be identified and investigated at the project level and corrected, if necessary, before the occurrence of wet-weather crashes.

- NCDOT should also investigate the feasibility of implementing a proactive friction management program that uses a CFME with macrotexture measurement capabilities to define threshold investigatory levels and use safety performance functions (SPFs) to identify sites with the highest potential payoff for friction improvement.

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1. INTRODUCTION

Research Needs and Significance

Pavement friction is important for maintaining safe driving on highways, particularly on horizontal curves, ramps, intersections, and elevated surfaces. Traditionally, pavement friction has been measured using a locked-wheel skid tester (LWST), but this approach has some known limitations, particularly testing on curves and short roadway segments. Recently, new tools and processes have emerged that provide detailed continuously measured friction values that can supplement and/or replace locked-wheel tangential friction measurements.

In June 2010, the Federal Highway Administration (FHWA) issued Technical Advisory 5040.38, Pavement Friction Management (PFM), which provides guidance to highway agencies on developing or improving Pavement Friction Management Programs (PFMPs). The guidance focuses on ensuring that agencies design, construct, and maintain pavement surfaces to provide adequate and durable friction properties to reduce friction-related crashes in a cost-effective manner. The advisory also recommends Continuous Friction Measurement Equipment (CFME) as "an appropriate method for evaluating pavement friction on US highways, with an advantage over the locked-wheel method because of its ability to operate continuously over a test section and the better relationship to braking with anti-lock brakes" (FHWA, 2010).

Although North Carolina has a strong Pavement Management Program and a strong Safety Improvement Program, the friction values currently available in its Pavement Management System were measured using the traditional LWST approach. As Technical Advisory 5040.38 suggests, friction data from CFME may be better suited to identifying road sections that have inadequate friction values for the actual friction demand and consequently improving safety outcomes.

Research Objective

The objective of this research was to explore the use of CFME for pavement friction management and the possibility of incorporating CFME data into the NCDOT Pavement Management Program to produce a stronger Safety Improvement Program. Detailed data from continuous friction measurement tools could allow a better understanding of road departures, wet crashes, and overall traffic performance and safety along ramps, loops, curves, and super-elevated sections that have been difficult to assess for friction. Such an improved understanding, in turn, can then help to better identify the most appropriate and effective treatments and better define their limits.

With these goals in mind, the research team evaluated and compared two CFME types of friction testing devices that can overcome the limitations of the LWST method, the Sideways Force Research Investigatory Machine (SCRIM) and the Grip Tester, and examined methods to compare the friction values produced by each. The results of that research are supplemented with guidelines for defining PFM investigatory and critical friction limits, and implementing continuous friction testing technology by NCDOT.

Report Organization

This report is composed of six chapters. Chapter 1 presents the needs and objectives. Chapter 2 summarizes the literature review that the research team conducted about the effect of pavement surface characteristics on roadway crashes, friction/texture–crash relationships, and friction and texture testing equipment and methods (see appendix for the full literature review). Chapter 3 describes the test sections and the equipment used to take the friction and texture measurements. Chapter 4 explains the comparisons made between the friction measurement devices used and the relationships developed to compare the measurements between them. Chapter 5 provides implementation guidelines on how to implement an effective PFM program in North Carolina. Chapter 6 presents the conclusions of this research and recommendations.

2. LITERATURE REVIEW AND THE RELEVANCE OF THE PROPOSED RESEARCH (SUMMARY)

The Effect of Pavement Surface Properties on Roadway Crashes

In 2008, the FHWA revised the Highway Safety Improvement Program (HSIP), a regulation that requires states to have a process for collecting and maintaining crash, traffic, and highway data, analyze it to identify highway hazardous locations on the basis of accident potential, and conduct engineering studies to solve the problems (23 Code of Federal Regulations Part 924). The vehicle crash database must contain pavement data relevant to and of sufficient detail to identify causal factors (including pavement-related factors) and identify potential high-crash locations.

The role that improved roadway conditions, and particularly pavement surface characteristics (PSCs), have on reducing the unacceptable number of annual deaths and serious injuries has been seriously underestimated in the past, probably due to the statistically significant but weak link between friction (or texture) and total and wet-pavement highway crashes. However, an example of how beneficial increasing the work in this area could achieve, is how the countries of Western Europe have experienced a 59% reduction in fatalities between 1970 and 2004 (from 80,093 to 33,158), compared to the U.S. reduction of 19% (from 52,627 to 42,636) over this period (Transportation Research Board, 2010).

Improving pavement friction can be an effective measure to reduce vehicle crashes. According to an FHWA report, *Desktop Reference for Crash Reduction Factors*, improving pavement friction can reduce crashes by 13% to 20%. In New Zealand, a recent study found an estimated savings in social costs of about NZ$61.5 million for an additional expenditure of NZ$2.4 million per annum in sealing cost, resulting in a benefit-to-cost ratio of 25.6. This demonstrates that the targeted skid resistance management of curves can be a very cost-effective safety measure (Cenek et al., 2011).

In order to improve highway safety, it is important to understand the complexity of linking friction and other PSCs to crashes. Technical Advisory 5040.38 on PFM provides guidance on the elements of, or outputs from, an HSIP, including PSC data (friction and texture) and crash-data analysis procedures.

One method commonly used in the United States to analyze friction and texture data at the network level relies on a Bayesian analysis of safety performance functions (SPFs). The SafetyAnalyst program (distributed as AASHTOWare) uses a similar approach to estimate the benefits of improving a pavement with poor skid resistance. SPFs for state-maintained highways in Virginia were developed for use with the SafetyAnalyst model and were found to fit better than the Interim SafetyAnalyst model based on Ohio data. However, separate models may need to be developed for roads maintained by cities or towns (Garber et al., 2010).

There is also considerable relevant experience outside the U.S. The U.K. began developing test devices for the measurement of skid resistance as early as the 1930s, although the introduction of material standards was not until the 1970s, and routine monitoring of skid resistance really began in the 1980s. Accident studies carried out prior to the introduction of these standards indicated a relationship between skid resistance and accidents, and led to the rather complicated requirements still in place today, with the level of skid resistance (including ranges of values based on site conditions) specified in 10 different categories, corresponding to different levels of friction demand. It is notable that other countries that have followed the U.K.'s approach (e.g., Australia, New Zealand) have introduced considerable simplifications.

Most highway crashes involve multiple causative factors, although crash investigations have consistently shown a basic link between crashes and pavement surface conditions and characteristics, such as friction and texture. The link is strongest when wet pavement conditions exist in conjunction with low friction levels and moderate-to-high traffic speeds, but there are also indications that dry pavements with inadequate friction can adversely affect the number or rate of roadway crashes.

The studies reviewed give particular attention to measurement equipment and methods that appear to have better crash prediction capabilities (i.e., provide particularly strong links between measured friction and crashes) for a variety of roadway conditions and circumstances (e.g., asphalt and concrete pavements, a range of macrotextures, different traffic compositions, and different climate zones). Such insights are highly valuable in the selection of a CFME device and the establishment of investigatory friction/texture levels as part of a PFM program.

The review examined the links between friction/texture and crashes. The studies reviewed always involved the use of only one piece of equipment (e.g., ASTM E 274 locked-wheel tester, SCRIM), and a corresponding friction/texture measurement index, such as FN or side-force coefficient [SFC]). None of the previous studies directly evaluated or compared two or more friction/texture measurement devices in terms of their ability to predict crashes (total or specific types) or crash severity levels (fatal, serious injury, property damage only).

Guidance on appropriate levels of friction and texture can be obtained from those studies. For example, the Ohio evaluation (Larson et al., 2008) provides investigatory levels of friction for both locked-wheel test tires and minimum macrotexture levels, at both an intervention and an investigatory level. New Zealand's specification T10 does the same (New Zealand Transport Agency, 2010).

Testing Equipment/Methods: Friction and Texture

The ASTM E-274 locked-wheel skid trailer, which has been the standard in the U.S. since about 1965, is used by all states except Arizona. When properly maintained and calibrated, it is considered very reliable and repeatable, as several studies have shown (Choubane et al., 2006; Fernando et al., 2013). However, this is not always the case, prompting recommendations to "have trailers calibrated at the same calibration center to further reduce variations" (Corley-Lay, 1998). Although continued use of this test method allows continuity of historical data, the method may be less sensitive to changes in friction than other currently available devices and, as expressly stated before, it has several limitations, including testing on curves and short roadway segments. Because all friction test methods can be insensitive to macrotexture under specific circumstances, it is also recommended that friction testing be complemented by macrotexture measurement (FHWA, 2010).

A widely used approach to measure friction on runways is CFME (Federal Aviation Administration). One advantage of CFME over the traditional ASTM E-274 test method is that friction is measured continuously rather than as an average value over several hundred feet. In 2015, the SCRIM was brought to the U.S. for the first time. It is used in the U.K. and at least a dozen other countries. The experiences in the US using a similar technical approach as that used in the GPF will be of great interest to this project to consider for future implementations.

Since the slip speed of the SCRIM is low, SCRIM skid resistance is dependent on the pavement microtexture (as measured by friction testing equipment at low speeds). The SCRIM also uses a high-speed laser device to measure macrotexture, in particular, mean profile depth (MPD). Good microtexture is needed on all pavements, but macrotexture is particularly important at higher speeds to assure good skid resistance and to minimize the hydroplaning potential on wet pavements, particularly with flat grades or areas with ponded water.

Research is underway in the U.S. and Europe to optimize surface texture, which has a major impact on safety, noise, and rolling resistance (energy use), but safety considerations should be given the highest priority. The TYROSAFE (TYre and Road surface optimization for Skid resistance And Further Effects) project in Europe identified needs for future research and proposed a way forward in order to optimize three key road properties: skid resistance, rolling resistance, and tire/road noise emissions (http://tyrosafe.fehrl.org). Another project, MIRIAM, is looking in more detail at reducing CO_2 emissions and rolling resistance (which is a function of macrotexture) and is sponsored by 11 countries in Europe and the California Department of Transportation (Caltrans). These studies agree on the need for more accurate descriptors of macrotexture that better address these issues than the MPD value currently used.

The most critical deficiency in current practice is the inability to directly relate pavement surface conditions (and specifically friction and macrotexture) to crash rates. The Ohio Pavement Friction Study showed that the wet/total crash ratio is a better predictor of crashes than either friction or macrotexture independently. The wet/total crash ratio can also be monitored annually to assess whether the overall condition of the highway system is being improved. However, this is a reactive approach.

There is also a serious need to predict friction and macrotexture properties during mix design, when the mix can be adjusted to meet frictional demand at the project location. The detailed information used to develop mix-specific performance equations can then be used to predict (and accurately monitor) the substantial benefits that can be expected from skid-resistant surface mixes and surface treatments. Additional research on blending aggregates to produce high-friction pavement surfaces in lieu of greater quantities of more expensive high polished stone value (PSV) aggregates is likely to be extremely cost effective.

3. DATA COLLECTION AND TEST EQUIPMENT

Routes Surveyed

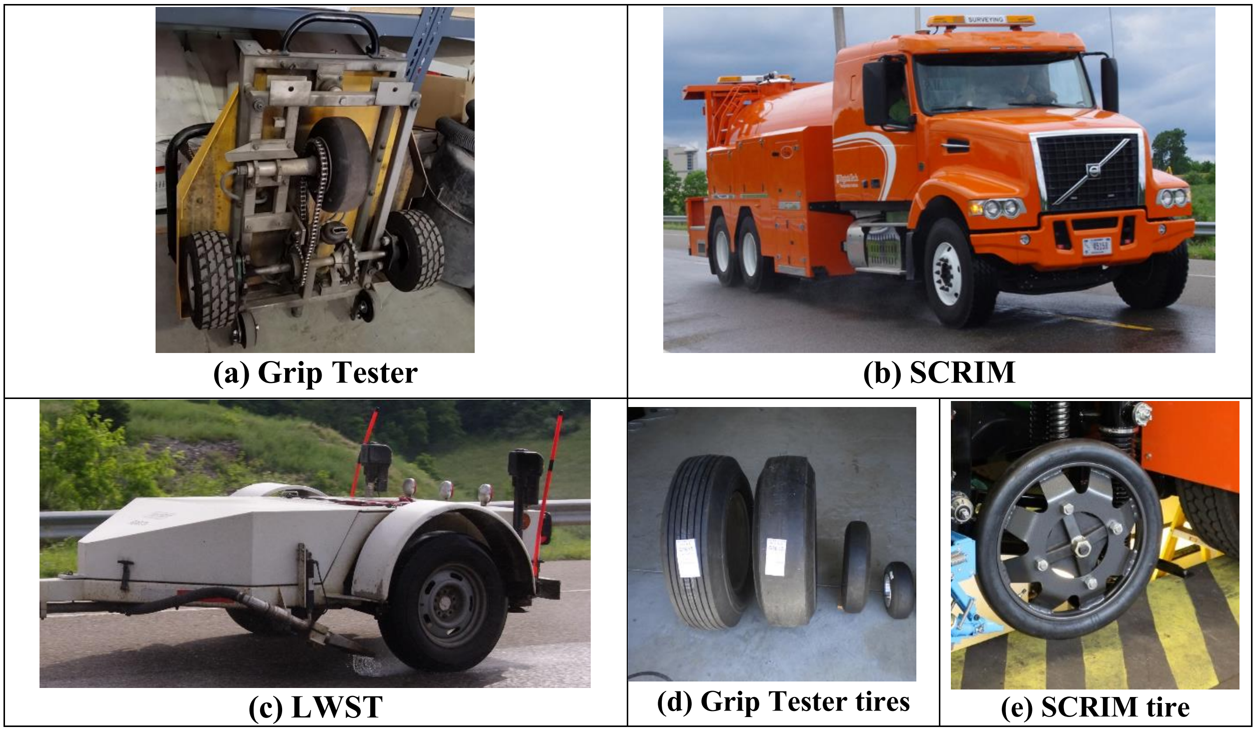
The research team conducted friction testing on 17 different roadway loops using the SCRIM and Grip Tester. Each loop included one or more highway sections. The pavement surfaces tested in each loop fell into four general groups: dense graded asphalt concrete (DGAC), open graded friction coarse (OGFC), bituminous surface treatment (chip seal), and Portland Cement Concrete Pavement (PCCP).

The pavements in the DGAC group had the following types of mixes: ultra-thin bonded wearing course (UBWC), heavy-duty surface mix (HDS), and a variety of Super Pave mixes (S9.5 A, B, C, and D). These pavement types were combined into one group because the available information was not complete and differentiating between them was not possible by viewing the videos available. Table 3-1 lists all 17 loops, their length in miles, and the amount of data collected with the Grip Tester and the SCRIM. Additionally, NCDOT used the LWST to perform both a ribbed tire test, and on two loops (H and L) a smooth tire test, every 0.5 miles.

Table 3-1. Miles of roads measured for NCDOT with the SCRIM and Grip Tester

NCDOT Loops for Friction Testing					*SCRIM*		*Grip Tester*	
Day	*Loop*	*Sections*	*Miles*	*Day Total (miles)*	*km*	*mile*	*meter*	*mile*
1	A	8	39.3	146.8	58.38	36.3	57,812	35.9
	B	10	35.5		57.13	35.5	51,985	32.3
	C	12	37.1		54.50	*33.9	58,854	36.6
	D	8	34.9		51.19	*31.8	52,070	32.4
2	E	9	37.0	103.2	59.42	36.9	0	*0.0
	F	14	37.1		59.60	37.0	56,180	34.9
	G	1	29.1		47.30	29.4	46,470	28.9
3	H	8	34.1	118.0	54.64	34.0	54,671	34.0
	I	14	35.3		59.05	36.7	59,223	36.8
	J	14	30.9		57.79	35.9	57,470	35.7
	K	1	17.7		28.58	17.8	28,393	17.6
4	L	11	41.9	138.5	63.81	39.7	63,736	39.6
	M	9	40.1		64.20	39.9	64,033	39.8
	N	10	36.2		57.81	35.9	57,651	35.8
	O	5	20.3		32.45	20.2	21,388	*13.3
5	P	5	34.1	70.6	50.34	*31.3	54,363	33.8
	Q	1	36.5		49.65	*30.9	29,612	*18.4
TOTALS:			577.1	***577.1***	***905.84***	***563.0***	***813,911***	***505.8***

The devices used are shown on Figure 3-1. The LWST mostly used a standard ribbed tire (ASTM E501), but some of the testing used the standard smooth tire (ASTM E524), both of which are shown in Figure 3-1(d) and compared with the SCRIM tire Figure 3-1(e).



(a) Grip Tester **(b) SCRIM** **(c) LWST** **(d) Grip Tester tires** **(e) SCRIM tire**

Figure 3-1. Friction measurement equipment

Both the Grip Tester and the SCRIM continuously measure wet pavement friction. However, they use different test tires and different slip ratios (and slip speeds); as a result, they produce different friction measurements. The Grip Tester uses a single test wheel equipped with a smooth-tread tire (ASTM E1844) oriented longitudinally to the direction of travel. A chain connected to the axle of the test wheel gives it an approximately 16% fixed-slip ratio. The test wheel configuration allows the Grip Tester to measure a longitudinal friction coefficient, referred to as a Grip Number (GN), at 3-foot (0.914-m) intervals.

The SCRIM uses a free-rolling test wheel oriented, or jawed, 20 degrees from the direction of travel. This produces a 34% slip ratio for the side-force coefficient, known as the SCRIM Reading (SR) (Hall et al., 2009; Highways England, 2015). In addition to measuring friction, the SCRIM used for this study also measures macrotexture (MPD, in mm), grade (%), cross-slope (%), and horizontal curvature (1/m). The SCRIM collects friction and texture data every 100 millimeters, which it then averages every 10 meters.

