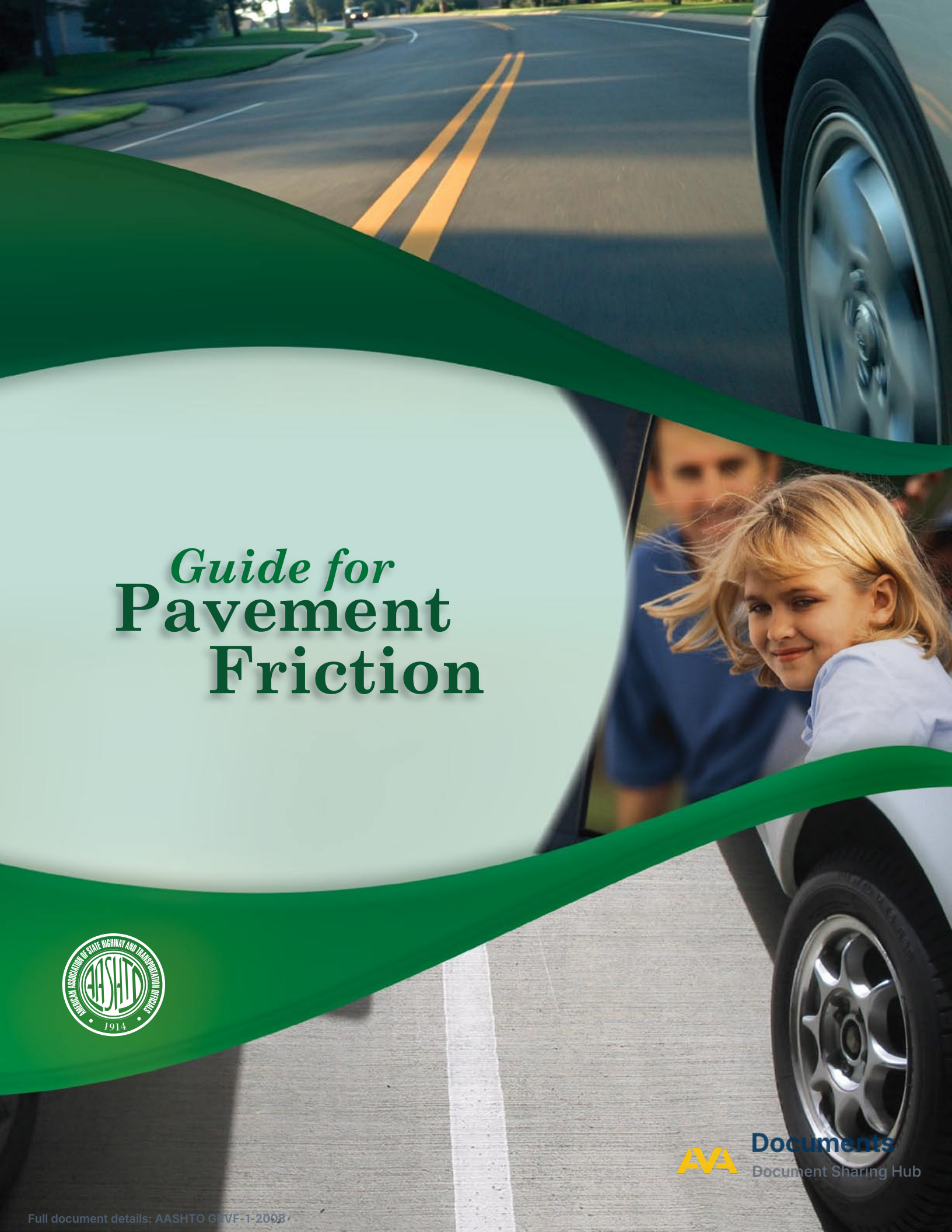


The background of the cover is a composite image. The top half shows a road with double yellow lines curving into the distance. The bottom half shows a close-up of a car's front wheel and a young child with blonde hair, wearing a light blue shirt, looking out from the car window. A large, light green, curved shape overlaps the road and car images, serving as a backdrop for the title.

Guide for **Pavement Friction**



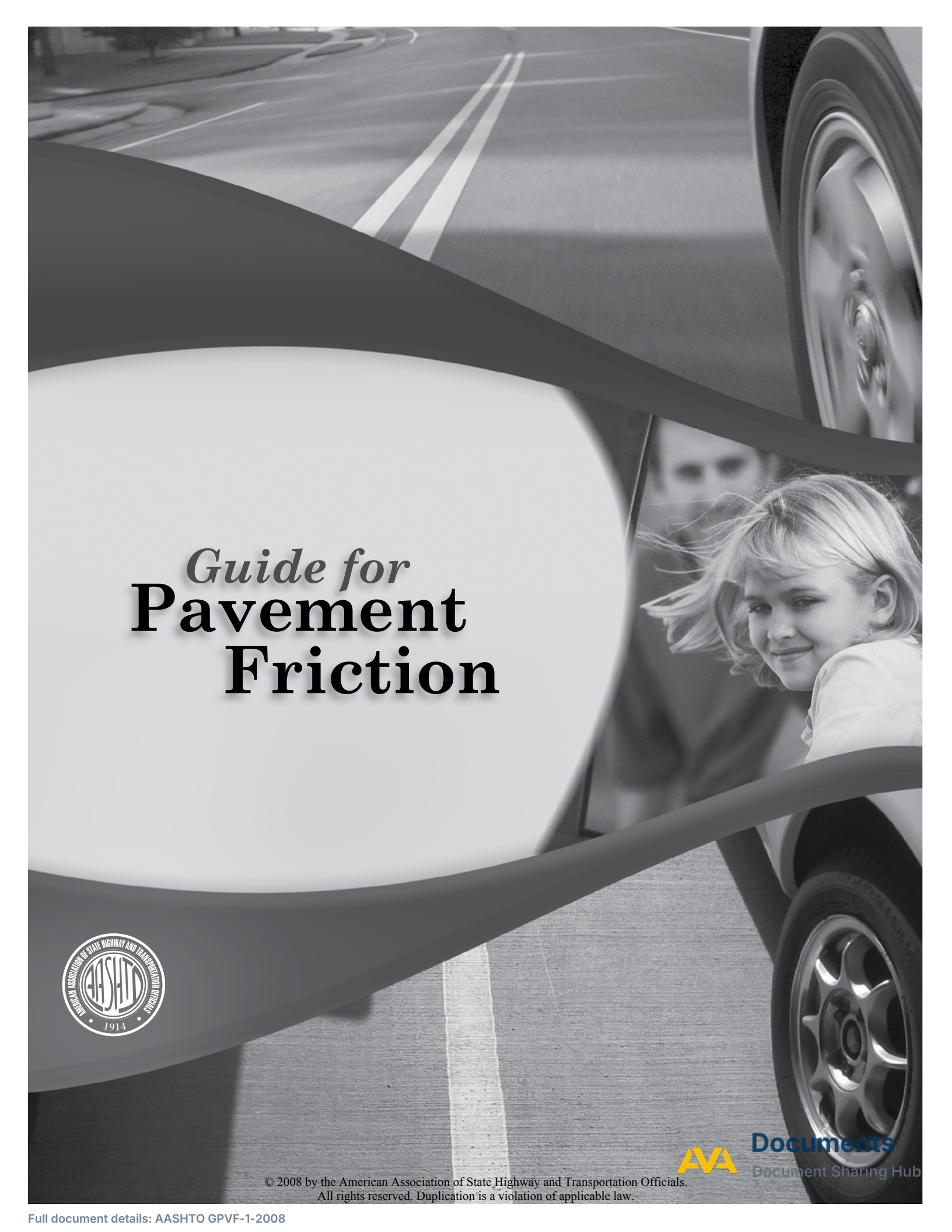
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The background of the cover is a grayscale photograph. It shows a road with white lane markings receding into the distance. On the right side, there is a close-up of a car's front wheel and a young child with blonde hair leaning out of the car window, smiling. The title text is overlaid on a large, light-colored, curved shape that resembles a road or a car's body.