Data Processing

Grip Tester and SCRIM

The acceptable range for performing Grip Tester and SCRIM friction measurements is 15 to 55 mph (25 to 85 km/h). The water flow for the Grip Tester has to be above 2 gallons/minute, although it will adapt dynamically to the speed. The SRs were averaged every 10 meters. The GNs were reported every 3 feet. The metric system was used to synchronize all the data, using averaging every 10 meters. However, the data do not align perfectly, which could possibly result in greater biases at short distances. To account for this, the GNs and SRs were also averaged every 100 meters for comparison between their measurements.

Locked-Wheel Skid Tester

After pairing the measurements of the Grip Tester with those of the SCRIM, the LWST was synchronized with the SCRIM using Global Positioning System (GPS) coordinates. This helped to adjust the distances for every measurement recorded with the LWST in order to best fit the distances of the SCRIM. To better match the measurements taken with the SCRIM and Grip Tester, each was separately averaged over the 30-meter footprint (15 m before and after) of each LWST measurement.

Two issues are worth bringing up for the NCDOT LWST data. The first issue is that the output water dispensed at each test, or water flow rate, reported by the system was not within the range recommended by the standard (±10 %). There were 1,250 tests done with the ribbed tire; 754 tests were okay, 490 tests were outside the allowable range, and 6 tests failed. There were 133 tests done with the smooth tire; 131 tests were okay, and only 2 failed. The majority of the tests that were outside the water flow range (462 of 490, or 94%) were taken on August 15, 2016, and August 16, 2016, and consistently reported more water. The 28 (6%) remaining tests that were outside the water flow range were done afterwards and reported less water than the allowable range, so it can be inferred that the equipment was fixed on August 17, 2016.

The second issue concerns the speed corrections made by the skid-tester system. The manufacturer-provided software computes what is referred to as the Skid Number Correction (SN Corr), and it provides two ways to achieve this (see Figure 3.2). The first method is to use a Speed Correction Factor that computes the correction to the standardized speed of 40 mph by applying it to the difference of the speed at which the test was done and 40 mph (see equation 10). Furthermore, there are two more options with this method, using a speed grid and using a speed correction factor directly.

The second method is to use what is referred to as the Transportation Research Center (TRC) SN correction. The TRC, located in Columbus, Ohio, is one of the locked-wheel skid tester calibration centers in the U.S. (the other is at Texas A&M in College Station, Texas). When skid testers are calibrated using the TRC method, the values for the gain and offset parameters for each type of tire have to be updated in the software in order to correct measurements done at speeds different from 40 mph.

It seems that neither of these methods has been updated for the NCDOT skid tester. When the results of the measurements are run, the corrections to obtain the equivalent 40 mph skid numbers (SN40R or SN40S) are not being processed correctly because the correction factors it produces vary with almost each measurement. It is important to remember that "there should be an expected decrease in SN with increasing speed" (Corley-Lay, 1998). In order to correct this, it would be advisable to calibrate the skid tester and input the correct values in the processing software so that the values can be corrected for speed variations.

Figure 3.2 below is a screenshot of the computer program for International Cybernetics Corporation skid testers like the ones that NCDOT uses. The values shown are not the same ones that NCDOT would use, given that these values have to be specific to each unit at the time of calibration. The data provided were processed using speed correction factors the research team obtained from locked-wheel skid tests at the Virginia Smart Road in Blacksburg (Flintsch et al., 2010).

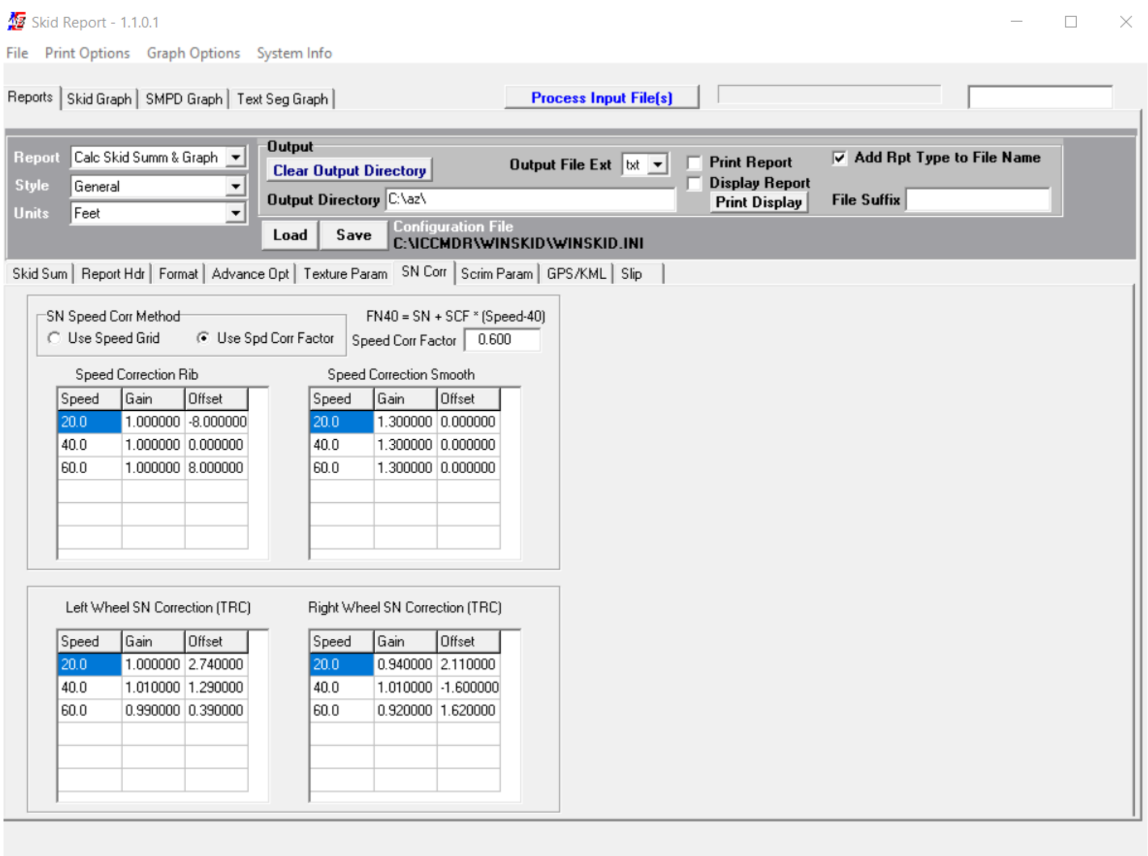


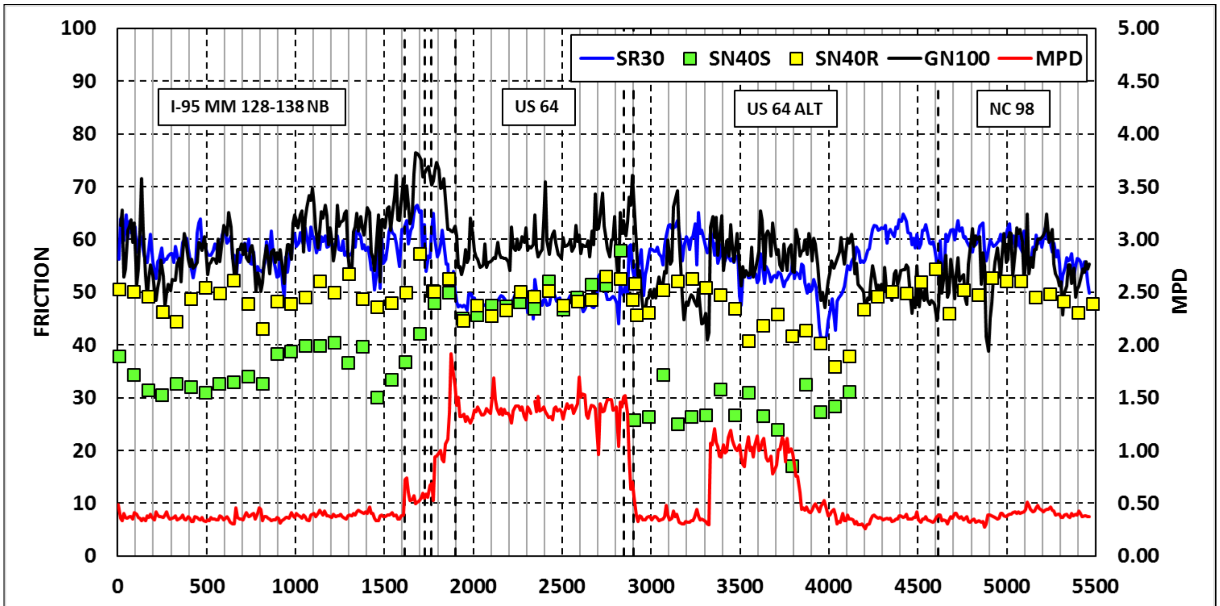
Figure 3-2. Screenshot of Speed Correction Factors window for ICC skid testers

Pre-Analysis: Friction and MPD Sensitivity

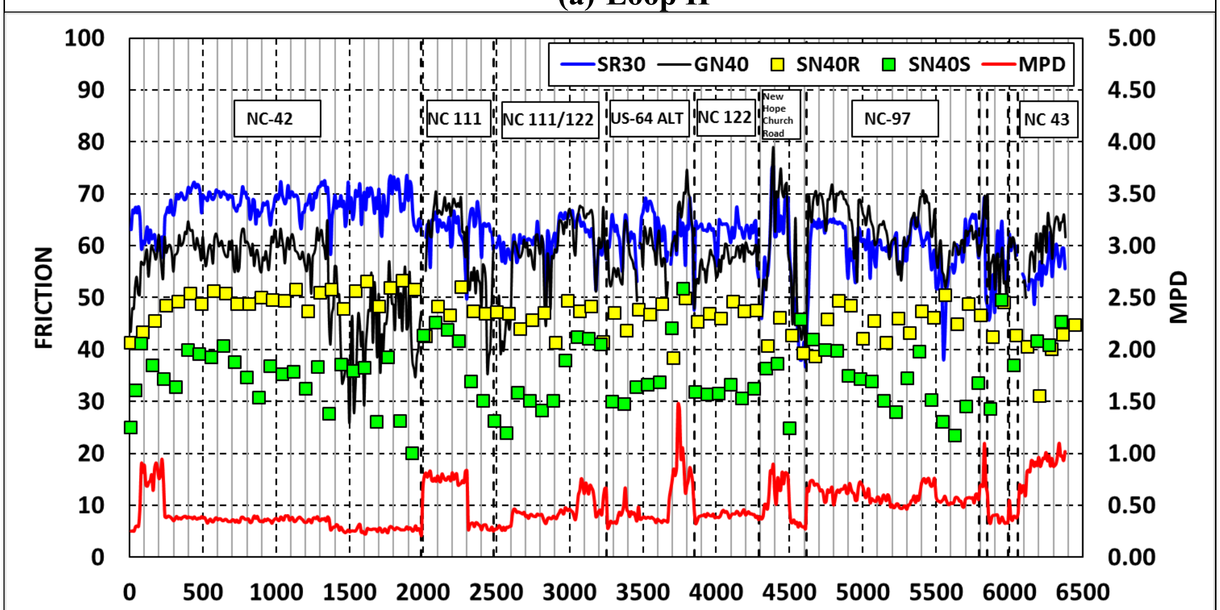
Differences in the design and configuration of the testing equipment and their test tires creates different sensitivities to speed and MPD. According to Hall et al. (2009), the LWST standard ribbed tire is *insensitive* to MPD, whereas the standard smooth tire is sensitive to MPD. Fuentes et al. (2014) explored this further by investigating the speed dependence of friction measured with the ribbed tire and the smooth tire on pavement surfaces with different levels of MPD. Fuentes et al. (2014) 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 3-3 compares the friction and MPD measured on 2 of the 17 sections (Loops H and L), which had LWST measurements with both the ribbed and the smooth tire.

The figure shows that where there are changes in MPD, there are also changes in the smooth tire measurements (SN-S). However, there do not appear to be any significant changes in the ribbed tire measurements (SN-R) for the same changes to MPD. In general, the figure appears to support Hall et al.'s (2009) statement that SN-R is relatively insensitive to changes in MPD.

Fifteen more figures similar to those shown on Figure 3.3 were made for the other loops. They will help the NCDOT Traffic Engineering (T&E) branch analyze differences in friction and texture measurements on all the routes. The video and raw data files have also been provided to T&E along with the installation modules for both the RAVCON and the SKID VID software packages provided by WDM Limited for use on all the data collected.



(a) Loop H



(b) Loop L

Figure 3-3. Comparing equipment sensitivity to MPD

Methodology

In simple linear regression (SLR), a response (y) is estimated as a linear function of some fixed, independent variable (x). In SLR, x is a fixed variable with minimal measurement error, whereas y is treated as a normally distributed random variable with unobserved measurement error. As a result, at every value of x, the unobserved measurement error is estimated as the difference between the observed (i.e., true) value and the estimated value of y. The strength of an SLR model is estimated with the coefficient of determination (R^2). The value of R^2 indicates the proportion of the variation in *y* that is explained by *x*. R^2 ranges from 0 to 1, where a value of 1 explains all of the variation in *y*, and 0 indicates a model that explains no variation in *y*. Unfortunately, SLR does not apply to situations where both *x* and *y* have equal amounts of measurement error.

When a device measures friction, each measurement will contain unobserved error (i.e., noise). If both *x* and *y* represent different devices used to measure friction, then neither *x* nor *y* will be fixed and both will have random measurement error. Since both *x* and *y* have random measurement error, either term can be estimated as a linear function of the other term using orthogonal regression (OR). In OR, the slope and intercept can be estimated using Equations 1 and 2, respectively. The slope (β_1) is estimated as a function of the corrected sum of cross products of *x*, *y*, and *x* and *y*. However, the value of $\hat{\beta}_1$ also depends on θ, which is the ratio of the variance of *y* to the variance of *x*. Finally, the intercept (β_0) is estimated as a function of the estimated slope ($\hat{\beta}_1$), and the average of *x* and *y* (Carroll and Ruppert, 1996).

$$\hat{\beta}_1 = \frac{S_{yy} - \theta S_{xx} + \sqrt{(S_{yy} - \theta S_{xx})^2 + 4\theta S_{xy}{}^2}}{2S_{xy}} \tag{1}$$

$$\hat{\beta}_0 = \bar{y} - \hat{\beta}_1 \bar{x} \tag{2}$$

In this study, repeatability was not tested with any of the three devices; therefore, all three are assumed to have similar measurement error (i.e., equal variance); therefore, $\theta = 1$. Furthermore, the strength of the OR model is estimated using simple correlation. The value of the correlation coefficient indicates the strength of the linear dependency of both terms, where values closer to ±1 indicate a *perfect positive* (or *negative*) *linear relationship* and 0 indicates *no linear relationship*.

4. FRICTION MEASUREMENT COMPARISONS

Grip Tester and SCRIM Comparison

Figure 4.1(a) and (b) compare GN and SR using their respective standardized friction-speed adjustments. The adjustment for travel speed corrects GN to 40 mph (64 km/h) and SR to 30 mph (48 km/h), respectively. GN is measured at travel speed (*v*) and corrected to GN40 using a speed correction factor (SCF) of 0.6/mile (see Equation 3). SR is corrected to 30 mph (50 km/h) using Equation 4, which is specified in the *British Design Manual for Roads and Bridges* (Highways England, 2015). Additionally, the plots show that the correlation was not changed significantly by averaging over 100 meters compared to 10 meters. This suggests that the biases associated with the amount of averaging used to synchronize the data were minor.

$$\mathrm{GN40\ mph} = \mathrm{GN(v)} + \mathrm{SCF} * (\mathrm{v} - 40) \tag{3}$$

$$\mathrm{SR30\ mph} = \mathrm{SR(50km/h)} = \mathrm{SR(v)} * (-0.0152 * \mathrm{v}^2 + 4.77 * \mathrm{v} + 799)/1000 \tag{4}$$

According to Hall et al. (2009), factors that affect the amount of available friction include pavement surface characteristics, the vehicle, the tire, driving characteristics, and the roadway environment. The way these factors interact can influence the value of friction measured by different equipment. In order to understand how these factors influence friction measurements, highway agencies have experimented with different tire-pavement friction models in order to harmonize friction measurements so that the measurements can be converted to a common value (PIARC, 1995).