Guide for **Pavement Friction**



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Abstract

This report contains guidelines and recommendations for managing and designing for friction on highway pavements. The contents of this report will be of interest to highway materials, construction, pavement management, safety, design, and research engineers, as well as others concerned with the friction and related surface characteristics of highway pavements.

Information is presented that emphasizes the importance of providing adequate levels of friction for the safety of highway users. The factors that influence friction and the concepts of how friction is determined (based on measurements of surface micro-texture and macro-texture) are discussed. Methods for monitoring the friction of in-service pavements and determining appropriate actions in the case of friction deficiencies (friction management) are described. Also, aggregate tests and criteria that help attain adequate micro-texture are presented, followed by a discussion of how paving mixtures and surface texturing techniques can be selected so as to impart the macro-texture required to achieve the design friction level.



Chapter 1

Introduction

1.1 Background

Pavement–tire friction (or, simply, pavement friction) is one of many factors determining highway safety and, in particular, the probability of wet skidding crashes. Highway agencies have recognized this fact since the 1920s (Moyer, 1959). The probability of wet skidding crashes is reduced when friction between a vehicle tire and pavement is high.

Skid-related crashes are determined by many factors, wet pavement friction being only one of them. Other factors, such as road geometry, traffic characteristics, vehicle speed, driver action, and weather conditions, must be considered together with friction data when evaluating the safety of a particular section of roadway.

The *Guide for Pavement Friction, Guidelines for Skid-Resistant Pavement Design*, published by the American Association of State Highway and Transportation Officials (AASHTO) in 1976, recommended pavement specifications that would yield the desired frictional properties upon completion of construction and that would maintain adequate long-term friction. This guide discussed the importance of aggregate selection and mixture design for both asphalt- and concrete-surfaced pavements, and the role of micro-texture and macro-texture in pavement surface friction.

Although much research has been conducted on pavement surface characteristics and pavement–tire interactions since development of the 1976 guide, the available information is somewhat fragmented and has not been integrated into a comprehensive, systematic approach for identifying friction needs and determining the optimum pavement strategy. Exacerbating the problem are the changes that have taken place with time, including changes in pavement construction materials and mixture design properties, construction procedures and standards, vehicle and tire characteristics, traffic loading, and friction-testing methods and equipment.

Continued introduction of new materials and technologies, coupled with the increasing focus on the needs of the highway user (safer and more comfortable roads), has placed even greater demands on highway engineers to design and build longer-lasting, cost-effective pavements. This *Guide for Pavement Friction* should help highway engineers accomplish such a task.

1.2 Purpose and Scope of Guide

This *Guide for Pavement Friction* was prepared under NCHRP Project 1-43 to provide highway pavement practitioners with guidance in designing, constructing, and managing pavement surfaces—as part of both new and rehabilitation projects—that meet the public’s demand for safe friction levels, while recognizing and considering the effects of noise generation and other pavement–tire interaction issues (e.g., splash and spray, tire wear).

The guide contains recommendations and tools for upper-level administrators and policy-makers, as well as front-line pavement designers and managers. These recommendations are intended to supplement but not replace an agency’s normal structural and/or mix design practices. The guide covers the following topics:

- Characteristics of pavement materials and surfaces that contribute to adequate wet-weather friction;
- Friction-testing methods, equipment, and indices;
- Methods for establishing friction levels that signify (a) design of new pavement surfaces, (b) increased potential for skid-related crashes, and (c) the immediate need for friction restoration; and
- Guidance for aggregates, mixtures, and surface types that result in long-lasting, high-quality friction surfaces, with proper consideration of noise, economics, and other friction-related issues (e.g., splash and spray, hydroplaning, tire wear).

The guide addresses both asphalt (i.e., flexible and semi-rigid) and concrete (i.e., rigid) pavements associated with both original construction (i.e., new construction and reconstruction) and maintenance and rehabilitation (M&R) treatments. It does not address winter maintenance issues (i.e., snow and ice removal/treatment) and does not deal with unpaved surfaces or non-highway pavements.

1.3 Guide Organization and Use

The guide is divided into four chapters dealing with the importance of pavement friction, the basic concepts of friction, how friction is measured and managed, and how to design for friction. Following this introductory chapter, Chapter 2 discusses the importance of providing adequate levels of friction for the safety of highway users and it provides an overview of pavement friction (what it is, what influences it) and describes the equipment and methods used to measure and report friction and texture.

Chapter 3 discusses friction from the management standpoint, covering both policy development and the application of procedures for monitoring and restoring friction, based on the principle of friction supply versus friction demand. Chapter 4 guides the user through the surface friction design process. It discusses the development of design policies that help promote long-term, network-wide friction improvements, and provides project-level how-to guidance for designing pavements with proper friction. Lastly, a glossary of terms is included in Appendix A to facilitate understanding of the terminology and nomenclature contained in the guide, and a list of standards relevant to pavement friction is provided in Appendix B.