The way that wet friction varies with travel speed is primarily influenced by MPD (Hall et al., 2009). Most models that define this relationship incorporate slip speed (S), which is the relative speed between the tire circumference and the pavement. The Penn State model (Equation 5) relates the friction F(S) measured at slip speed (S) to S_0 and F_0, where S_0 and F_0 are MPD-dependent constants for speed and friction (at zero speed for each of the four testing methods), respectively (Hall et al., 2009; Henry, 2000; PIARC, 1995).

$$\mathrm{F(S)} = \mathrm{F_0} e^{\left(\frac{-\mathrm{S}}{\mathrm{S_0}}\right)} \tag{5}$$

The PIARC model, or International Friction Index (IFI) was derived from the Penn State Model (Henry, 2000). The PIARC model (Equation 6) replaced F_0 with a constant derived at different slip speeds “S” using a smooth tire. Finally, FR60 replaced F_0 as a “measure of safety,” representing “a typical average stopping speed for vehicles” at a slip speed of 60 km/h (PIARC, 1995).

$$\mathrm{FR60} = \mathrm{F(S)} e^{\left(\frac{\mathrm{S}-60}{\mathrm{S_P}}\right)} \tag{6}$$

In Figure 4-1(c) and (d), the GN and SR IFI FR60 conversions are shown (see Equations 5 and 6). These two plots show that converting the measurements to FR60 by including the macrotexture produces a higher correlation than adjusting directly for travel speed. FR60 increased the correlation by 54%. Adapted from the plot in Figure 4-1(a), Equation 7 can be used to convert SR30 to GN40. On the other hand, when friction is corrected using IFI, Equation 8 (adapted from Figure 4-1[b]) can be used to convert FR60(SR) to FR60(GN).

$$GN40 = 2.62 * SR30 - 99.39 \tag{7}$$

$$FR60(GN) = 1.60 * FR60(SR) - 24.84 \tag{8}$$

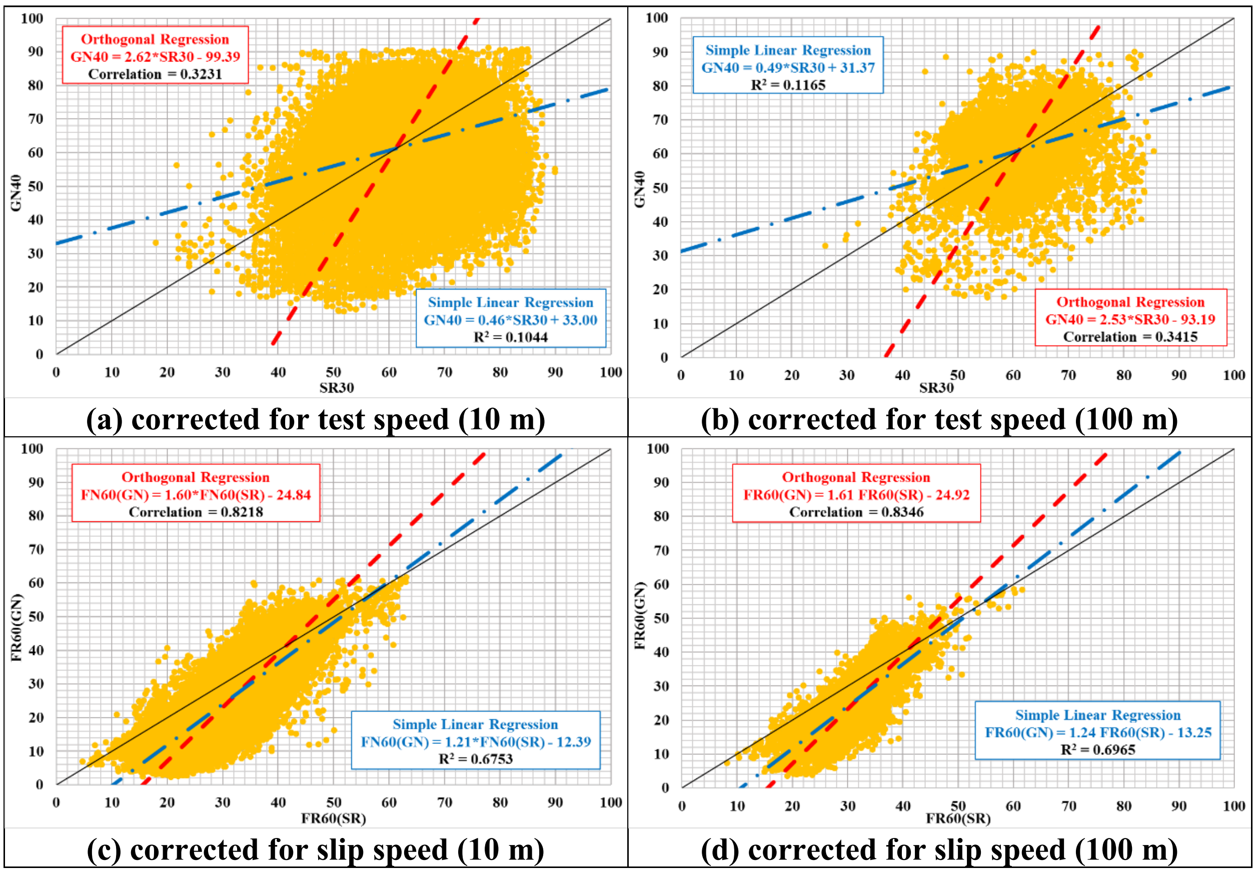


Figure 4-1 Comparison of Grip Tester and SCRIM

Locked-Wheel Skid Tester

Ribbed Tire Comparisons

The friction measured using an LWST standard ribbed tire was compared to both GN and SR. The friction from the LWST ribbed tire was corrected to 40 mph (64 km/h) using Equation 10. For Equation 10, the SCF was selected based on the results from a study conducted on the Virginia Smart Road. In that study, Flintsch et al. (2010) tested friction using an LWST fitted with both types of standard tires at different speeds on various pavement surfaces. Based on

Flintsch et al. (2010), for the standard ribbed tire, the best average SCF was found to be 0.5 for most pavement surfaces.

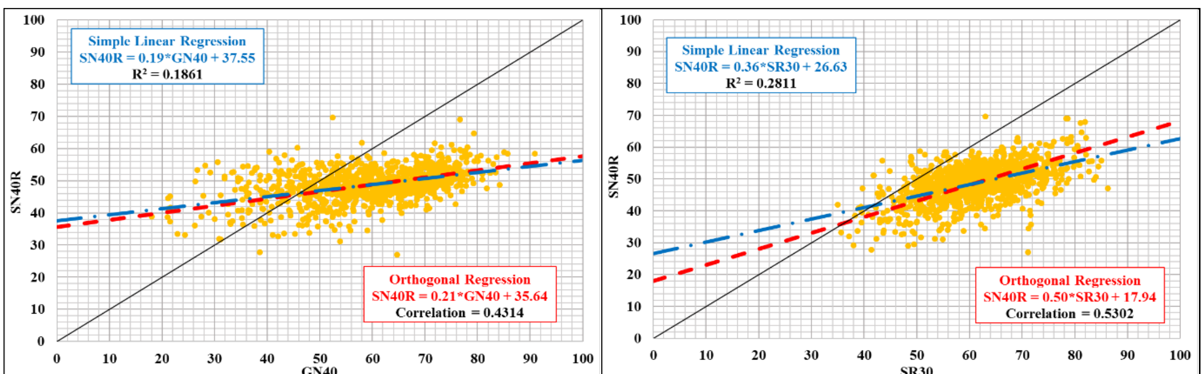
$$\mathrm{SN40R} = \mathrm{SN(v)} + \mathrm{SCF} * (\mathrm{v} - 40) \tag{10}$$

Figure 4.2 compares the friction measured with the LWST ribbed tire to GN and SR. The figure shows that SN40R is more highly correlated with SR30 than with the GN40. Figures 3.3(a) and (b) show that the LWST ribbed tire is less sensitive to changes in MPD. Likewise, the strength of the correlation between the LWST and SR suggests that the SCRIM is also less sensitive to changes in MPD. This finding corroborates previous studies from the U.K. that found that the SCRIM friction measurements are "independent of their macrotexture" because of the "very little correlation between SR and MPD" (Roe et al., 1991; Roe et al., 1998).

Based on the results shown in Figure 4-2(a) and (b), Equations 11 and 12 can be used to obtain a predicted SN40R value from the GN40 and SR30 measurements, respectively. These equations should be used with caution since the highest correlation of the data is approximately 0.5.

$$\mathrm{SN40R} = 0.21 * \mathrm{GN40} + 35.64 \tag{11}$$

$$\mathrm{SN40R} = 0.50 * \mathrm{SR30} + 17.94 \tag{12}$$



(a) LWST Ribbed vs. Grip Tester **(b) LWST Ribbed vs. SCR**

Figure 4-2. Comparison with LWST ribbed tire

Smooth Tire Comparisons

For the final comparison, the LWST smooth tire measurements were compared with the measurements of the Grip Tester and the SCRIM using a smaller sample size. The friction measurements with a smooth tire were also converted to FR60 after being corrected for vehicle travel speed. Figure 4-3 compares the standard smooth tire to GN and SR. It also confirms the results shown earlier in Figure 3-1, where the LWST standard smooth tire was also more sensitive to changes in MPD, and the Grip Tester shows the higher correlation compared to the SCRIM. Using the regression models shown in Figure 4-3(a) and (b), Equations 13 and 14 can be used to predict FR60(SN) from FR60(GN) and FR60(SR), respectively, with very low correlations.

$$\mathrm{FR60(SN)} = 0.66 * \mathrm{FR60(GN)} + 21.00 \tag{13}$$

$$\mathrm{FR60(SN)} = 2.13 * \mathrm{FR60(SR)} + 27.12 \tag{14}$$

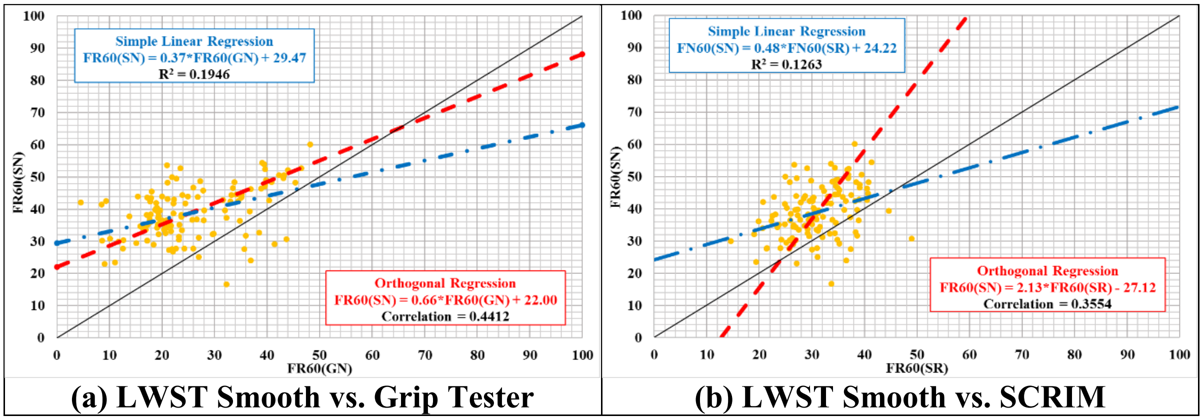


Figure 4-3. Comparison with LWST smooth tire

Texture Sensitivity

Figure 4-4 shows the difference of the sensitivity of the friction devices to the macrotexture of the different kinds of pavements tested. In the first two plots, all of the sections that were tested with the LWST ribbed tire are shown by pavement type against their respective MPD values, showing that both the LWST-R (Figure 4-4[a]) and the SCRIM (Figure 4-4[b]) do not have the sensitivity to differentiate this property in their respective friction measurements. A few of the older DGAC measurements were characterized as “Old DGAC,” and that is why their MPD values are so high. In some cases their MPD were even higher than those measured for OGFC pavements.

It is interesting to note that the LWST ribbed tire measurements are bundled in a very small range of values, even though we know that higher MPD values should contribute to friction, confirming again that this tire is very insensitive to macrotexture. The SCRIM values for these same sections are also insensitive to the higher macrotexture and are impossible to differentiate from those with lower macrotexture, although the range of values is more open, thus being more sensitive than the ribbed tire example. It is also interesting to note that the SCRIM friction values for the OGFC were actually the lowest values measured, thus confirming its insensitivity to this property, which again confirms that this device truly requires the macrotexture laser to measure MPD.

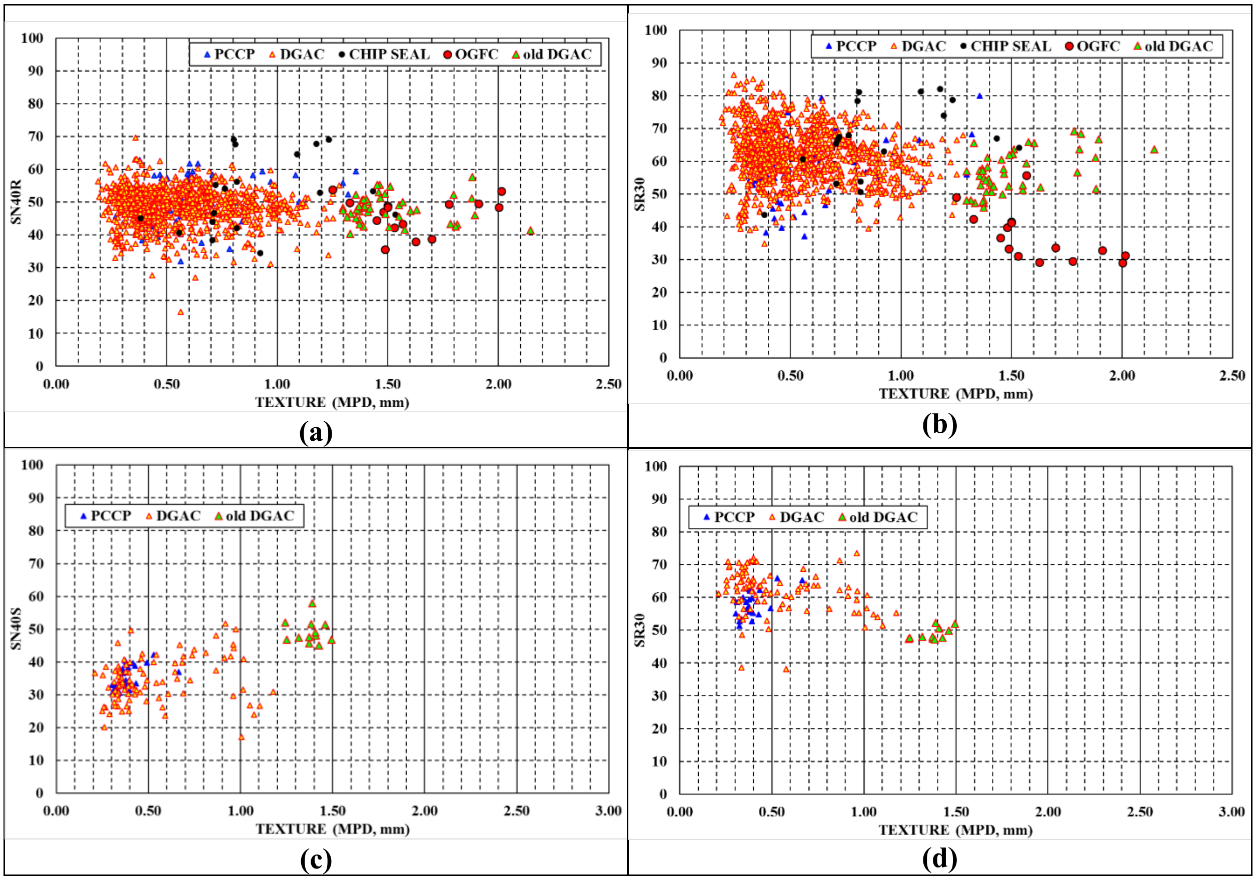


Figure 4-4. Comparison of LWST (ribbed and smooth) and SCRIM

The last two plots represent all of the sections that were tested with the LWST smooth tire and are shown by pavement type against their respective MPD values. It was unfortunate that in the sections where the smooth tire was used (Loops H and L) there were not any OGFC or chip seal sections, which is why they are not shown. The LWST-S (Figure 4.4[c]) and the associated SCRIM measurements for these sections (Figure 4.4[d]) tell a very different story. It is clear that the smooth tire has a very high sensitivity and can differentiate MPD in its respective friction measurements, as shown in the few older DGAC measurements that were characterized as “Old DGAC.” The SCRIM was again unable to differentiate those sections and again represented some of the lowest values measured, confirming again its insensitivity to this property.

Microtexture, Macrotexture, Friction and their effect on roadway crashes

The lack of sufficient friction between the tire and pavement, especially during wet weather conditions, is one of the factors that can increase the risk of car crashes. Therefore, improving the friction of a pavement can be an effective measure to reduce vehicle crashes. However, the concept of “good” pavement friction is not straightforward and easy to understand because there are several things that affect a vehicles’ ability to slow down or stop under wet conditions.

Some of these things are outside the control of a DOT; e.g. the vehicle's braking system, the age, condition, inflation pressure, depth and tread pattern of the tires in a vehicle, etc. Similarly, the DOT has no control over a driver's reaction time, alertness, or speed at which they are driving. An agency only has control over the physical factors that affect the friction such as the geometrics (vertical and horizontal curves, cross-slope), design/posted speed limits, sight distances, and the surface texture of the road (Ohio DOT, 2016).

In this report, friction is entirely a function of two components of the surface texture of the road: microtexture and macrotexture. The microtexture of the road surface is what contacts the rubber of the vehicle tire and allows friction from adhesion between the two. 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 (Ohio DOT, 2016).

Findings

Understanding why both microtexture and macrotexture are important and complimentary is necessary to understand what is necessary for a road to have "good friction". Individual states have defined the minimum numbers they consider appropriate. For example, in North Carolina, using a locked-wheel skid tester with a ribbed tire SN40R, the minimum number is 37 (Corley-Lay, 1998). This number is indicative of the microtexture of the road as has already been explained above. However, macrotexture is not measured in North Carolina.

The results of the measurements done on Loop Q highlighted this deficiency, as seen on Figure 4-5. Loop Q is a section of US Route 74 that is located in Richmond and Scotland Counties. The figure shows the results of the locked-wheel skid tester (SN40R), the SCRIM (SR30) and the macrotexture (Mean Profile Depth–MPD). Both friction measurements SN40R and SR30 are indicative of the microtexture of the road whereas the MPD is a direct measurement of the macrotexture.