Chapter 2

Pavement Friction Overview

2.1. Importance of Pavement Friction

2.1.1 Highway Safety

Between 1990 and 2003, an average of 6.4 million highway crashes (all vehicle types) occurred annually on the nation's highways, resulting in 3 million injuries, 42,000 fatalities, and countless amounts of pain and suffering. This rate of fatality equates to 115 fatalities per day, or 1 death every 12 minutes (Noyce et al., 2005; National Highway Traffic Safety Administration [NHTSA], 2004). In 2000, the cost of highway crashes was estimated at \$230.6 billion (Noyce et al., 2005; NHTSA, 2004).

Figures 2-1 and 2-2 present summaries of the total number of crashes and resulting fatalities in the United States between 1988 and 2006. According to the National Transportation Safety Board (NTSB) and the FHWA, approximately 13.5 percent of fatal crashes and 25 percent of all crashes occur when roads are wet (Kuemmel et al., 2000).

One or more factors contribute to highway crashes. These factors fall under three main categories: driver-related, vehicle-related, and highway condition-related (Noyce et al., 2005). Of these three categories, only highway condition can be controlled by highway agencies through design, construction, maintenance, and management practices and policies. Although many highway-related conditions influence safety (e.g., geometric design, intersection and roadside design, pavement surface conditions [friction, texture, distress, smoothness]), this guide focuses on the provision and maintenance of adequate levels of friction.

2.1.2 Crash Reduction

The friction developed between vehicle tires and a pavement surface is a critical factor in controlling and reducing crashes (Henry, 2000; Ivey et al., 1992). Studies conducted in the United States and elsewhere have generally shown that wet-weather crash rates increase as pavement friction decreases (all other factors such as speed and traffic volumes remaining the same). For instance, as seen in Figure 2-3, crash and measured pavement friction data obtained from mostly rural interstates and parkway roads in Kentucky (Rizenbergs et al., 1973) showed wet crash rates decreased with increased pavement friction values (*SN40*, skid/friction number determined with a locked-wheel friction tester operated at 40 mi/h [64 km/h]) for low and moderate traffic levels.

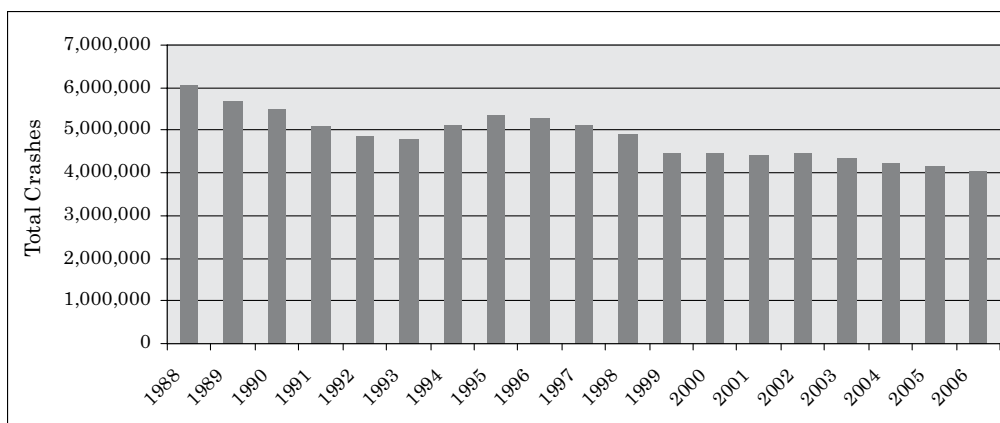


Figure 2-1. Total Crashes (from All Vehicle Types) on U.S. Highways from 1988 to 2006 (*NHTSA, 2007*).

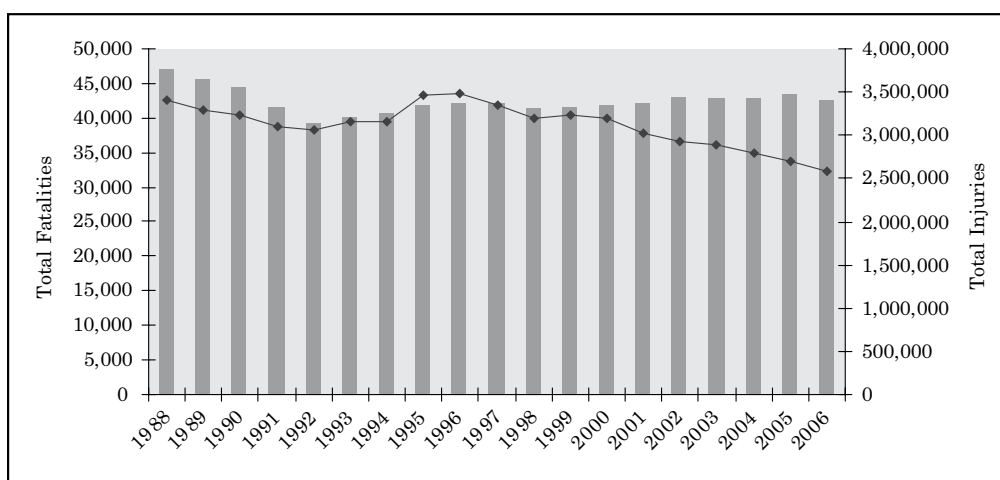


Figure 2-2. Total Fatalities and Injuries (from All Vehicle Types) on U.S. Highways from 1988 to 2006 (*NHTSA, 2007*).

In a study for the Texas Department of Transportation (TXDOT), McCullough et al. (1966) found increasing fatal and injury crashes with decreasing coefficient of friction at 50 mi/h (80 km/h). More recent research in this area (Agent et al., 1996; Wallman and Astrom, 2001) has provided similar trends, emphasizing the need to design for, monitor, and expeditiously restore pavement surface friction properties. Recent research in the United Kingdom also indicated an increase in crash risk as friction levels are reduced. Figure 2-4 provides the relationships determined in that study for tangent alignments in wet conditions using the SCRIM device at 13 percent slip. (Viner et al., 2004).

Although research has confirmed a basic relationship between pavement friction and wet crash rates, it has not established an exact relationship nor identified any specific threshold friction values below which wet crash rates increase substantially (Henry, 2000; Larson, 1999). This is because friction demand (i.e., the level of friction needed to prevent a vehicle from slipping or sliding) varies with location and time due to changing site conditions, traffic characteristics, and driver/vehicle characteristics. While a particular friction value may satisfy demand at one location and at one moment in time, the same value may not satisfy the demand at another location or at a different

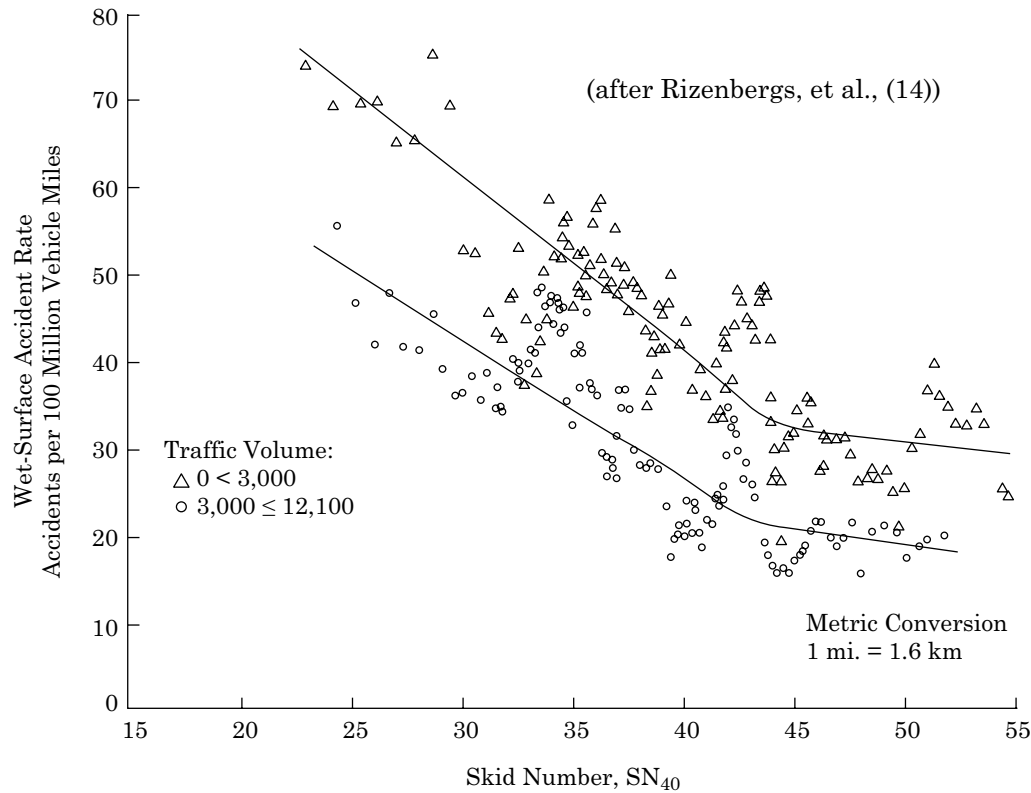
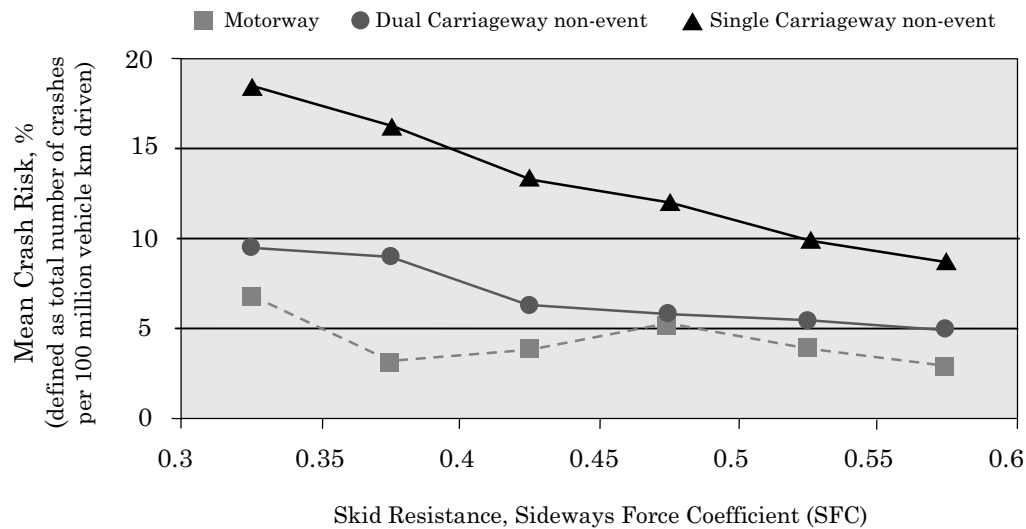


Figure 2-3. Relationship between Wet-Weather Crash Rates and Pavement Friction (*Rizenbergs et al., 1973*).



Note: Dual Carriageway = 4-lane divided highway, Single Carriageway = undivided highway;
Non-Event = segments with no junctions, crossings, or notable bends or gradients).

Figure 2-4. Mean Crash Risk for Roadway Network in the United Kingdom (*Viner et al., 2004*).

moment in time. Thus, control of friction at the network level must be based on periodic assessments of friction (and crashes) at the pavement segment/unit level.

2.2 Pavement Friction Principles

2.2.1 Definition (of Pavement Friction)

Pavement friction is the force that resists the relative motion between a vehicle tire and a pavement surface. This resistive force (illustrated in Figure 2-5) is generated when the tire rolls or slides over the pavement surface. A measure of the resistive force is the non-dimensional coefficient of friction, μ , which as expressed in Equation 2-1, is the ratio of the tangential friction force (F) between the tire tread rubber and the horizontal traveled surface to the perpendicular force or vertical load (F_w).

$$\mu = \frac{F}{F_w} \quad (2-1)$$

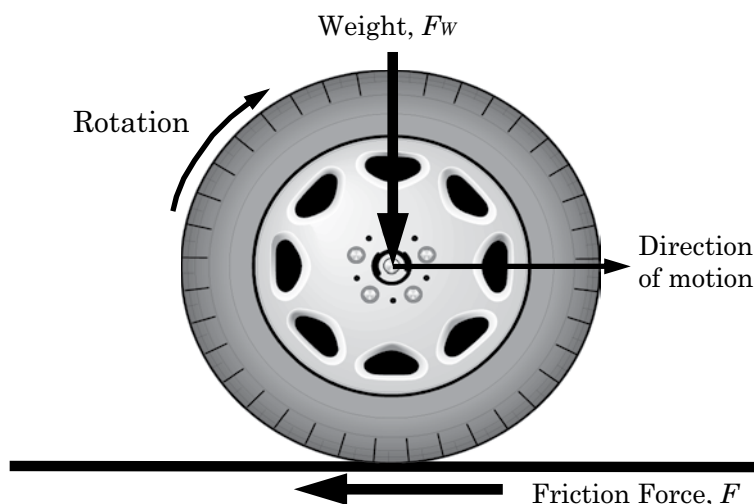


Figure 2-5. Simplified Diagram of Forces Acting on a Rotating Wheel.