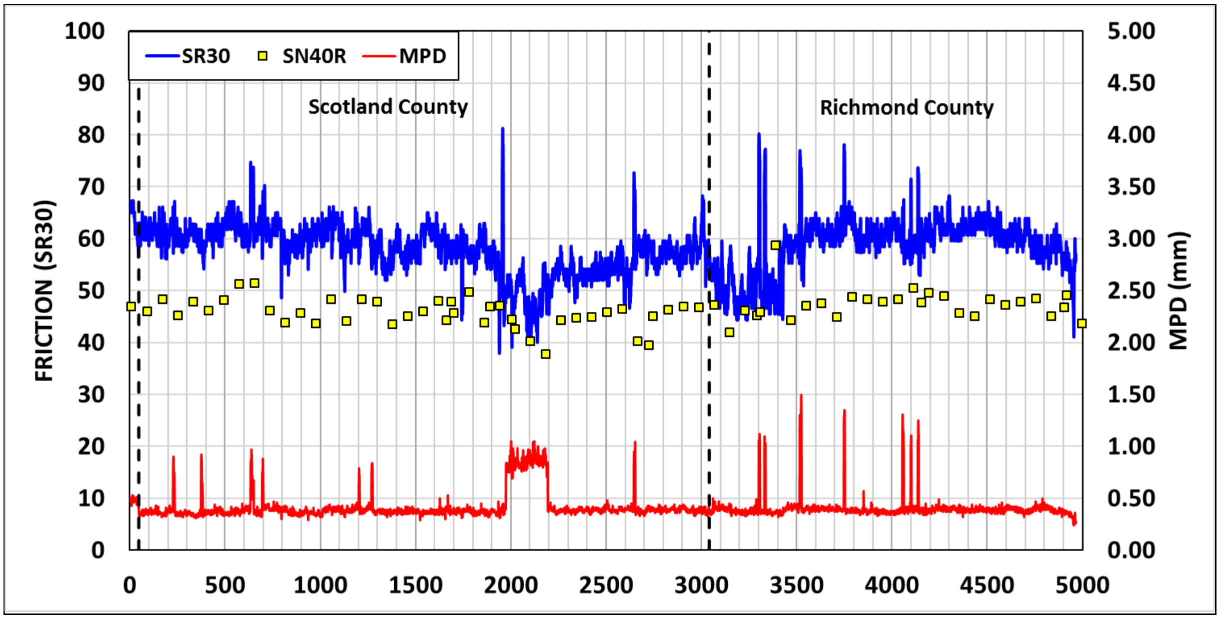


Figure 4-5 Loop Q US Route 74 Scotland and Richmond Counties

For the majority of the section, the MPD is relatively constant around 0.4 mm, except from stations 1,975 to 2,190. These correspond to mile markers 4.896 to 6.585 and they represent the only section that did not have a newer pavement in the full loop and that is why the macrotexture is higher (average 0.80 mm). The two pictures in Figure 4-6 are from the beginning and the end of the older pavement clearly showing the different pavement textures where the macrotexture is higher (speed limit is 45 mph).

Figure 4-6 Loop Q US Route 74 Scotland County ~MP 4.896-6.585

The Traffic Safety Unit made a summary of the number of wet weather crashes that had occurred in the three previous years to the paving of this road and after, which at the time of the macrotexture measurements was only 1.21 years. The results of the analysis are separated by speed limit to better appreciate the effect that the low macrotexture has on the crashes, especially as the speed increases, as is seen in Table 4-1 and Table 4-2 below.

Table 4-1 Crash Analysis for 55 mph sections US Route 74

Speed limit 55 mph		AADT 15,000 – 18,000
Total Length 9.09 miles	Years before – 3.00	Years after – 1.21
Total Crashes	Before = 119	After = 72
Wet Crashes	Before = 33 *(28%)*	After = 21 *(29%)*
Wet/Year/Mile	Before = 1.21	After = 1.91 *(+58%)*
Mix Type S9.5C (2015)	Average friction SR30 = 51.3-57.1	Average Macrotexture MPD = 0.37 – 0.40 mm

Table 4-2 Crash Analysis for 70 mph sections US Route 74

Speed limit 70 mph		AADT 15,000 – 18,000
Total Length 24.10 miles	Years before – 3.00	Years after – 1.21
Total Crashes	Before = 269	After = 234
Wet Crashes	Before = 112 *(42%)*	After = 157 *(67%)*
Wet/Year/Mile	Before = 1.55	After = 5.38 *(+248%)*
Mix Type S9.5C (2015)	Average friction SR30 = 60.4 – 60.5	Average Macrotexture MPD = 0.38 – 0.40 mm

The two tables show an increase in the number of wet weather crashes after the new paving was finished in 2015. The new paving has very low macrotexture values (MPD~0.4 mm) which could be a reason for the spike in wet weather crashes in all sections of US Route 74. Furthermore, because higher macrotexture is needed at higher speeds, the low macrotexture could also be a reason why there is a much higher increase in the number of wet weather crashes in the sections with higher speed limit (58% vs. 248%).

This example shows the need for NCDOT to start collecting macrotexture measurements aside from doing friction measurements with the locked-wheel skid tester with the ribbed tire. One way in which they can indirectly monitor the macrotexture would be to use a smooth tire, but the lack of experience with this will make it more difficult to determine what to do if the skid measurements were lower than expected. Macrotexture measurement should be done especially on new pavements in areas with speeds higher than 50 mph where the researchers believe that the MPD should not be lower than 0.80 mm, and for speeds higher than 70 mph, preferably 1.0 mm after construction. Open Graded mixes, which have even higher macrotexture, would be acceptable too, although these mixes tend to present certain challenges in areas where chemicals are used for winter maintenance.

5. PAVEMENT FRICTION MANAGEMENT IMPLEMENTATION GUIDELINES

The principal deliverable for this project was the comparison of friction values obtained from the different equipment, and the average friction values by pavement condition, type, and any associated feature in the road (curve/ramp/loop/super-elevated section/section on grade). In addition, the research team was to provide guidelines about the feasibility of defining PFM investigatory and critical friction limits, and potential implementation guidance for continuous friction testing technology by NCDOT. These guidelines can enhance information about non-tangent roadway segments and the use of new testing equipment and methods for pavement evaluation that would complement, replace, and/or extend NCDOT's strong pavement management efforts.

Pavement Friction Management Programs

Modern PFMPs require that adequate levels of friction be maintained on all roadway sections based on the friction demand needed for different types of roadway segments. If this approach is used, different friction threshold values or *investigatory levels* can be set based on *friction demand categories*. When friction (and macrotexture) thresholds are not met, a detailed project-level pavement evaluation needs to be done to verify if a raise in the friction level is warranted to reduce the risk (e.g., of roadway departure fatalities and serious injuries). Critical aspects of a PFMP include the equipment used to collect friction data; the processes needed to analyze and interpret skid data, crash data, and the geometric parameters that might influence the vehicle's response; and the comparison of the cost-effectiveness of possible treatments. Furthermore, the PFMP should be an integral part of a network-level systemic approach that involves widely implemented improvements based on high-risk roadway features.

Data Collection

The first step in the implementation of a pilot PFM that is aligned with the DOT's pavement and safety management practices is to compile all the available pavement, inventory, and crash data for the selected network, which includes interstate, primary, and secondary roads, with both Portland cement concrete and hot-mix asphalt pavements and different traffic levels. Additional data have to be collected (friction, macrotexture, and geometry) and processed using a 0.1-mile analysis segment. Friction needs to be standardized for speed; for example, the SCRIM does theirs to 30 mph (50 km/h), whereas the locked-wheel is done to 40 mph (64 km/h).

Crash rates should then be computed to convey the risk for a crash with various severity levels (i.e., fatality, serious injury, and total) occurring along each 0.1-mile segment due to the exposure. That information should be paired with friction data collected using GPS coordinates. Since the distribution of fatality and severe injury crashes with friction follows a very similar trend to the total crashes, the PFMP should focus on total crashes to have a larger sample and assume that a reduction in the total number of crashes will likely result in a reduction in fatalities and serious injury crashes.

Data Analysis

The 0.1-mile segment data need to be divided into friction demand categories based on the factors perceived as having the most influence on the friction-crash relationship. These could include, for example, interstate and divided highways and non-divided highways, with and without events (with curves and/or intersections). Finer levels of aggregation considering other factors, such as traffic and type of pavement, should investigate any other relationships, being careful that sample sizes account for a meaningful analysis.

An analysis of the data should be done to establish data-backed friction thresholds for each friction demand category. Total crash rates instead of the wet/dry crash rates should be considered to take into account all relationships between crashes and both friction and macrotexture for divided and undivided roadways and segments with and without events (intersections and sharp curves).

Once the appropriate thresholds are established, high-crash risk areas can be identified using SPFs and Empirical Bayes (EB) rate estimation from observed crashes. In this process, SPFs incorporating friction and other relevant parameters are developed using the negative binomial model to predict the number of crashes in, for example, a 3-year period for each 0.1-mile road segment. The EB method is then used to produce an estimate of the number of crashes in each segment and the possible crash reduction that can be obtained due to various surface treatments, for example hot-mix asphalt overlays for asphalt pavements, conventional diamond grinding for PCC, and high-friction surfaces on critical locations with both types of pavements.

The overall potential savings of various treatments can then be assessed using potential crash reductions estimated using the final SPF and the EB method and average treatment costs. The results will show potential crash reductions due to the friction-improving interventions, providing very high return on investment.

Equipment Recommendations and Cost Analysis

An assessment of the advantages of using continuous friction measurements versus the traditional LWST sampling approach can be made based on the spatial coverage of friction measurement devices and their costs. The continuous devices provide much higher spatial coverage, thus reducing the chances of missing localized areas with friction deficiencies. The typical LWST measuring practice uses one test per half-mile, sampling approximately only 2% of the surface (120 ft. /5280 ft.). In contrast, the CFME measures the totality of the road, which is needed for a proactive, network-level PFMP, such as in an SPF-EB method.

The importance of having a higher resolution has been illustrated with examples in the presentations that have shown how critical locations can be missed by using current LWST sampling approaches. These critical locations occur in locations such as curves and intersections where there is high demand for friction and texture, more polishing of the pavement because of the braking and turning maneuvers, and where the current methods of measuring pavement friction in North Carolina have limitations.

The following cost comparison is based on cost and productivity estimates for network-level friction measurements using CFME devices that the research team has experience with—the Grip Tester and SCRIM—and the LWST.

The following list details the assumptions made regarding the productivity of the three devices, mostly based on their water capacity, fuel consumption, personnel costs, etc. The cost analysis is dependent on the inputs as outlined below. The inputs are based on existing systems that the research team has experience with and not an optimized configuration that a DOT would investigate for their specific conditions.

1. The typical period for friction data collection in most states in the U.S. is normally from April to October (±150 workdays). Beyond these dates, data collection is not possible.

2. The total NCDOT network consists of 15,000 miles of primary highways and 65,000 miles of secondary highways. These numbers will be used to estimate the costs, and it is assumed that testing the entire primary network and a fraction of the secondary network would be optimal. Two scenarios can be formed: one with a 4-year cycle (25%) and one with a 2-year cycle (50%), so each year either 46,250 or 62,500 miles would be surveyed. (Note: This number can be adjusted when the actual miles of testing are provided.)

3. Daily Production:
    a. NCDOT's E-274 unit can do about 200 tests per tank; assuming four tanks of water/day at 10 tests per mile (testing every 0.1 mile) equals about 60 miles/day.
    b. The Grip Tester has a water tank that allows about 22.5 miles/tank of continuous testing. Assuming also four tanks per day, the Grip Tester will measure 90 miles/day.
    c. The SCRIM has a water tank that allows it to run for 150 miles; a conservative estimate would be at least two tanks/day for 300 miles/day.

4. Annual Production – downtime for calibration, repairs, service, etc., is assumed to be about 20% of the total time for all units. Working with the estimated daily production rates from above, the production for the total 150 days is estimated at:
    a. Locked-wheel (60*150)*0.8 = 7,200 miles
    b. Grip Tester (75*150)*0.8 = 10,800 miles
    c. SCRIM (300*150)*0.8 = 36,000 miles

5. The Grip Tester and SCRIM require both a driver and an operator. The LWST uses one operator.

6. Per diems and hotel expenses are an average of $300/week and $400/week, respectively, for the operators and drivers.

7. The equipment costs for all three devices are estimated but caution is to be taken when comparing them because the prices used for the LWST and the Grip Tester do not represent a unit with a macrotexture laser and the inertial differential GPS system capable of measuring the cross-slope, grade, and curvature of the roads. The cost of the NCDOT LWST is around $160,000. The price of a truck to haul the Grip Tester has been ignored.
    a. Locked-wheel $160,000
    b. Grip Tester $ 80,000
    c. SCRIM $800,000

8. All the devices have been assigned a service life of 10 years for depreciation purposes and another 10% for yearly maintenance cost during their life.

9. Fuel mileage is around 10 miles/gallon for the trucks towing both the LWST and the Grip Tester but only 5 miles/gallon for the SCRIM truck.

With these estimations, estimates of the overall direct costs and the cost per mile for each type of device are presented for two possibilities, 25% and 50% of the secondary network and the totality of the primary networks each year for the NCDOT network.

Table 5-1. Direct costs, cost per mile, and units needed for two network scenarios

Road Network	**Miles**	**ASTM E-274**	**Grip Tester**	**SCRIM**
Primary and 25% Secondary	46,250	$621,249	$616,610	$401,433
Units Needed		6.4	4.3	1.3
Primary and 50% Secondary	62,500	$839,525	$833,256	$542,477
Units Needed		8.7	5.8	1.7
Direct Costs/Mile		$13.43	$13.33	$8.68
Estimated Production/Device/Year		7,200	10,800	36,000

From these results, if NCDOT continues to use the LWST and test on a 4-year cycle, it would need to acquire about three more units and have three more operators, resulting in more than 50% of the cost of using the SCRIM alternative. The Grip Tester alternative provides 100% coverage but it would require about four Grip Testers.

If the decision would be to test on a 2-year cycle, there is a need for two SCRIMs, nine LWSTs, or six Grip Testers. Again, it cannot be emphasized enough that the CFMEs test every foot of each mile, while the LWST only tests about 10% IF the change is made to start making 0.1-mile measurements, but only 2% if the testing is done every half-mile.

6. CONCLUSIONS AND RECOMMENDATIONS

This chapter presents some of the major conclusions derived from the reviews of friction/texture–crash relationship studies and pavement safety programs, and the results of the experimental program that surveyed more than 560 miles of pavement in North Carolina. It also presents key recommendations regarding the proposed implementation of a PFM program for NCDOT.

Conclusions

- **Harmonization/ Interconversion of Equipment** – The direct results of the comparison showed that:

    - Comparing LWST to the GN and SR measurements produced low to moderate correlations (under 50%).
    - The LWST standard ribbed tire shows better correlation with the SCRIM, and both are relatively insensitive to MPD.
    - Although based on a small sample size, the LWST standard smooth tire shows better correlation with the Grip Tester, and both are relatively sensitive to MPD.
    - SR and GN correlate better to the LWST when corrected to a common slipping speed using the IFI speed correction equation, which is based on macrotexture.

    Despite extensive international efforts (PIARC, HERMES, TYROSAFE) to develop harmonization constants for relating the friction measurements from different friction devices to one universal friction index, there are still major shortcomings that prevent full harmonization from occurring, but simple and practical approximations can be done.

- **Macrotexture** – Macrotexture is a very important parameter for understanding the full frictional properties of the pavement. Several studies have been successful correlating texture depth (e.g., mean texture depth [MTD], MPD) with crashes. Results conflict somewhat regarding macrotexture's impact on wet-weather crashes, but there is more consensus on its impact on total crashes. The literature review lists several examples of threshold values that can be helpful in establishing these values. From this review, the researchers recommend that for speeds greater than 50 mph, the as constructed macrotexture of the pavement MPD should be greater than 0.8 mm, and for speeds greater than 70 mph, the as constructed macrotexture of the pavement MPD should be greater than 1.0 mm.

- **PFM Development** – The development and implementation of a PFM program must consider the scope of network friction testing (i.e., concentrate efforts in areas or on facilities where friction is significantly in question and the benefits of routine testing are more profound). Furthermore, it should recognize the agency's unique highway conditions, policies, and practices for managing the highway system.

- Although similar difficulties were noted in obtaining repeatable and reproducible friction measurements for all kinds of pavements with all the devices, the use of CFME has an advantage over the locked-wheel tester as it measures 100% of the highway available friction at any location.
- A comparison of the cost of data collection per mile showed that CFME data collection costs are lower than those of the LWST, and that the entire road is measured instead of just a 2% sample.
- The use of continuous friction and macrotexture measurements should facilitate the definition of investigatory friction levels that can help flag sections with marginal friction levels based on crash trends.

Recommendations

- NCDOT should investigate the feasibility of collecting macrotexture data to complement the agency's friction data collection. This will allow areas with potentially deficient macrotexture to be identified and investigated at the project level and corrected, if necessary, before the occurrence of wet-weather crashes.

- NCDOT should also investigate the feasibility of implementing a proactive friction management program that uses a CFME with macrotexture measurement capabilities to define threshold investigatory levels and use SPFs to identify sites with the highest potential payoff for friction improvement.

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APPENDIX: LITERATURE REVIEW

1. PAVEMENT SURFACE CHARACTERISTICS

In 2008, the Federal Highway Administration (FHWA) revised 23 CFR 924 Highway Safety Improvement Program (HSIP; 23 C.F.R. § 924, 2008), a regulation that requires states to have a process for the following:

(1) collecting and maintaining a record of accident, traffic, and highway data….
(2) analyzing available data to identify highway locations, sections and elements determined to be hazardous on the basis of accident experience or potential.
(3) conducting engineering studies of hazardous locations, sections, and elements….