Longitudinal Friction

For the longitudinal dynamic friction process between a rolling pneumatic tire and the road surface, there are two modes of operation—free-rolling and constant-braked. In the free-rolling mode (no braking), the relative speed between the tire circumference and the pavement—referred to as the slip speed—is zero. In the constant-braked mode, the slip speed increases from zero to a potential maximum of the speed of the vehicle. The following mathematical relationship explains slip speed (Meyer, 1982):

$$S = V - V_p = V - (0.68 \times \omega \times r) \quad (2-2)$$

where:

- S = Slip speed, mi/h,
- V = Vehicle speed, mi/h,

V_p = Average peripheral speed of the tire, mi/h,
 ω = Angular velocity of the tire, radians/sec, and
 r = Average tire radius, ft.

A locked-wheel state is often referred to as a 100 percent slip ratio and the free-rolling state is a zero percent slip ratio.

The coefficient of friction between a tire and the pavement changes with varying slip, as shown in Figure 2-6 (Henry, 2000). The coefficient of friction increases rapidly with increasing slip to a peak value that usually occurs between 10 and 20 percent slip (critical slip). The friction then decreases to a value known as the coefficient of sliding friction, which occurs at 100 percent slip. The difference between the peak and sliding coefficients of friction may equal up to 50 percent of the sliding value, and this disparity is much greater on wet pavements than on dry pavements.

Vehicles with an anti-lock braking system (ABS) are designed to apply the brakes on and off (i.e., pump the brakes) repeatedly, such that the slip is held near the peak. The braking is turned off before the peak is reached and turned on at a set time or percent slip below the peak. The actual timing is a proprietary design feature.

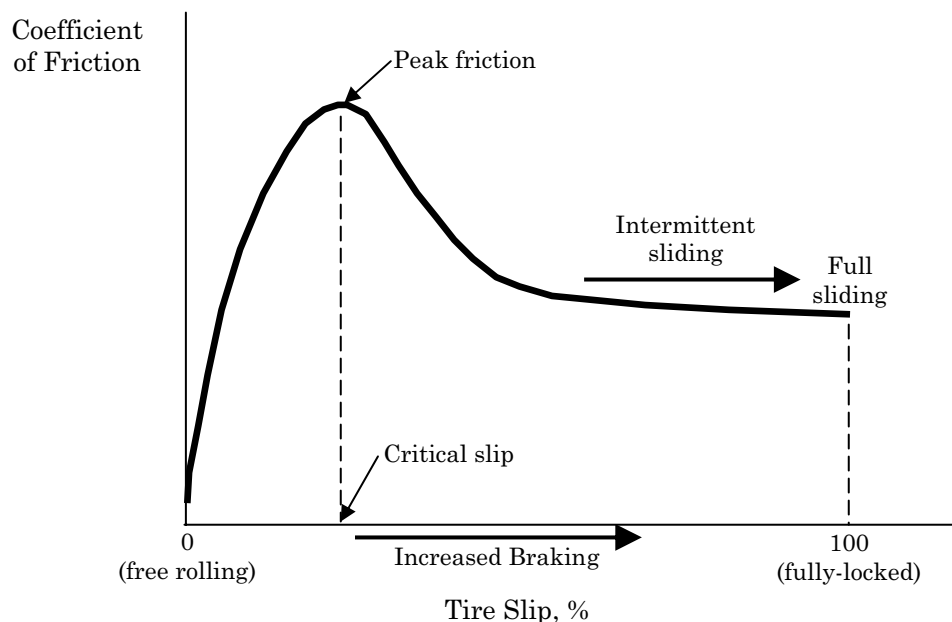


Figure 2-6. Pavement Longitudinal Friction Versus Tire Slip (Henry, 2000).

Side Force Friction

Another important aspect of friction relates to the lateral or side force friction that occurs as a vehicle changes direction or compensates for pavement cross-slope and/or cross-wind effects. The pavement–tire steering/cornering force diagram in Figure 2-7 shows how the side force friction factor acts as a counter balance to the centripetal force developed as a vehicle performs a lateral movement. The basic relationship between the forces acting on the vehicle tire and the pavement surface as the vehicle steers around a curve, changes lanes, or compensates for lateral forces is as follows (AASHTO, 2004):

$$F_s = \frac{V^2}{15R} - e \quad (2-3)$$

where:

- F_s = Side friction,
 V = Vehicle speed, mi/h,
 R = Radius of the path of the vehicle's center of gravity
 (also, the radius of curvature in a curve), ft, and
 e = Pavement superelevation, ft/ft.

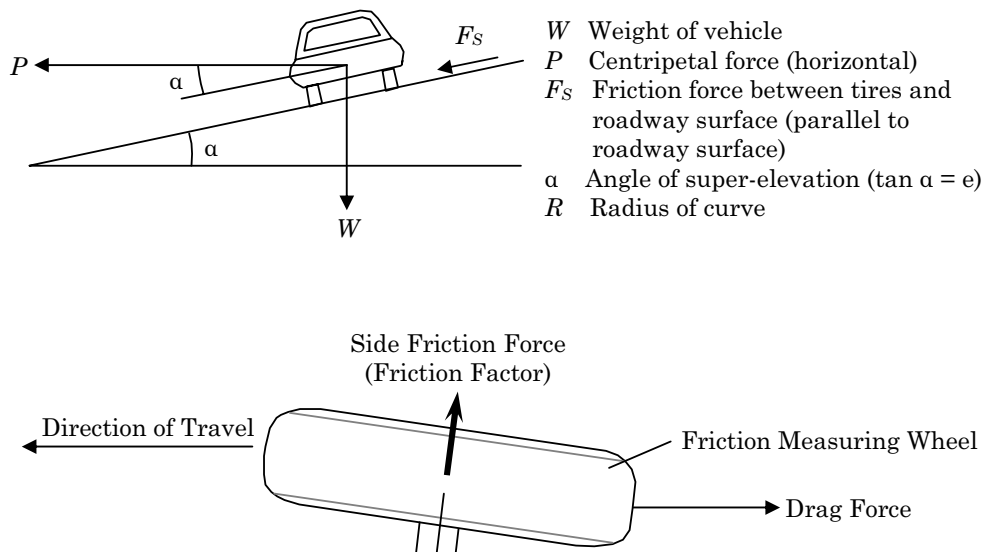


Figure 2-7. Dynamics of a Vehicle Traveling around a Constant Radius Curve at a Constant Speed, and the Forces Acting on the Rotating Wheel.

Combined Braking and Cornering

With combined braking and cornering, a driver either risks not stopping as rapidly or losing control due to reduced lateral/side forces. When operating at the limits of tire grip, the interaction of the longitudinal and lateral forces is such that as one force increases, the other must decrease by a proportional amount. Commonly referred to as the friction circle or friction ellipse (Radt and Milliken, 1960), the vector sum of the two combined forces when depicted graphically (longitudinal force on the x-axis and lateral force on the y-axis, or vice versa) remains constant (circle) or near constant (ellipse). When operating within the limits of time grip the amount of braking and turning friction components can vary independently as long as the vector sum of these components does not exceed the limits of tire grip as defined by the friction circle or friction ellipse. The degree of ellipse or circle depends on the tire and pavement properties. (Gillespie, 1992)

2.2.2 Mechanisms

Pavement friction is the result of a complex interplay between two principal frictional force components—adhesion and hysteresis (Figure 2-8). Although there are other components of pavement friction (e.g., tire rubber shear), they are insignificant when compared to the adhesion and hysteresis force components. Thus, friction can be viewed as the sum of the adhesion and hysteresis frictional forces:

$$F = F_A + F_H \quad (2-4)$$

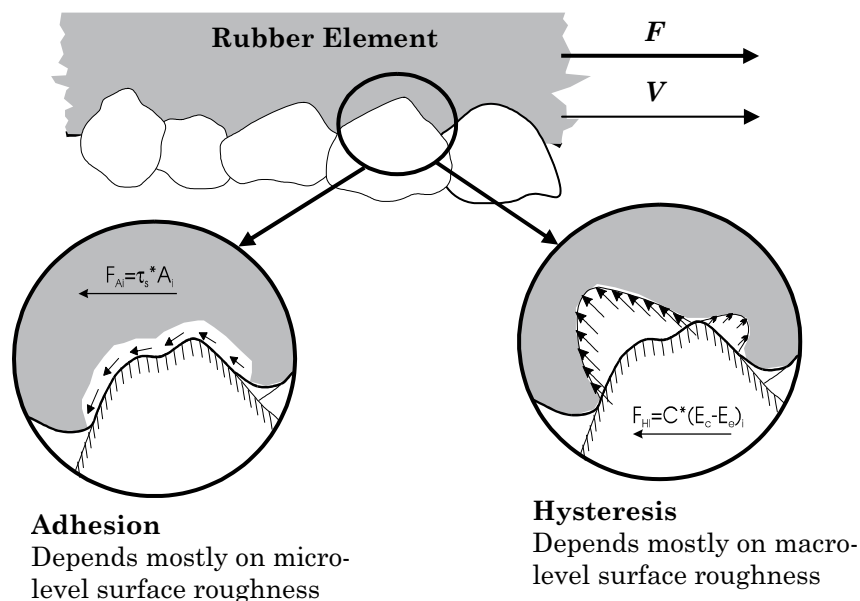


Figure 2-8. Key Mechanisms of Pavement–Tire Friction.

Adhesion is the friction that results from the small-scale bonding/interlocking of the vehicle tire rubber and the pavement surface as they come into contact with each other. It is a function of the interface shear strength and contact area. The hysteresis component of frictional forces results from the energy loss due to bulk deformation of the vehicle tire. The deformation is commonly referred to as enveloping of the tire around the texture. When a tire compresses against the pavement surface, the stress distribution causes the deformation energy to be stored within the rubber. As the tire relaxes, part of the stored energy is recovered, while the other part is lost in the form of heat (hysteresis), which is irreversible. That loss leaves a net frictional force to help stop the forward motion.

Surface texture influences both mechanisms. The adhesion force is proportional to the real area of adhesion between the tire and surface asperities. The hysteresis force is generated within the deflecting and visco-elastic tire tread material, and is a function of speed. Generally, adhesion is related to micro-texture, whereas hysteresis is mainly related to macro-texture. For wet pavements, adhesion drops off with increased speed, while hysteresis increases with speed. Also, because tire rubber is a visco-elastic material, each component is affected by temperature and sliding speed.

2.2.3 Factors Affecting Available Pavement Friction

The factors that influence pavement friction forces can be grouped into four categories—pavement surface characteristics, vehicle operational parameters, tire properties, and environmental factors. Table 2-1 lists the various factors comprising each category. Because each factor in this table plays a role in defining pavement friction, friction must be viewed as a process instead of an inherent property of the pavement. It is only when all these factors are fully specified that friction takes on a definite value.

The more critical factors are shown in bold in Table 2-1 and are briefly discussed below. Among these factors, the ones considered to be within a highway agency's control are micro- and macro-texture, pavement material properties, and slip speed.

Table 2-1. Factors Affecting Available Pavement Friction (*Wallman and Astrom, 2001*)

Pavement Surface Characteristics	Vehicle Operating Parameters	Tire Properties	Environment
Micro-texture Macro-texture Mega-texture/ unevenness Material properties Temperature	Slip speed ▪ vehicle speed ▪ braking action Driving maneuver ▪ turning ▪ overtaking	Foot Print Tread design and condition Rubber composition and hardness Inflation pressure Load Temperature	Climate ▪ Wind ▪ Temperature ▪ Water (rainfall, condensation) ▪ Snow and Ice Contaminants ▪ Anti-skid material (salt, sand) ▪ Dirt, mud, debris

Note: Critical factors are shown in bold.

Pavement Surface Texture

Pavement surface texture is made up of the deviations of the pavement surface from a true planar surface. These deviations occur at three distinct levels of scale, each defined by the wavelength (λ) and peak-to-peak amplitude (A) of its components. The three levels of texture, as established by the Permanent International Association of Road Congresses—also known as World Road Association—(PIARC) (1987), are as follows:

- Micro-texture ($\lambda < 0.02$ in. [0.5 mm], $A = 0.04$ to 20 mils [1 to 500 μm])—Surface roughness quality at the sub-visible/microscopic level. It is a function of the surface properties of the aggregate particles within the asphalt or concrete paving material.
- Macro-texture ($\lambda = 0.02$ to 2 in. [0.5 to 50 mm], $A = 0.005$ to 0.8 in. [0.1 to 20 mm])—Surface roughness quality defined by the mixture properties (shape, size, and gradation of aggregate) of an asphalt paving material and the method of finishing/texturing (dragging, tining, grooving; depth, width, spacing, and orientation of channels/grooves) used on a concrete paving material.
- Mega-texture ($\lambda = 2$ to 20 in. [50 to 500 mm], $A = 0.005$ to 2 in. [0.1 to 50 mm])—This type of texture is the texture which has wavelengths in the same order of size as the pavement–tire interface. It is largely defined by the distress, defects, or “waviness” on the pavement surface.