The vehicle crash database must contain pavement data relevant to and with sufficient detail to identify causal factors (including pavement-related) and identify potential high-crash locations. Thus, in order to improve highway safety, it is important to understand the complexity of linking friction and other pavement surface characteristics (PSCs) to crashes. Technical Advisory 5040.38 on pavement friction measurement (PFM) provides guidance on the elements of, or outputs from, an HSIP, including PSC data (friction and texture) and crash-data analysis procedures (FHWA, 2010).

The role that improved roadway conditions, and particularly PSCs, have on reducing the unacceptable number of annual deaths and serious injuries has been acutely underestimated in the past, probably due to the statistically significant but weak link between friction (or texture) and the number of total and wet-pavement highway crashes.

In order to reduce the number of highway fatalities in the U.S., an aggressive HSIP is required that comprehensively addresses all safety factors, including critical PSCs, such as friction and texture. Although other factors are often the primary cause(s) of crashes, ensuring adequate friction and texture can help to prevent or lessen the consequences of crashes. This is because, in emergency situations, drivers tend to brake hard and/or steer rapidly to avoid a crash, and if good, uniform friction is available, a higher deceleration rate can be achieved that will either help avert or reduce the impact of a crash as a result of the lowered speed at impact.

U.S. Crash and Fatalities History

In the U.S., highway safety has been recognized as a critical issue since at least the 1930s. In the last two decades, highway safety has received a renewed focus in many transportation organizations and highway agencies. This is reflected in the development of such documents as the American Association of State Highway and Transportation Officials (AASHTO) Strategic Highway Safety Plan (AASHTO, 2005), the guidelines on various aspects of highway safety (National Cooperative Highway Research Program [NCHRP] Report Series 500; National Academies of Sciences, Engineering, and Medicine, 2009), the aforementioned FHWA HSIP, the AASHTO *Highway Safety Manual* (AASHTO, 2010), and all the Toward Zero Deaths initiatives, among others.

While the crash fatality rate has steadily improved since the 1970s, the total number of fatalities has nevertheless become of greater concern, particularly in light of the gains that other countries have made in this area. For instance, the countries of Western Europe experienced a 59 percent reduction in fatalities between 1970 and 2004 (from 80,093 to 33,158), compared to the U.S. reduction of only 19 percent (from 52,627 to 42,636) over this same period. From 1995 to 2007, the U.S. decreased annual fatalities by only 2 percent, compared to reductions of 50 percent in France, 20 percent in Australia, and 19 percent in the United Kingdom (U.K.) (Transportation Research Board [TRB], 2010). Over a more recent period (2001–2009), Europe reduced annual fatalities by 36 percent, while the U.S. reduced annual fatalities by 20 percent. However, the U.S. has experienced a 14% increase since 2014. It is clear that, from this perspective, the U.S. can and should be doing much more to reduce crashes and the fatalities and injuries associated with crashes.

In 2010, the U.S. safety goal was revised from the fatality rate-based goal (1 fatality per 100 million vehicle miles traveled [VMT]) to a fatality number goal in order to emphasize the goal in more human terms. The new goal is to reduce the number of fatalities by half in 20 years (2010–2030). In addition, AASHTO has endorsed the Global Safety Initiative to reduce fatalities by half over 10 (2010 to 2020) years as part of the Toward Zero Deaths initiative.

Factors Affecting Crashes

Many factors contribute to the high number of traffic fatalities. Most factors fall under three broad categories: human, vehicle, and roadway environment (Larson & Smith, 2010). Although the exact percentages are unknown and certainly vary over time and by location, it is commonly accepted that human factors play a predominant role in highway crashes, followed by roadway factors and vehicle factors, and that a significant level of interaction between two or all three categories takes place. Figure 1 shows Australia's New South Wales Roads and Traffic Authority 1996 approximation of the relative contribution of driver, vehicle, and roadway factors in highway crashes (FHWA, 2010). A more recent (2006) U.S. study showed poor roadway conditions contributed to (not caused) 31.4 percent of total crashes, 38 percent of 5,746,231 non-fatal crashes, and 52.7 percent of 42,642 fatalities (Miller & Zoloshnja, 2009).

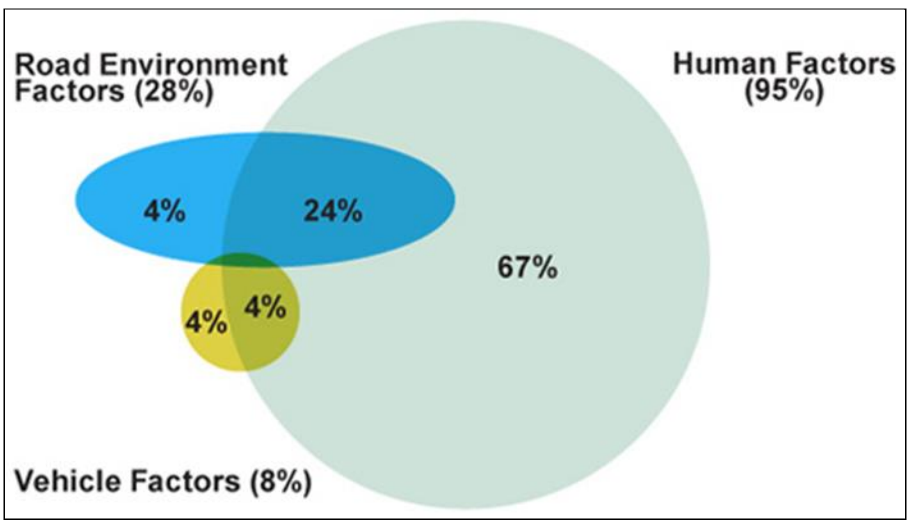

Figure 1. Approximation of the relative contribution of driver, vehicle, and roadway factors in highway crashes in New South Wales, Australia (FHWA, 2010).

The recently developed Model Inventory of Roadway Elements system attempts to standardize consideration of roadway inventory features (Lefler et al., 2010), but pavement condition, and surface characteristics in particular, are given minimal consideration. Some information on crash modification factors for increasing friction or skid resistance is available at the Crash Modification Factors Clearinghouse (www.cmfclearinghouse.org). The contribution of good roadway condition to improved highway safety has been greatly underemphasized in part because of past difficulties in relating friction and texture and surface defects to crash rates. The 2010 AASHTO *Highway Safety Manual* addresses many of the geometric related issues, but specific information on PSCs is not even identified. Improved data and analysis procedures (particularly the empirical Bayesian analysis approach) are now available to significantly improve this situation. The 2008 AASHTO *Guide for Pavement Friction* is a major step in addressing this important consideration.

Wet-pavement crashes, in particular, have plagued the highways for many years. A 1980 report by the National Transportation Safety Board (NTSB) concluded that, in the U.S., fatal accidents occur on wet pavements at a rate of between 3.9 and 4.5 times the rate of occurrence on dry pavements. The NTSB and the FHWA have reported that 13.5 percent of fatal crashes and 18.8 percent of all crashes occur when the pavement surface is wet (Dahir & Gramling, 1990; FHWA, 1990).

Most past safety improvement efforts in the U.S. have focused on driver behavior and vehicle design factors, as well as roadway geometric design and traffic safety features. The regulations and guidance put forth in the FHWA HSIP, the NCHRP 500-series reports (*Guidance for Implementation of the AASHTO Strategic Highway Safety Plan*), and AASHTO *Highway Safety Manual* represent major advancements in the latter category of safety improvements. However, because of liability concerns and complexity, less emphasis has been placed on PSCs, even though they have been shown to be significant factors in highway safety (Larson & Smith, 2010).

PSCs are largely defined by the top layer of the pavement surface and include both physical and dynamic attributes. Physical attributes represent the stand-alone pavement surface properties of the pavement surface, such as transverse and longitudinal profile, surface texture, and porosity. Dynamic attributes represent the dynamic interaction properties that occur because of a vehicle traversing over the pavement surface. They include friction, hydroplaning potential, splash/spray, smoothness, tire-pavement noise, as well as several other ancillary characteristics (e.g., rolling resistance, tire wear, light reflectance/luminance).

A pavement's physical attributes directly affect many of the dynamic attributes; for example, surface texture is a key determinant in friction, hydroplaning potential, splash/spray, and noise, and transverse and longitudinal profiles have a significant influence on hydroplaning potential and splash/spray. Dynamic attributes, in turn, have certain impacts on the safety and comfort of highway users, as well as the economic impacts on society.

Considering all the PSCs, friction and texture combined play the greatest role in contributing to highway crashes (Larson & Smith, 2010). This is in part due to the low sensitivity or awareness that drivers have to these characteristics, especially during wet conditions. Studies indicate that approximately 80 percent of all crashes and fatalities on slippery pavements (i.e., wet, snowy/slushy, or icy) are associated with wet conditions (Erwin, 2007) and that up to 70 percent of wet-pavement crashes can be prevented or minimized by improved pavement friction and texture (Henry, 2000; FHWA, 2011a). Some research has shown that where wet pavement friction has been improved, there is a significant reduction in dry pavement crashes (Larson & Smith, 2010; Erwin & Tighe, 2008; Larson et al., 2008).

Critical Locations for Friction and Texture

The FHWA Safety Program has identified four focus areas that constitute major safety problems based on their levels of involvement in fatalities. These areas include the following (FHWA, 2011b):

- Roadway departure crashes, involved in 53 percent of traffic fatalities.
- Intersection-related crashes, accounting for 21 percent of fatalities.
- Pedestrian crashes, which account for 12 percent of fatalities.
- Speed-related crashes, a contributing factor in 31 percent of fatalities.

Although the FHWA identified nine countermeasures or strategies that have been determined to be effective in reducing incidences of these crashes, and promotes them to state and local agencies for implementation on roadways under their jurisdiction (International Traffic Safety Data and Analysis Group, 2010), none of the countermeasures relate to improved pavement condition, friction, and/or macrotexture.

The positive contribution of pavement friction and texture to reducing vehicle crashes is considered to be greatest at horizontal curves, intersection approaches, congested areas and merging/weaving areas of freeways, and work zones. Sharp horizontal curves are often the sites for run-off-the-road and wet-weather crashes (Julian & Moler, 2008). In fact, in 2006, about 25 percent of the fatal crashes in the U.S. occurred along sharp horizontal curves, mostly on two-lane rural highways. About 76 percent of curve-related fatal crashes were single-vehicle incidents where the vehicle left the roadway and struck a fixed object or overturned. The average crash rate for horizontal curves is about three times that of other highway segments, according to NHTSA's Fatality Accident Reporting System data (Julian & Moler, 2008).

Past research by The California Department of Transportation on wet-weather accident rates found that curves have the highest accident rates followed by weave sections and intersections (Corsello, 1993). Similarly, Bray (2003) noted that "A review of recent issues of [NHTSA's] annually published *Traffic Safety Facts* reveals that a little more than half of combined fatal and injury crashes, for which we have adequate location data, occur at intersections (or are intersection related)."

At the same time, it is recognized that rural roads account for approximately 40 percent of the VMT in the U.S., yet account for about 55 percent of fatalities. The fatality rate for rural crashes is more than twice the rate for urban crashes. Rural area crashes and their consequences differ from urban crashes in several ways (FHWA, 2011c):

- Rural crashes are more likely to occur at higher speeds.

- Crash victims are more likely to be unbelted than their urban counterparts.
- Crashes are more likely to produce fatalities due to longer response times.

2. RELEVANCE AND APPLICATIONS OF FRICTION/TEXTURE–CRASH RELATIONSHIP STUDIES

As discussed previously, most highway crashes involve multiple causative factors, although crash investigations have consistently shown a basic link between crashes and pavement surface conditions/characteristics, such as friction and texture. The link is most profound when wet pavement conditions exist in conjunction with low friction levels and moderate-to-high traffic speeds, but there are also indications that dry pavements with inadequate friction can adversely affect the number or rate of roadway crashes.

The following study reviews give special focus to measurement equipment and methods that appear to have better crash prediction capabilities (i.e., provide particularly strong links between measured friction and crashes) for a variety of roadway conditions and circumstances (e.g., asphalt and concrete pavements, a range of macrotextures, different traffic compositions, and different climate zones). Such insight is deemed highly valuable in the selection of a continuous friction measuring equipment (CFME) device and the establishment of investigatory friction/texture levels as part of PFM programs.

A comprehensive review of the literature collected in this study indicates that there have been no past studies in which two or more friction/texture measurement devices have been directly evaluated or compared in terms of their ability to predict crashes (total or specific types) or crash severity levels (fatal, serious injury, property damage-only). The studies that have examined the link between friction/texture and crashes always involved the use of only one particular piece of equipment (e.g., ASTM E 274 locked-wheel tester, Side-force Coefficient Routine Investigation Machine [SCRIM]) and a corresponding friction/texture measurement index (e.g., friction number [FN], side-force coefficient). As a result, any insight regarding particularly effective equipment and/or threshold levels has to be gleaned collectively and somewhat subjectively.

Earlier Studies

In 1993, a technical working group representing state highway agencies (SHAs) industry, academia, and the FHWA convened to address the issue of pavement-tire noise on Portland cement concrete (PCC) pavements (Hibbs & Larson, 1996). The issue stemmed from an FHWA policy advocating the use of transverse tining to improve highway safety. That policy led to the widespread implementation of transverse tining on PCC pavements, which later was identified as problematic because of its objectionable noise emissions. The group published a comprehensive report addressing a variety of surface texture-selection issues, including safety considerations. Among other things, the report concluded that “available information supports only a general correlation between friction numbers and wet-weather crash rates” and “while friction properties are a convenient way to estimate the safety characteristics of various pavement types and surface textures, the real test is whether the pavement texture reduces the number and severity of wet weather accidents.” The report recommended that additional multi-year analyses were needed to establish relations between FN (as measured with a locked-wheel tester) and crash occurrence.

Cairney (1997) presented and discussed a number of past studies examining the relationship between skid resistance (i.e., friction) and crashes. The studies covered various time periods between the early 1960s and the early 1990s and represented a variety of locations, including several U.S. states, Canada, U.K., Germany, the Netherlands, Australia, and South Africa. Each study had a unique focus in terms of the crash and friction parameters analyzed (and the measurement method/equipment used), the types, locations, and traffic levels of the roadways included, and the characteristics/nature of the roadway segments analyzed. The studies were organized around the following three basic methods of examining the friction versus crashes relationship (Cairney, 1997):

- Before-and-After Studies—In this method, crash data and/or skid resistance data prior to and after a resurfacing event along a stretch of roadway [were] collected and analyzed to determine the extent of crash reduction effected by the resurfacing activity.
- Comparison to the Norm Studies—In this method, sites or locations where skid crashes occurred [were] identified and the associated skid resistance values at these sites [were] compared with values at a number of randomly selected control sites that [were] representative of the distribution of skid resistance found on the road network.
- Regression Studies—This method entail[ed] plotting one variable (e.g., wet-weather crashes) as a function of another (e.g., skid resistance) and observing how changes in one variable relate to changes in the dependent variable. Typically, data from a large number of sites [were] compiled and plotted so as to show the relationship between crashes and skid resistance over a wide range of values encountered.

While all of the studies examined by Cairney showed a general trend of increased friction leading to decreased crashes, the scatter in the data and the uncertainty in the nature of the relationship (i.e., linear, curvilinear with or without a point of inflexion) clearly indicate the involvement of other factors (e.g., access control, traffic flow, rainfall). Cairney (1997) pointed out some of the limitations of the studies as follows:

- Insufficient time-series friction and/or crash data—lack of year-to-year corresponding values of friction and crashes, or lack of post-resurfacing friction and crash data for before-and-after analysis method.
- Lack of friction data for inside/passing lanes on multi-lane roads—friction values for the more heavily trafficked outside/driving lanes are usually only available and are thus used in the analysis.
- Lack of consideration of friction demand, as influenced by factors such as vehicle speed and/or road geometrics (e.g., longitudinal grade).
- Lack of consideration of the types of accidents upon which skid resistance has an effect.

In developing the updated AASHTO *Guide for Pavement Friction*, Hall et al. (2009) re-examined the work done to date (2004 at the time of the review) in investigating the relationship between pavement friction and crashes. The focus of that review was specifically on wet-weather crashes. Although Hall et al. (2009) included several of the studies covered in Cairney's 1997 report, some more recent studies were presented and briefly described. These included works by various U.S. highway agencies, as well as works in the U.K., France, and Sweden.

While it was anticipated that the review of past studies would provide a more definitive basis for identifying threshold levels of friction, Hall et al. (2009) noted the same kinds of general trends as Cairney. The researchers concluded that "the exact nature of the relationship between pavement friction and wet crashes is site-specific, as it is defined by not only pavement friction but many other factors." The researchers subsequently identified a myriad of factors that should be considered as the basis for a PFM program when evaluating the friction–versus-crashes relationship and in establishing appropriate friction demand categories.

Recent Studies

In the last 10 years, several additional attempts have been made to develop or quantify the relationship between friction/texture and crash occurrence. Some of these studies have considered only the general friction/texture qualities, as defined by a type of surface texturing (e.g., transverse and longitudinal tining) applied to concrete pavement or a type of mix (e.g., open-graded friction course [OGFC], microsurfacing, dense-graded hot-mix asphalt [HMA]) used for the surface layer in an asphalt pavement. Others have assessed actual friction/texture data obtained using different test equipment and methods.

Various forms of crash data (e.g., total crashes, wet crashes, wet crash rates, wet-to-dry crash ratios) and crash types (e.g., run-off-the-road, rear end) have been analyzed in these studies, and different analysis techniques have been used. Both U.S. and international studies are presented and briefly discussed in relation to the objectives of this study.