Wavelengths longer than the upper limit (20 in. [500 mm]) of mega-texture are defined as roughness or unevenness (Henry, 2000). Figure 2-9 illustrates the three texture ranges, as well as a fourth level—roughness/unevenness—representing wavelengths longer than the upper limit (20 in. [500 mm]) of mega-texture (Sandburg, 1998).

It is widely recognized that pavement surface texture influences many different pavement–tire interactions. Figure 2-10 shows the ranges of texture wavelengths affecting various vehicle–road interactions, including friction, interior and exterior noise, splash and spray, rolling resistance, and tire wear. As can be seen, friction is affected primarily by micro-texture and macro-texture, which correspond to the adhesion and hysteresis friction components, respectively.

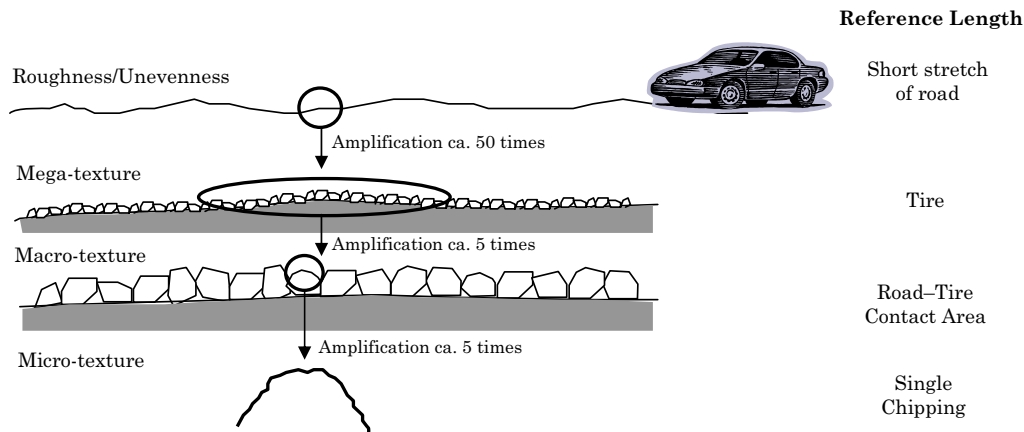
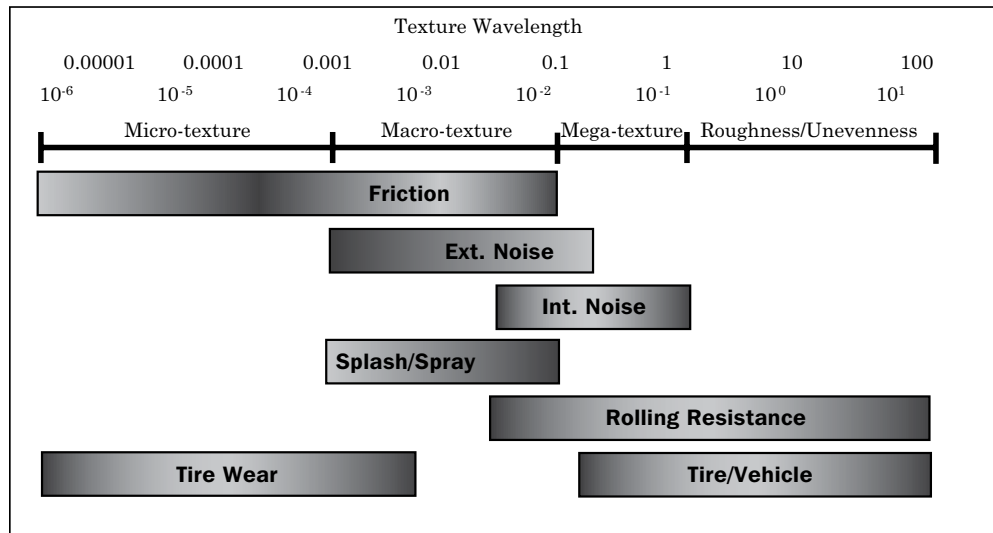


Figure 2-9. Simplified Illustration of the Various Texture Ranges that Exist for a Given Pavement Surface (Sandburg, 1998).



Note: Darker shading indicate more favorable effect of texture over the range.

Figure 2-10. Texture Wavelength Influence on Pavement-Tire Interactions (adapted from Henry, 2000 and Sandburg and Ejsmont, 2002).

At low speeds, micro-texture dominates the wet and dry friction level. At higher speeds, the presence of high macro-texture facilitates the drainage of water so that the adhesive component of friction afforded by micro-texture is re-established by being above the water. Hysteresis increases with speed exponentially, and at speeds above 65 mi/h (105 km/h) accounts for over 95 percent of the friction (PIARC, 1987).

Pavement Surface Material Properties

Pavement material properties (i.e., aggregate and mix characteristics, surface texturings) influence both micro-texture and macro-texture. These properties also affect the long-term durability of texture through their capacities to resist aggregate polishing and abrasion/wear of both aggregate and mix under accumulated traffic and environmental loadings.

Slip Speed

The coefficient of friction between a tire and the pavement changes with varying slip. It increases rapidly with increasing slip to a peak value that usually occurs between 10 and 20 percent slip. The friction then decreases to a value known as the coefficient of sliding friction, which occurs at 100 percent slip.

Tire Tread Design and Condition

Tire tread design (i.e., type, pattern, and depth) and condition have a significant influence on draining water that accumulates at the pavement surface. Water trapped between the pavement and the tire can be expelled through the channels provided by the pavement macro-texture and by the tire tread. Tread depth is particularly important for vehicles driving over thick films of water at high speeds. Some studies (Henry, 1983) have reported a decrease in wet friction of 45 to 70 percent for fully worn tires as compared to new ones.

Tire Inflation Pressure

Tire over-inflation causes only a small loss of pavement friction, whereas tire under-inflation can significantly reduce friction at high speeds (Henry, 1983; Kulakowski, 1990). This is because of the constriction of drainage channels within the tire tread and reduced contact pressure.