U.S. State Studies

Virginia

Kuttesch (2004) reviewed selected past studies that examined the relationship between friction and crashes, and subsequently performed analyses of data to quantify the effect of skid resistance on wet accident rates in Virginia. Summary accident data for 2002 were combined for analysis with traffic data (average annual daily traffic and locked-wheel friction data (skid number SN64S) for the same year, corresponding to 1-mi (1.61-km) sections throughout the state having available SN data. The SN data were not network-wide inventory data, but instead represented data for sites that were either (a) identified by the Virginia Department of Transportation's Wet Accident Reduction Program as being potential accident trouble spots or (b) paved with Superpave™ mixes.

Additional analyses of the data by Kuttesch (2004) included consideration of only interstate sites and a breakdown of sites by Virginia DOT districts. The plot of wet accident rate versus SN for the interstate sites was similar to the plot generated for all sites in terms of large scatter and a poor degree of correlation between the two variables when linearly regressed. However, the author noted a slight improvement in the r-squared value ($R^2 = 0.014$) and suggested that "by selecting sites with similar geometric characteristics, more of the variation in wet accident rates can be explained by changes in the skid number."

Wisconsin and California

Drakopoulos and Kuemmel (2004; 2007) investigated crash statistics for longitudinally tined PCC pavements, transversely tined PCC pavements and asphalt pavement surfaces using crash data from Wisconsin and California for the years 1991 through 1998. While pavement friction was originally intended to be a key part of the study, the correlation of friction with crash experience was found to be weak due to the high variability of FN values in the compiled database and the inability to accurately match friction test locations with crash locations. The variability in friction was attributed to many factors, including time of testing (seasonal, daily, after a long dry period, after a strong rain), testing speed (i.e., extrapolation of measured friction values to reflect friction at higher speeds), limited sampling (e.g., one lane, one wheelpath, 3 to 5 tests per mile), and the effects of traffic and pavement surface material quality.

The analyses focused on California and Wisconsin rural freeways on level or rolling terrain with design speeds of 50 mph (80 km/h) or higher (Drakopoulos & Kuemmel, 2004 & 2007). California urban freeways were also examined, and breakouts were made for traffic in terms of freeways with average daily traffic less than 60,000 vehicles/day and those with more than 60,000 vehicles/day. Safety performance measures of effectiveness used in the analyses included crash rate (total crashes per 100 million vehicle miles traveled [MVMT]), wet-to-dry crash ratio, and liquid precipitation safety ratio (LPSR), a parameter that takes into account the percentage of time a pavement is wet.

Key findings of the study were that transversely tined PCC pavements in Wisconsin had higher crash rates than asphalt surfaces, but that the wet-to-dry crash ratios and the LPSRs were lower for transversely tined pavements as compared to asphalt pavements (Drakopoulos & Kuemmel, 2004). For the California sections, the longitudinally tined PCC pavements had lower crash rates than the asphalt surfaces, but higher wet-to-dry crash ratios and LPSRs. In comparing the transversely tined pavements in Wisconsin with the longitudinally tined pavements in California, the crash rates were found to be the same, whereas the LPSR was slightly lower (although not statistically) for the Wisconsin transversely tined pavements.

Although no explanation was given for the inverted trends observed in the two states (i.e., crash rate versus wet-to-dry crash ratio and LPSR, when comparing a PCC texture to asphalt), it was noted that the database of sections analyzed for Wisconsin was much smaller than the California section database (530 mi [853 km] versus 1,372 mi [2,209 km]). It is also likely that the surface characteristics of the asphalt surfaces in Wisconsin were considerably different from those in California. Additionally, the geometrics, traffic composition, and other site conditions could have been considerably different between the two states.

New York State

The New York State DOT has shown that their Skid Accident Reduction Program (SKARP), which was implemented in 1995, has been highly successful through a before-and-after study performed by the DOT in the late 1980s/early 1990s (Bray, 2003; Lyon & Persaud, 2008). In the study, 10 sites experiencing high proportions of wet road accidents (38 percent or more of total) and subjected to resurfacing during the early 1980s, were evaluated to examine the effect of a high-friction top course on wet road accidents. Although one of the 10 project sites showed a relatively small reduction (10 percent) in wet road crashes, the remaining nine locations showed very large reductions, ranging from 35 to 88 percent. Wet road crashes at those locations declined by a statistically significant 61 percent. Total crashes at the locations reflect the reductions in wet road crashes by their decline of 28 percent.

An evaluation of the effectiveness of SKARP in the early 2000s entailed before-and-after studies of 75 locations identified by SKARP as being high wet road crash locations (Bray, 2003). Each location received a friction restoration treatment in the form of either a 1.5-in (38-mm) HMA overlay (using non-carbonate aggregates) or a 0.5-in (13-mm) microsurfacing. Of the 75 locations targeted for study, 40 had at least 7 months each of pre- and post-treatment crash data available for analysis. Results for these 40 locations were categorized and summarized according to the before/after time period.

Post-treatment friction tests were performed at 64 of the 75 locations targeted in the New York study (Bray, 2003). Although specific friction test results were not available in the study paper, it was noted that 50 of the 64 locations had relatively high FNs (FN40R greater than 32) during the "after" period.

Ohio

In a study for the Ohio DOT, as part the agency's strategic initiative to reduce total highway crashes by 10 percent and rear-end crashes by 25 percent by 2015, Larson et al. (2008) evaluated locked-wheel friction testing results and wet weather crash data. This was done to determine if a correlation exists between the two parameters and, if so, (a) which test tire (ribbed or smooth) is more correlated and (b) what the desirable or target FN values should be for different site categories.

Ninety sections throughout the state—30 each representing the three site categories considered to have the greatest potential to reduce rear-end crashes (i.e., signalized intersections, unsignalized intersections, and congested freeways)—were identified and tested for ribbed and smooth tire friction, macrotexture, rutting, and roughness. In addition, sections were chosen to include surfaces with known skid resistance problems as well as surfaces with high skid resistance.

For each individual section (standard length of 0.5 mi [0.8 km]), 3-year crash data totals (for the years 2003 through 2005) were compiled for analysis, covering the following crash types:

- Total crashes (total number, rear-end crashes, wet pavement crashes, wet-to-total ratio, and rear end crash rate (per 100 million entering vehicles for intersections, per 100 MVMT for freeways).
- Day crashes (total number, rear end crashes, and wet pavement crashes).
- Night crashes (total number, rear end crashes, and wet pavement crashes).
- Percent crashes by direction.

Friction testing was conducted on the various pavement sections in 2007. Friction values obtained included FN40R and FN40S, and depending on the facility, either FN20R and FN20S (intersections) or FN60R and FN60S (congested freeways).

The analysis of data centered on the development of plots of wet-to-total crash ratio versus FN, macrotexture, speed gradient, average annual daily traffic, and International Roughness Index. Results showed the ribbed tire provided a higher correlation to crashes than the smooth tire test results on Ohio's pavements, which consist primarily of limestone or crushed gravel aggregates.

On each of the data plots produced in the analysis, best-fit trend lines were fit through each logical set of data. While different equation types were tried, the logarithmic or linear equations provided the best fit in all cases (in terms of the R^2 value, which was used to assess the goodness of each data trend included in the plots). Trendline equations and R^2 values were included on each plot, although the R^2 values were typically less than 0.5.

A common observation from the plots where all 90 sections were included in the same data set was that the variability of the data around the trends was very large. This was also indicated by extremely low R^2 values associated with the trends. Because of this, the remaining analysis plots were produced with data sets specific to only one site category type (i.e., congested freeways, signalized intersections, and unsignalized intersections). Therefore, each investigated trend resulted in a group of three different analysis plots that could be viewed side-by-side to see how trends differed between site category types. Table 1 presents the overall recommended values.

Table 1. Recommended intervention (minimum) and investigatory (desirable or target) friction, texture, and roughness levels for Ohio network-level evaluations (Larson et al., 2008).

Check	Variable	Intervention Level	Investigatory Level
1	a. If wet/total crash rate, and	≥ 35 percent	≥ 25 percent
	b. Annual average number of wet pavement crashes (2 or 3-year average), then	> 3 for rural settings > 5 for urban settings	> 2 for rural settings > 3 for urban settings
	c. Check minimum friction number	$FN40R_{min}$ < 32 or $FN40S_{min}$ < 23	$FN40R_{min}$ < 42 or $FN40S_{min}$ < 32
2	Minimum macrotexture	Use the appropriate MTD_{min} value from table 8 in chapter 4	< 0.04 in (1.0 mm) (sand patch) (Based on U.K. criteria)
3	Roughness spikes based on 20-ft (6.1-m) sliding baselength	Use current Ohio DOT requirements	300 in/mi (4.7 m/km)

Notes:

1. Check 1 - Minimum wet/total crash rate, minimum annual average number of wet pavement crashes, and the ribbed tire friction numbers ($FN40R_{min}$) are based on SKARP criteria. Sections meeting the check 1a and 1b criteria are then friction tested to determine if poor skid resistance is the likely cause of the crashes. The smooth tire criterion ($FN40S_{min}$) is the corresponding minimum smooth tire friction number for those sections that failed the SKARP criteria based on $FN40R_{min}$ < 32. If all three variable criteria for check 1 are met, then a skid resistant overlay should be planned without the need for any further evaluations. A skid resistant overlay with non-carbonate aggregate will likely be very cost effective.
2. The minimum macrotexture depth is based on the French criteria in LCPC Bulletin Special Issue #255 on Skid Resistance (Dupont & Bauduin, 2005). Alternatively, a 0.2 in (0.5 mm) (sand patch) minimum criteria could be used here, but it would not be appropriate for slow speed roadways.
3. Proactive approach—Desirable or Target (Investigatory Level) Criteria where low friction, texture, or spikes in roughness *may be* contributing to increased numbers of wet pavement and total crashes.

Wisconsin

The Wisconsin DOT conducted a study in 2000 to evaluate the impact on exterior vehicle noise associated with the placement of a high-friction surface (Italgrip system) on a PCC pavement in Waukesha County (Kuemmel et al., 2000). The surface treatment was installed with 0.125-in (3-mm) aggregate on the eastbound lanes and 0.156-in (4-mm) aggregates on the westbound lanes. The study concluded that the Italgrip produces a 2- to 3-decibel decrease in noise level compared to the existing PCC pavements at highway speeds.

A follow-up study published in 2008 reported on the durability and effectiveness of the Italgrip system (Bischoff, 2008). Locked-wheel friction testing showed that the surface treatment increased the FN from an average of 42.9 (prior to application) to 72.6 (after application). After 5 years in service, the sites averaged 59.4, still 38 percent higher than before the application. The study also showed (through a before-and-after crash analysis) that the number of crashes at the sites during a 3-year period decreased by 93 percent and the number of vehicles involved in accidents decreased by 89 percent. A subsequent benefit-cost analysis of the Italgrip sections resulted in benefit-to-cost ratios ranging from 2 to 8 (de León et al., 2010).

Florida

In a before-and-after study by Reddy et al. (2008) for the Florida DOT, the impact on safety of applying a proprietary high-friction surface treatment (Tyregrip) on a curved section of an interstate (I-75 in Weston, Florida) on-ramp was evaluated. Crash data obtained from the Florida DOT's Crash Analysis Reporting System were compiled for the 4-year period prior to the installation of the Tyregrip and a 1-year period following the installation. Although sufficient crash data were not available to determine a statistically significant difference in crash frequency or rate, preliminary results suggest a reduction in crashes for the Tyregrip-treated on-ramp.

A before-and-after comparison of friction levels was also performed using measurements obtained with the Florida DOT's locked-wheel friction tester. The results of this testing showed a substantially higher FN40R following the placement of the high friction surface—35 for the original pavement surface and 104 for the Tyregrip surface.

North Carolina

In a study by Pulugurtha (2008), laser profilometer data obtained from the North Carolina DOT on six different highway corridors (two interstate freeways, one U.S. route, and two state routes) were processed to calculate estimated pavement macrotexture at 0.16-mi (0.25-km) intervals according to the ASTM standards. Crash data collected over the same lengths of the corridors were integrated with the calculated pavement macrotexture. Scatter plots, bivariate analysis and multivariate analysis showed that a strong relationship exists between pavement macrotexture and crash incidences on North Carolina roads. Analyses and evaluation indicated that crashes decrease with an increase in pavement macrotexture on North Carolina roads and that macrotexture greater than or equal to 0.06 in (1.5 mm) (but typically less than 0.12 in [3 mm]) is most appropriate to provide safe and efficient transportation to road users. It must be noted that the results may be biased since there are likely many more miles of road with low texture than with high texture and the crashes should have been normalized.

Other States

Recent unpublished research conducted at the Virginia Tech Transportation Institute has confirmed that both wet and dry crash rates decrease with increased friction. The relevant study showed an overall decrease in the crash rate when the FN increases. It is important to note that Virginia does not routinely collect network-level friction values and a large percentage of the available data correspond to tests conducted on crash sites identified by the Wet Accident Reduction Program.

A similar trend can be observed for data collected over a period of 2 years with a locked-wheel trailer using a ribbed tire (FN40R) in another state that regularly collects network-level friction data. The ratio of wet-to-dry crashes was also calculated for this second state to exclude the impact on crash rates of factors other than the FN, which can potentially affect the safety of a road segment. The study showed that the wet-to-dry crash ratio decreases as FN increases.

U.S. National Studies: FHWA

One of the most promising set of ongoing studies are the pavement safety performance evaluations being conducted under FHWA pooled fund study TPF-5(099), *Evaluations of Low Cost Safety Improvements*. The work currently underway in TPF-5(099) involves evaluating the effect of pavement surface type or surface treatment on the number and severity of highway crashes in several states. This research overcomes the deficiencies of many related safety research studies that do not include consideration of pavement condition.

Preliminary results of a recent study in one state were presented at the 2011 Annual Meeting of the Transportation Research Board and at the 3rd International Friction Conference in Gold Coast Australia (Amjadi et al., 2011). In another exploratory study, the influence of seasonal temperature was evaluated on three different pavement types in the subject state:

- Pave1: HMA overlay on flexible pavement.
- Pave2: HMA overlay on rigid pavement.
- Pave3: Jointed plain concrete pavement.

Study results showed that the three types of pavements perform significantly differently for their contributions to single-vehicle run-off-road crashes in warm and cold seasons. Statistical analyses confirmed that a significant difference exists between warm and cold season crashes on flexible pavements (Pave1). However, no statistically significant difference was found between warm and cold season crashes for the other two pavement types. The FHWA exploratory study recommended further research for asphalt surface property sensitivity to temperature, and for the impact of pavement surface temperature on pavement reliability using analysis of crash data.

Sherwood et al. (2011) recently examined the impact of the placement (in 1995) of a dense-graded HMA overlay on a pavement containing an OGFC surface layer. A before-and-after analysis of the crash data indicated that for the after period (represented by the dense-graded HMA overlay), the wet-to-dry crash ratio was statistically significantly increased by a factor of 7.4 for run-off-the-road crashes. Average friction (FN40R) values for the two different surfaces were 66 for the OGFC and 41 for the dense-graded HMA overlay. While friction/texture was considered to be a primary factor in the higher crash ratio for the dense-graded HMA overlay, roughness was also thought to be a factor, given that the OGFC surface was considerably rougher than the dense-graded overlay for the time periods examined, which may have caused speeds to be reduced.

The above two case studies by FHWA demonstrate the ability of Bayesian analysis methods to better quantify the effect of various pavement-related factors on crash rates (based on an analysis of crash data) than previously used methods.

International Studies

United Kingdom

Viner et al. (2005) described the effort to conduct a network-level analysis of the influence of skid resistance on accident risk for the U.K. Highways Agency. The study was intended as a review and update of the agency's 1988 skid resistance policy (HD28) for trunk roads. That policy intended to equalize the risk of skidding accidents across the network and was centered around routine friction measurements using the SCRIM friction tester and comparison of those results with investigatory friction levels established for 13 different highway site categories (e.g., motorway, single carriageway [two-lane undivided] minor intersection, bends/curves with <820 ft [<250 m] radius, roundabout approaches).

Using a comprehensive and updated trunk roads database and a modeling process that accounts for a variety of factors, including traffic flow, road condition, and geometry, Viner et al. (2005) developed a series of plots of accident risk (i.e., defined as crash rate) versus skid resistance (for intervals of 0.05 SCRIM side-friction coefficient units) for each of the 13 site categories. Trends for both the mean accident risk and the 95th percentile accident risk were developed.

While most of the plots exhibited a general decrease in accident risk for higher levels of skid resistance, the variation in risk was determined to be significant enough that the setting of an investigatory level (i.e., for identifying sections for detailed investigation) instead of a straight-out intervention level (for identifying sections to be treated for surface safety) would be more appropriate. Subsequently, the investigatory levels contained in the original HD28 standard were revised in accordance with the accident risk–friction plots. In addition, some revisions to the site category descriptions were made, leading to a reduction in categories from 13 to 10. The new site categories and corresponding investigatory levels were incorporated in 2004 into U.K.'s current skid resistance policy HD28/04.

As part of an effort to review the suitability of the U.K.'s national investigatory levels for pavement friction to the conditions of Cornwall County (a rural county in southwest England), Stephenson et al. (2008) analyzed historical (2004 and 2005) crash data and SCRIM friction data on three different roadway networks: strategic routes (2a designation), principal roads (2b designation), and main distributor roads (3a designation). Plots of accident rates versus the Mean Summer SCRIM Coefficient (MSSC) for the following ten SCRIM site categories were developed:

- Bend/Curve Dual <1,640 ft (500 m) radius.
- Bend/Curve Single <1,640 ft (500 m) radius.
- Crossings etc. Approach.
- Gradient >10 percent.
- Gradient 5 to 10 percent.
- Junction/Intersection Approach.
- Non-Event Dual.
- Non-Event Single.
- Roundabout.
- Roundabout Approach.

The plots indicated that crash rates increased significantly as skid resistance decreased, as illustrated for single carriageway non-event sections (Stephenson et al., 2008) and minor and major intersections (Stevenson et al., 2011). The plots demonstrated that some modifications to the national investigatory level standards were justified for Cornwall County and that a different categorization for curves was appropriate for the county road network.

In another U.K. study, Stevenson et al. (2011) undertook a before-and-after evaluation of nine random sites in Cornwall County, where skid resistance improvements were made using different maintenance surface treatments. The majority of the treatments were performed in 2008. The study showed the number of yearly crashes (by severity and road surface condition) before the treatments were applied versus the number of crashes that occurred in the first year following the treatments. The annual number of wet crashes was significantly reduced, with the combination of fatal and serious-injury wet crashes eliminated. Although the effects of the treatments on dry crashes were negligible, the number of total (wet + dry) crashes involving fatal or serious injuries was also eliminated. Because of the reductions, the study computed a 90 to 94 percent First-Year Rate of Return on the investment, as determined using the collective treatment costs and the estimated value of crash reduction.

Australia

Cairney (2006) provided an overview of the few published studies to date on the relationship between macrotexture and crashes, and also reported on a subsequent Australian exploratory study evaluating that relationship. In addition to citing a 1991 U.K. study that indicated a substantial increase in crashes for macrotexture below 0.025 to 0.032 in (0.6 to 0.8 mm) and a 1993 French study that indicated a substantial increase in the wet road crash rate for macrotexture levels below 0.02 in (0.5 mm), Cairney recounted a 2001 Australian study that showed the frequency distributions of macrotexture for all segments of four urban routes and four rural routes (designated as “reference”) in Victoria, and the corresponding distributions of macrotexture for just the segments exhibiting crashes. The distributions for the rural roads showed clear over-representation of crashes at low macrotexture sites (nearly 40 percent of the “accident” segments versus 25 percent of the “reference” segments at a texture level of 0.04 in [1 mm]). For the case of urban roads, it was observed that there was no over-representation of crashes at low macrotexture sites.

In the Australian exploratory study described by Cairney (2006), a 175-mi (281-km) stretch of the Princes Highway West in Victoria was evaluated for macrotexture (collected in 2000 using the Australian Roads Research Board multi-laser profilometer) and crashes (collected between 1998 and 2002). In the study, macrotexture was measured throughout the project and at specific crash sites within the project. Crash risk (defined by percent of crashes) for rural (speed limit > 50 mi/hr [80 km/hr]) portions of the roadway was found to be considerably above the average for sites with a sensor measured texture depth (SMTD) of 0.012 in (0.3 mm), about average for sites with an SMTD of 0.016 to 0.02 in (0.4 to 0.5 mm), and lower than average for sites with an SMTD of 0.024 in (0.6 mm) or greater.

Similar results were observed for the urban (speed limit ≤ 50 mi/hr [80 km/hr]) portions of the roadway. Additional analyses revealed that, although low macrotexture is associated with increased crash risk, it is not associated with an increased percentage of (a) severe crashes, (b) wet weather crashes, and (c) crashes involving heavy vehicles or inexperienced drivers. It was revealed, however, that low macrotexture is associated with increased crashes at intersections where unexpected braking maneuvers are most likely.

A broader analysis of the same road using 2 years of macrotexture data (2000 and 2002) and crash data for the 1999 to 2003 time period gave similar results (Cairney, 2006). However, the analysis took into account traffic flow (i.e., crash risk was defined in terms of the crash rate, instead of the number of crashes) and it was determined that the crash rate is approximately 80 percent higher when macrotexture drops below an SMTD of 0.016 in (0.4 mm).

Working off previous studies suggesting that crash rates increase rapidly when macrotexture falls below a sand patch mean texture depth (MTD) of 0.04 in (1.0 mm), Cairney and Bennett (2008) reported on a study of the relationship between macrotexture and crashes (intersection and non-intersection) on selected two-way undivided carriageways in urban and rural locations throughout the State of Victoria. Crash, traffic, and pavement surface characteristics (macrotexture, roughness, and rutting collected using the Australian Roads Research Board multi-laser profilometer) data were compiled representing 861 mi (1,386 km) of road and 1,344 crashes. The data were aligned on 164-ft (50-m) segments and plots of crash rate versus each surface characteristic were developed. The crash rate was found to be fairly constant for textures above 0.08 in (2 mm), but begins to increase for texture in the 0.05- to 0.07-in (1.2- to 1.8-mm) category, and greatly increases for texture less than 0.05 in (1.2 mm).

Analysis of wet crashes and macrotexture indicates that low macrotexture did not result in a higher proportion of wet-weather crashes. Moreover, statistical analysis using the chi-square test revealed no statistically significant difference between the two. Despite this finding, it was suggested that the evidence of the macrotexture–crash rate trend in the previous figure would support the need to eliminate all road sections with an MTD of 0.04 in (1 mm) or less.

New Zealand

A recent before-and-after study of a section of state highway near Wellington, New Zealand revealed a dramatic reduction in crashes because of the application of a calcined bauxite pavement surface-treatment (Dunlop, 2011). Before the treatment, approximately one crash per week occurred on the subject section, which is located at a tight curve that passes under an overpass. After the treatment, the number of crashes was reduced to approximately two per year. Before and after friction measurements were not reported, nor were traffic, environmental, and other site information.

In another study, texture depth requirements (Cenek et. al, 2002) set investigatory and minimum levels of texture for three types of road surfaces that later gave way to the development of the T10 specification in 2013, derived from the French maintenance practices.

Region of York, Ontario, Canada

Erwin (2007) reported on a comprehensive before-and-after study involving microsurfacing and HMA overlay treatments placed in the Region of York between 2001 and 2004. The investigation focused on the 7-year crash statistics (combined before and after treatment application) of 28 microsurfacing sites and 12 HMA resurfacing sites located throughout the region. Friction and texture data were not included in the analysis; it was presumed that higher levels of friction were achieved due to the application of microsurfacing or an HMA overlay.

Although an empirical Bayesian analysis was originally intended, whereby the number of crashes predicted to occur during the after period had the treatment not been implemented would be compared with the before period, the data required for such an analysis were not available at the time of the study (Erwin, 2007). Consequently, a simple before-and-after analysis was performed, which revealed that an (statistically significant) 18 percent reduction in total crashes and a 32 percent reduction in wet crashes could be anticipated following the application of the microsurfacing treatment. For the resurfacing treatment, it was found that a (not statistically significant) 4 percent reduction in total crashes and 22 percent reduction in wet crashes could be anticipated as a result of application. Further analyses involving the removal of crash data for the first post-treatment year resulted in greater reductions (41 and 25 percent reductions in wet crashes for microsurfacing and resurfacing, respectively), likely due to the wearing away of asphalt binder in the treatment during the first year.

Switzerland

Seiler-Scherer (2004) investigated the relationship between friction and crashes on both freeways and main roads in Switzerland. For the freeways evaluation, SCRIM friction data (measured on 328-ft [100-m] intervals for each lane) collected for the years 1999 through 2002 were subdivided into four categories—2 x 2 lanes with direct separation, 2 x 3 lanes with direct separation, two lanes without direct separation, and mixed traffic roads with two-way traffic. The data were then transformed to a 1,640-ft (500-m) interval (for direct comparison with accident data) by assigning the lowest friction value to a given accident interval.

To analyze any possible correlation between skid resistance and accident occurrence, all intervals of SCRIM friction values and accident rates were grouped into 16 different friction ranges, with each range being 0.05 SCRIM units. The number of 1,640-ft (500-m) intervals (i.e., roadway evaluation segments) comprising each SCRIM range varied greatly, with most SCRIM ranges composed of between 50 and 500 intervals/segments. Plots of the mean accident rate and the mean wet accident rate as a function of the SCRIM friction ranges showed no quantifiable correlations between the variables; accident rates were fairly constant over most of the range (0.3 to 0.8) of SCRIM friction.

3. FRICTION AND TEXTURE TESTING

Today, most SHAs in the U.S. measure pavement friction with an ASTM E 274 locked-wheel trailer using either a standard ribbed or smooth (blank) tire (in accordance with ASTM E 501 or ASTM E 524, respectively) to determine friction numbers. A 2005 survey conducted under NCHRP Project 1-43 indicated that 41 of 45 responding agencies use the locked-wheel tester; 23 of the 41 agencies use the ribbed tire exclusively, six of them the smooth tire exclusively, and 12 of them both tires (Hall et al., 2009). Although a few agencies perform routine network-level friction testing, the vast majority of SHAs typically conduct friction testing as part of a skid accident reduction program or wet accident reduction program on areas with high numbers of crashes (Anderson et al., 1998).

Macrotexture testing by SHAs is less common. About half of the states surveyed under NCHRP Project 1-43 reported testing for macrotexture as part of research (presumably in part for evaluating potentially unsafe areas), and only three states indicated routine testing (Hall et al., 2009). While most agencies reported using the sand patch method, it is believed that portable and high-speed laser devices are becoming more commonly used, given the increased interest in recent years in evaluating the friction and noise characteristics of highways.

Past studies on the relationship between friction and crashes found no device with a superior ability to predict friction-related crashes, largely because poor friction is seldom the lead cause of a crash. However, CFME devices, such as the SCRIM, provide a better chance of achieving a good relationship than locked-wheel testers due to a more complete characterization of friction. Moreover, CFME devices are the only type that will ensure that there are representative friction data available for making comparisons of friction to crashes analyses, regardless of the analysis length chosen. Locked-wheel testers may not be appropriate because most modern vehicles are now equipped with anti-lock braking systems (ABS), which do not lock the brakes.

To better understand how ABSs work, it is useful to plot how the coefficient of friction between a tire and a pavement surface changes with varying slip, as shown in Figure 2a (Henry, 2000). Initially, when the tire is rolling free (zero slip), there is no friction. Friction begins to increase with increasing slip to a peak friction value found when the brakes are working between 18 and 30 percent slip speed. If the slip applied increases, the friction coefficient will start decreasing until it reaches a full sliding value when the brakes are fully applied, as in the case of locked-wheel devices. The values of the coefficient of friction at this point can be up to 50 percent lower than the values experienced at the critical slip during wet conditions. Conversely, the wet friction measured by fixed-slip devices is typically 40 to 50 percent greater than the wet friction determined with LWSTs.

The increasing use of ABS is a key reason why a change in the type of friction testing device used by SHAs appears desirable. Vehicles with ABS systems are typically designed to turn on-and-off before the peak is reached so that the slip is held near the critical slip value, and thus near the peak friction in the rising part of the curve. The tire characteristics (and pavement microtexture) dominate the braking behavior in the left side of the curve, which is often called the "tire influence area." Beyond the critical slip, braking is more influenced by the properties of the pavement surface, specifically the pavement macrotexture. Therefore, it is recommended that the slip-ratio of the network measurement device used be in the pavement surface influence area (greater than 30 percent) and not close to the peak, as it has been observed that occasionally those types of devices tend to move and make measurements on the lower side of the friction curve influenced more by the tire influence area (Wambold, 2012). Another major advantage of the devices that allow friction measurements with less than 100 percent slip ratios is that they produce less tire wear and also allow continuous data collecting.

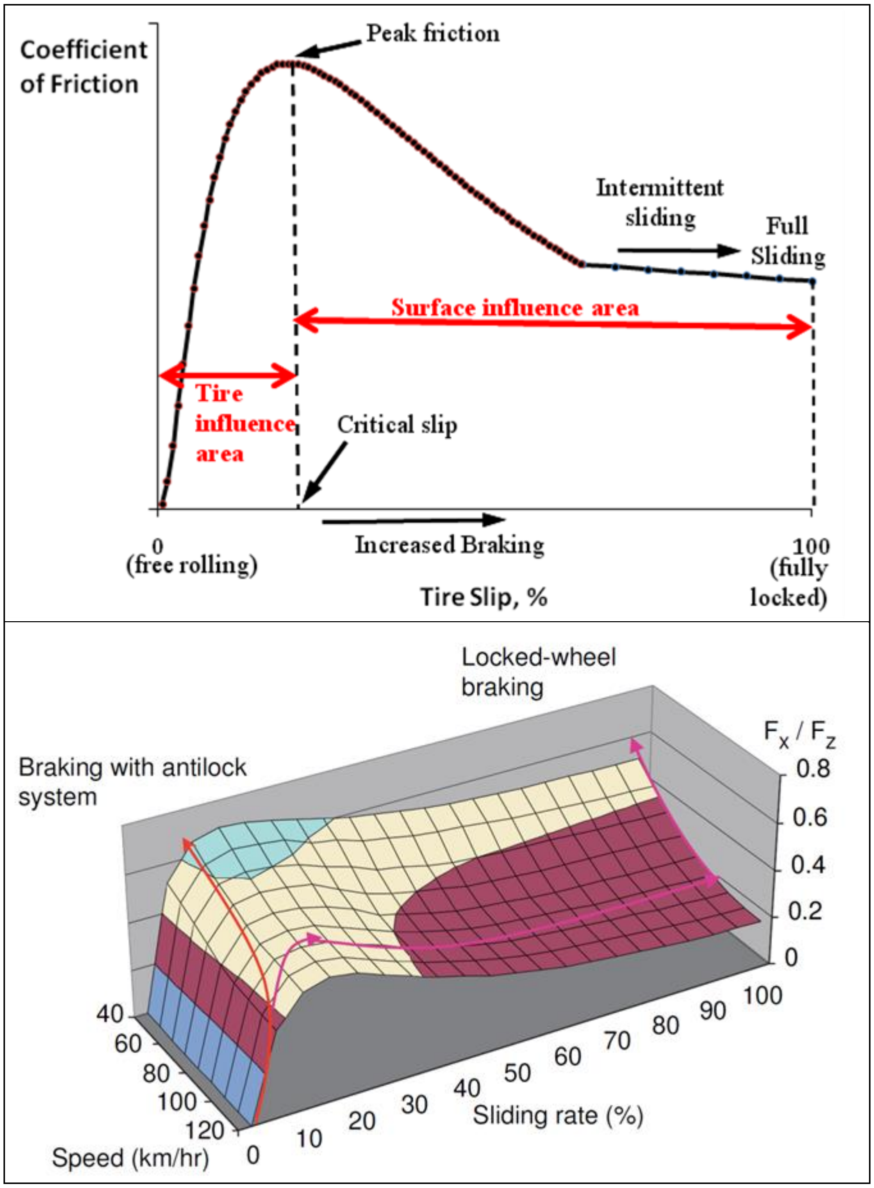

Figure 2. Pavement longitudinal friction vs. (a) tire slip (after Henry, 2000) and (b) slip ratio and vehicle speed (Delane, 2005).

Tire-pavement friction is affected by many factors other than the slip ratio, especially at higher speeds on wet pavements. Hall et al. (2009) found that at speeds above 56 mi/hr (90 km/hr) on wet pavements, macrotexture is responsible for a large portion of the friction, regardless of the slip speed. This supports the need to measure macrotexture with a tire insensitive to macrotexture, such as the ribbed tire.

As mentioned previously, the vast majority of SHAs in the U.S. currently use locked-wheel devices for evaluating pavement friction. The friction testing is typically conducted as part of the state's pavement safety program on areas with high numbers of crashes (Anderson et al., 1998). Thus, a great deal of consideration has to be given to the possibility of correlating the selected device's measurement with available historical records. Harmonization considerations will need to be weighted heavily in order to make valid comparisons with all the historical data in each state.

The recommended equipment slip ratio of a network-level friction device should be preferably greater than 30 percent, and thus the use of a side-friction coefficient device is recommended. Among all the literature reviewed there seems to be no evidence of a better correspondence with measurements on curves, although this is an intuitive concept. It is suspected that these devices will better characterize the frictional properties of PCC pavements, especially those with longitudinal grooving, as their anisotropic surface texture could introduce biases among devices that measure a longitudinal friction coefficient. It is also recommended and desirable to include a dynamic load (both vertical and horizontal) measurement system in real time, and a speed-controlled watering system to provide a 0.02-in (0.5-mm) water film thickness (tank capacity to test 100 to 200 mi [161 to 322 km] of roadway per day). A 0.02-in (0.5-mm) water film thickness is the standard used in highway measurements, whereas airfields measurements use a 0.04-in (1.0–mm) film thickness. It would also be desirable to have a device that could accommodate both water film thicknesses for comparison purposes.

The recommended device should also have a Macrotexture laser sensor (60+ kHz), a temperature recording system at test tire, at the pavement surface, and for ambient temperature, GPS coordinates, and a three-dimensional inertial system (i.e., gyroscopes and accelerometers) to find the radius of curvature, grade, and cross-slope. Originally, this was not necessary, but as the analysis has evolved, the research team believes it is now an imperative requirement for the chosen device for the following reasons, all related to increased friction demand or hydroplaning potential:

- Roadway departures are a major contributor to fatalities and serious injuries. The device chosen for this study should have the capability to record the necessary horizontal and vertical alignment features of the road to analyze possible causes for roadway departures. These geometric features are critical on curves with radius of curvature less than 1,200 to 1,500 ft (366 to1,200 m) and on steep grades, as the amount of friction required to maintain control of the vehicle is increased in both cases. If these data can be measured by the friction-testing device, it will help establish the friction demand required and help quickly identify the corrective action needed.
- Over half of all fatalities occur on the rural road system, with many taking place off the main state road network where good as-built geometric data may not be available.
- Hydroplaning potential is heavily influenced by insufficient cross-slope and other geometric design problems that contribute to standing water in the roadway. Michigan has estimated that up to 5 percent of wet-pavement crashes are related to hydroplaning because if this condition is present, the amount of friction available for braking is negligible (Nejad, 1976). The AASHTO Safety Analyst and the FHWA Integrated

Highway Safety Design Module do not automatically check for hydroplaning potential. However, the Florida *PaveSuite* software tools currently being promoted by the AASHTO Technology Implementation Group (FHWA, 2011d) do accomplish this.

- Hydroplaning is most often related to ponding of water on the roadway surface due to plugged or inadequate catch basin capacity or vegetation blocking surface runoff. Water in rutted asphalt concrete pavements is also a concern, but we know of no study that verifies that it increases crashes. However, during a review of legal issues (Larson & Smith, 2010), hydroplaning was found to be used more as a factor in court cases than poor skid resistance, as it is harder to prove that low skid resistance was the cause of the crash. Also, as noted in the TRB's Transportation Research Circular E-C134: Influence of Roadway Surface Discontinuities on Safety, it was found that large tractor/trailer rigs are subject to hydroplaning at normal highway speeds when in an unloaded condition (Yager et. al., 2009).
- Finally, the implementation of the different highway categories is directly linked to the differentiation of those stretches of road with different alignments (grade, slope, etc.) among other factors. If this project is to rely on state SHAs having detailed information for these parameters for all of the roads to be surveyed, relying on a device that neglects to include all of the aforementioned measurements might prove to be a costly oversight in the end.

As a corollary to requiring all of these features for a device to measure network-level friction, it should be emphasized that all of the different components need to be readily integrated and with a proven record of functionality. The research team is convinced that the analysis of the information that will be obtained with the proposed device can significantly reduce the unacceptable number of deaths and serious injuries on U.S. roads.

In-Vehicle Safety Systems

The impact of improved in-vehicle safety systems on the need for improved skid resistance was reviewed in a recent paper by Cairney (2011). According to the author, a range of technologies to improve safety are either being deployed in the vehicle fleet or have reached an advanced pilot state. Some of these newer technologies were also be evaluated as part of the 2,000-car fleet in the Second Strategic Highway Research Project now underway. These technologies may diminish the role for skid resistance in the future in three ways: (1) reduction in excessive speed via roadway speed cameras and in-vehicle speed warning systems, (2) reduction in the demand for unexpected braking, and (3) better traction during stopping. However, these factors are likely to be balanced by changed expectations about the level of safety provided and by a different mix of road user types requiring a more detailed approach to road surface management.

While ABSs increase the available friction, this comes at the expense of potentially longer stopping distances, and research indicates that there has been no overall crash reduction in cars and light vehicles since their introduction (Cairney, 2011; Insurance Institute for Highway Safety, 2010). Electronic stability control allows the driver to maintain better steering control during braking, making collision avoidance more feasible. Recent studies (Cairney, 2011) have confirmed that electronic stability control is highly effective in preventing single vehicle crashes, especially rollovers in SUVs (for single-vehicle crashes, electronic stability control reduced the risk of a fatal crash involvement by 31 percent for passenger cars and 50 percent for SUVs).

Power-assisted braking systems, when combined with ABSs and electronic stability control, result in reduced stopping distances and are likely to result in fewer crashes and reduced impact forces when crashes occur. On a dry road, braking distances can be reduced by as much as 45 percent. Other technologies, such as collision avoidance systems, use radar to apply the brakes to reduce driver reaction time and should also reduce crashes. Used together, these technologies are likely to greatly decrease the number of crashes in the coming years. However, many of the potential benefits of the new safety technologies will be dissipated unless skid resistance is maintained close to current levels. In addition, higher skid resistance will make these devices even more effective.

There are also a number of factors likely to change the way people travel. Increasing fuel prices and congestion are likely to lead to less travel by private auto and more travel by public transport, walking, cycling, and motorcycling. The increasing use of motorcycles and their higher fatality rate is already a concern. Motorcycle riders are more vulnerable to low skid resistance than are drivers of four-wheeled vehicles, and are particularly vulnerable to inconsistencies in skid resistance. The use of CFME devices should help ensure consistency of skid resistance across high risk sites. An increase in the number of pedestrians also increases the need for higher skid resistance at crosswalks and other areas of potential conflict. Greater emphasis on the provision of high levels of skid resistance to accommodate two wheeled vehicles and pedestrians will be required. The overall conclusion given by Cairney (2011) in evaluating the future of skid resistance was that, “Skid resistance is likely to remain a key element in the provision of a safe road system in the future, although priorities for the detailed manner in which they are provided may change.”

Equipment Calibration/Harmonization

There has been considerable effort in Europe to produce a method for reporting the results of different devices on standard scale, but the results of both the International Friction Index and the later European Friction Index are not sufficiently precise to be of practical use in their current form. The results of the Harmonization of European Routine and Research Measurement Equipment for Skid Resistance of Roads and Runways project, which intended to develop a method for harmonizing measurements from European skid testing devices that would form the basis of a European Standard, were somewhat disappointing. Subsequently there has been further thinking to develop a “road map” for harmonization, which recognizes that restrictions on the measuring and operating principles will be needed to improve precision.

The TYROSAFE project began in 2008 and has now been completed. The project has resulted in a number of important publications, including the 2010 final report and the following documents (TYROSAFE, 2011):

- State of the art report on test methods (D04), which reviews the main measurement principles, the 25 individual devices with precision data available (this includes the main candidates for use in the U.S.), and the required calibration procedures to ensure consistent operation of an individual device and consistency when compared with others of the same type.
- Analysis and findings of previous skid resistance harmonization research projects (D05)

- Report on policies and standards concerning skid/rolling resistance and noise emissions (D06)
- Report on state-of-the-art of test surfaces for skid resistance (D07)
- Recommendations for harmonized [European Union] policies on skid resistance, rolling resistance and noise emission (D08)
- Roadmaps and implementation plan for harmonized skid resistance measurement methods (D09)
- Report on different parameters influencing skid resistance, rolling resistance and noise emissions (D10)

The TYROSAFE work will be a useful resource for a PFM study. Also of value will be the European Enhanced Driver Safety due to Improved Skid Resistance (SKIDSAFE) project, which has the objective of identifying the micro-mechanical factors controlling skid resistance at the pavement-tire interface in asphalt concrete pavements and relating them to asphalt mix characteristics on the basis of experimental data and computational studies.

Friction and Texture Testing Frequencies and Timings

In the U.K., as in the U.S., the friction-testing regime is oriented around testing during the summer months, when friction on its network of roads (over 95 percent of which are asphalt-surfaced) is lowest. This policy appears to be justified, based on the preliminary findings by Amjadi et al. (2011) and the conclusions of Jayawickrama and Thomas (1998), who found that skid resistance is typically higher in the autumn and winter and lower in the spring and summer, and that the seasonal variation can be quite significant, with wider swings for flexible pavements as compared to rigid pavements.

In a full and comprehensive friction/texture testing program, such as the ones implemented in the U.K. and Australia, all pavement sections within a network are tested annually due to year-to-year variations in pavement friction. However, with restraints on resources and limitations on suitable testing periods when greater numbers of crashes occur, a more practical approach to testing is a rolling or cyclical testing regime, whereby portions of the network are tested once every few years (AASHTO, 2008). This type of approach is used by a few SHAs and international agencies.

Seasonal and weather variations have an influence on the friction of pavement surfaces. For this reason, it is important that friction testing be limited to a specific season or time of year when friction is typically lowest. Although an alternative approach of developing and applying correction factors to normalize raw friction test data to a common baseline season (ideally to the time of year when friction is lowest and crash likelihood is highest) exists, this requires extensive modeling of friction throughout the year and even the best models tend to produce results with an unacceptably wide uncertainty band. With such wide uncertainty, skid resistance results are therefore only part of the process of assessing the road condition.

4. FRICTION AND MACROTEXTURE THRESHOLDS

Friction Demand Categories

The 2008 AASHTO Guide for Pavement Friction (GPF) defines pavement friction demand as the level of friction (microtexture and macrotexture) needed to safely perform braking, steering, and acceleration maneuvers. The GPF states that friction demand categories should be established logically and systematically based on highway alignment, highway features/environment, and highway traffic characteristics. It further indicates that friction demand categories should be established for individual highway classes, facility types, or access types, and that the number of demand categories should be kept reasonably small so that a sufficient number of PFM sections are available for each category from which to define investigatory friction levels.

The literature review indicates that agencies use different roadway segmentations and friction demand (or site) categories. Although the number of categories varies from five to ten, the categories do reflect a changing sense of friction demand, with intersection approaches and sharp curves representing the greatest need along with higher-speed and higher-volume roads, while maneuver-free tangents with minimal gradients represent the lowest need along with lower-speed and lower-volume roads.

One interesting concept identified in the review is the establishment of regional zones of surface friction demand that would have an associated recommended minimum level of testing based on contributing risk factors. This approach can be useful in determining an appropriate level of friction testing for the network by prioritizing the network according to risk factors such as average annual rainfall, population density, topography, and traffic. Pavement safety for areas with low risk could be managed solely by crash history or perhaps by macrotexture data collected with high-speed profilers as part of the PFM program. Pavement safety for high risk areas could be managed more aggressively using network-level friction and macrotexture data and crash-based friction investigatory and intervention levels established by the agency for the site category in question.

Examples of Friction Demand Categories and Threshold Values

Washington State

Following the data filtering and reduction into 0.1-mi segments, the data was further divided into friction demand categories, as recommended by the AASHTO GPF. Based on the data available for this study and the factors perceived as having the most influence on the friction-crash relationship, the following four friction demand categories were proposed (Table 2).

Table 2. SCRIM fiction threshold results using GPF Methods 3.

Type of Roadway	SR Investigatory Level
Divided	30-35
Undivided	50-55
Curves	50-55
Intersections	55-60

The trends to establish the macrotexture thresholds were not as clear as the friction analysis, because unlike friction, macrotexture is very different for asphalt and concrete pavements. The GPF reports typical ranges of mean profile depth (MPD) values for different asphalt pavement surfaces between 0.6 to 3.0 mm and for new PCC between 0.7 to 1.4 mm. Combining this information, the values summarized in Table 3 were estimated to illustrate a suggested starting point for selecting macrotexture thresholds, with the warning that these values will need additional assessment.

Table 3. Illustrative level 1 SCRIM macrotexture threshold results using GPF Methods 3.

Type of Roadway	Method 3 MPD Investigatory Level
Divided	0.5 - 0.7 mm
Undivided	0.7 mm
Curves	0.7 mm
Intersections	NA

NA: Not available.

United Kingdom

In 1988, the U.K. Department of Transport first introduced requirements for skid resistance on its trunk road network; it introduced the concept of “investigatory levels” to be compared with measurements from routine skid resistance surveys. At the heart of the process was a link between the risks of wet skidding accidents occurring and the levels of measured skid resistance on the road. Initially, this was based upon a survey of a sample of the network, which at the time was limited by survey capacity and computing power. The skidding standards were revised in 2004 and a new assessment of the link between accident risk and skid resistance was made. This involved a study of the whole trunk road network. The results compared the historic work and the changes that were shown to be appropriate for application in the revised standard introduced in August 2004 (Viner et al., 2005). Table 4 is a modification of the investigatory levels (and ranges for some site categories) currently used in the U.K. Equivalent U.S. road classifications are provided along with the established 30-mph (50 km/h) friction investigatory levels.

The Specifications for Highway Works for Bituminous Materials (Series 900), Clause 921 establishes the initial surface macrotexture for bituminous surface courses and specifies that it shall be measured using the volumetric sand patch method (British Standards EN 13036-1). The values are shown in Table 5.

Table 4. Friction demand categories and friction investigatory levels in the U.K. (Viner et al., 2005).

Road Classification Definitions		Investigatory Level at 30 mph (50 km/h)							
		0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65
A	Motorways (Interstate highways)								
B	Dual carriageways non-event (Divided highways non-event)								
C	Single carriageways non-event (Two-lane roads non event)								
Q	Dual carriageways (all purpose)—minor junctions (Divided highways—intersection/roundabout approaches)								
K	Approaches to pedestrian crossings and other high-risk situations								
R	Roundabouts								
G1	Gradients 5-10%, longer than 50 m (Slopes 5-10%, longer than 160 ft)								
G2	Gradients ≥ 10%, longer than 50 m (Slopes ≥ 10%, longer than 160 ft)								
S1	Bend radius <500 m—dual carriageway (Curve radius <1,600 ft—divided highways)								
S2	Bend radius <500 m—single carriageway (Curve radius <1,600 ft—two-lane highways)								

Notes: No events are tangent segments (no intersections, curves with radius > 1600 feet and slopes < 5%).
A reduction of 0.05 is allowed for categories A, B, C, G2 and S2 in low risk situations such as low traffic levels or where risk is well mitigated and a low incidence of accidents has been observed (pink).

Table 5. Requirements for initial texture depth for trunk roads including motorways.

Road type	Surfacing type	Average / 1,000 m	Average / 10 measures
High Speed roads >50 mph	Thin surface overlay Aggr. size<14mm	MTD > 1.3 mm (MPD 1.4)	MTD > 1.0 mm (MPD 1.0)
	Surface treatments	MTD > 1.5 mm (MPD 1.6)	MTD > 1.2 mm (MPD 1.25)
Lower Speed roads <40 mph	Thin surface overlay Aggr. size<14mm	MTD > 1.0 mm (MPD 1.4)	MTD > 0.9 mm (MPD 0.9)
	Surface treatments	MTD > 1.2 mm (MPD 1.25)	MTD > 1.0 mm (MPD 1.0)
Roundabout, high speed >50 mph	All surfaces	MTD > 1.2 mm (MPD 1.25)	MTD > 1.0 mm (MPD 1.0)
Roundabout, low speed <40 mph	All surfaces	MTD > 1.0 mm (MPD 1.0)	MTD > 0.9 mm (MPD 0.9)

New Zealand

According to Cenek at al. (2011), since the issuing of the T10 Specification for State Highway Skid Resistance Management,

> "Curves with a horizontal radius of curvature less than 250 metres have been effectively managed to a skid resistance level that is 25% greater than for all other curves on rural state highways. This was a consequence of the T10 specification, which aimed to equalize the risk across the state highway network of a skidding crash in the wet by assigning investigatory skid resistance levels (in terms of equilibrium SCRIM coefficient [ESC]) for different site categories, which are related to different friction demands."

The description of these site categories and associated investigatory levels are summarized in Table 6. As the table shows, curves below 250 m horizontal radius of curvature are assigned a higher investigatory level than curves with a horizontal curvature of radius 250 m or greater.

In practice, the policy results in curves below 250 m horizontal radius of curvature being immediately investigated and treated when the skid resistance falls below the TL of 0.4 ESC. Curves equal or greater than 250 m horizontal radius of curvature are immediately treated only when the skid resistance falls below the TL of 0.3 ESC. Table 7 shows the minimum macrotexture requirements for New Zealand (New Zealand Transport Agency, 2010).

Table 6. T10:2002 skid site categories.

<table>
<tr><th>Site Category</th><th>Description</th><th colspan="3">Notes</th><th colspan="3">Investigatory Level (ESC)</th><th>Skid assessment Length (m)</th></tr>
<tr><td>5</td><td>Divided carriageway</td><td colspan="3">Event free</td><td colspan="3">0.35</td><td>100</td></tr>
<tr><td>4</td><td>Normal roads</td><td colspan="3">Undivided carriageways only (event free)</td><td colspan="3">0.40</td><td>100</td></tr>
<tr><td>3d</td><td>Roundabouts, circle only</td><td colspan="3">Circular section only</td><td colspan="3" rowspan="3">0.45</td><td>60</td></tr>
<tr><td>3b and 3c</td><td>Down Gradients 5% -10%</td><td colspan="3">Includes motorway on/off ramps</td><td>50</td></tr>
<tr><td>3a</td><td>Approaches to junctions</td><td colspan="3"></td><td>60</td></tr>
<tr><td rowspan="4">2</td><td>Urban curves R < 250m</td><td colspan="3">All risks</td><td colspan="3">0.50</td><td rowspan="4">50</td></tr>
<tr><td>Rural curves R < 250m</td><td>Low risk</td><td>Med risk</td><td>High risk</td><td>0.45</td><td>0.50</td><td>0.55</td></tr>
<tr><td>Rural curves,
250 <R < 400m</td><td>Low risk</td><td>Med risk</td><td>High risk</td><td>0.40</td><td>0.50</td><td>0.55</td></tr>
<tr><td>Down Gradients > 10%</td><td colspan="3">Includes on ramps with ramp metering</td><td colspan="3">0.50</td></tr>
<tr><td>1</td><td>Highest priority</td><td colspan="3">Railway level crossing, approaches to roundabouts, traffic lights, Pedestrian crossings and similar Hazards</td><td colspan="3">0.55</td><td>60</td></tr>
</table>

Table 7. Minimum macrotexture requirements for New Zealand (New Zealand Transport Agency, 2010).

Minimum macrotexture – Mean Profile Depth (MPD in mm)						
Permanent speed limit PSL (km/h)	Chip Seal		Asphaltic concrete ESC > 0.40		Asphaltic concrete ESC < 0.40	
	ILM[1]	TLM[2]	ILM	TLM	ILM	TLM
PSL < 50	1.00	0.70	0.40	0.30	0.50	0.50
50<PSL<70	1.00	0.70	0.40	0.30	0.70	0.50
PSL > 70	1.00	0.70	0.40	0.30	0.90	0.70

[1] Investigatory level for macrotexture
[2] Threshold level for macrotexture

To gather the complete texture data and overcome the limitations of static test methods, dynamic methods, such as high-frequency laser equipment, have been developed and applied for texture measurement (McGhee & Flintsch, 2003). With this type of laser equipment, significant resolution of texture measurements has been achieved at highway speeds.

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