Temperature

Modern rubber compounds are formulated to remove the effect of temperature on friction under normal running speeds and temperatures. However, friction is reduced at high temperatures where the rubber becomes soft because hysteresis is affected by the visco-elastic property of the tire. These higher temperatures are typically only reached when a lot of braking is performed. Perhaps the biggest effect is under locked-wheel conditions, where the rubber can melt and cause rubber hydroplaning.

Surface Water

The effect of surface water layer depth (or water film thickness [WFT]) on friction is minimal at low speeds (<20 mi/h [32 km/h]) and quite pronounced at higher speeds (>40 mi/h [64 km/h]). The coefficient of friction of a vehicle tire sliding over a wet pavement surface, decreases exponentially as WFT increases. The effect of WFT is influenced by tire design and condition, with worn tires being most sensitive to WFT.

A particularly hazardous situation involving relatively thick water films and vehicles traveling at higher speeds is hydroplaning. Hydroplaning occurs when a vehicle tire is separated from the pavement surface by the water pressure that builds up at the pavement–tire interface (Horne and Buhlmann, 1983), causing friction to drop to near zero. This phenomenon is affected by several parameters, including water depth, vehicle speed, pavement macro-texture, tire inflation pressure and tread depth, and tire contact area.

Snow and Ice

Snow and ice covering the pavement surface present the most hazardous condition for vehicle braking or cornering. The level of friction between the tires and the snow- or ice-covered pavement

is such that almost any abrupt braking or sudden change of direction results in locked-wheel sliding and loss of vehicle directional stability. This guide does not address winter-related friction issues.

2.2.4 Friction and Texture Measurement Methods

Overview

The measurement of pavement friction and texture has been of primary importance to state highway agencies (SHAs) for at least 50 years. Many different types of equipment have been developed and used to measure these properties. Their differences, in terms of measurement principles and procedures and the way measurement data are processed and reported, can be significant.

For friction-testing alone, there are several commercial devices that can operate at fixed or variable slip, at speeds up to 100 mi/h (161 km/h), and under variable test tire conditions, such as load, size, tread design and construction, and inflation pressure. Measurement of pavement surface texture can be done using a variety of laser devices, volumetric techniques, water drainage rates (outflow meter), and sliding rubber pad apparatus (portable British Pendulum Tester [BPT]). This section provides an overview of the different friction and texture measurement methods and available representative equipment.

Methods and Equipment

AASHTO and ASTM have developed a set of surface characteristic standards and measurement practice standards for both friction and texture. These standards ensure comparability of the measurements for specific purposes; they are grouped according to measurements performed at highway speeds (i.e., high-speed devices) and measurements requiring lane closure (i.e., low-speed/walking and stationary devices).

In general, the measurement devices requiring lane closure are simpler and relatively inexpensive, whereas the highway-speed devices are more expensive and require more training to maintain and operate. With the recent development of technology in data acquisition, sensor technology, and data processing power of computers, the once true superiority of data quality for the stationary and low-speed devices is diminishing. The resolution and accuracy of the acquired data for the measurement devices that are low-speed or stationary can still surpass that of the high-speed devices, but with smaller and smaller margins.

The locked-wheel friction tester (AASHTO T 242) is the predominant high-speed device used on U.S. roads. This device requires a tow vehicle and a locked-wheel skid trailer, equipped with either a standard ribbed tire (AASHTO M 261) or a standard smooth tire (AASHTO M 286). Friction measurements are obtained by locking the test tire (ribbed or smooth) on a wetted pavement surface while traveling at a specified speed (40 mi/h [64 km/h] is the standard speed given in AASHTO T 242). The smooth tire is more sensitive to pavement macro-texture, while the ribbed tire is more sensitive to micro-texture changes in the pavement.

Portable friction measurement equipment requiring lane closures include the BPT (AASHTO T 278) and the Dynamic Friction Tester (DFT) (ASTM E 1911).

- The manually operated BPT provides an indicator of friction through the swinging of a pendulum-based rubber slider and its contact with the pavement surface. The elevation to

which the pendulum swings after contact provides the basis for the friction indicator, termed British Pendulum Number (*BPN*).

- The DFT is an electronic modular system that measures the torque necessary to rotate three small, spring-loaded rubber pads in a circular path over a wetted pavement surface at different speeds. Results are typically recorded at 12, 24, 36, and 48 mi/h (20, 40, 60, and 80 km/h), from which the speed–friction relationship is plotted.

High-speed texture measuring equipment includes laser profilers, such as the FHWA Road Surface Analyzer (ROSANV). These non-contact devices use a combination of a horizontal distance measuring device, a very high-speed (64 kHz or higher) laser triangulation sensor, and a portable computer to collect and store pavement surface elevations (vertical resolution usually 0.002 in. [0.05 mm] or better) at intervals of 0.01 in. (0.25 mm) or less. From these elevations, the system calculates the mean profile depth (*MPD*), which is an overall measure of macro-texture.

Texture measuring equipment requiring lane closures include the Sand Patch Method (SPM) (ASTM E 965), the Outflow Meter (OFM) (ASTM E 2380), and the Circular Texture Meter (CTM) (ASTM E 2157).

- The SPM is a volumetric-based spot test method that assesses pavement surface macro-texture through the spreading of a known volume of glass beads in a circle onto a cleaned surface and the measurement of the diameter of the resulting circle. The volume divided by the area of the circle is reported as the mean texture depth (*MTD*).
- The OFM is a volumetric test method that measures the water drainage rate through surface texture and interior voids. It indicates the hydroplaning potential of a surface by relating to the escape time of water beneath a moving tire. The equipment consists of a cylinder with a rubber ring on the bottom and an open top. Sensors measure the time required for a known volume of water to pass under the seal or into the pavement. The measurement parameter, outflow time (*OFT*), defines the macro-texture; high *OFT*s indicating smooth macro-texture and low *OFT*s rough macro-texture.
- The CTM is a non-contact laser device that measures the surface profile along an 11.25-in. (286-mm) diameter circular path of the pavement surface at intervals of 0.034 in. (0.868 mm). The texture meter device rotates at 20 ft/min. (6 m/min) and generates profile traces of the pavement surface, which are transmitted and stored on a portable computer. Two different macro-texture indices can be computed from these profiles: mean profile depth (*MPD*) and root mean square (*RMS*). The *MPD*, which is a two-dimensional estimate of the three-dimensional *MTD* (Flintsch et al., 2003), represents the average of the highest profile peaks occurring within eight individual segments comprising the circle of measurement. The *RMS* is a statistical value, which offers a measure of how much the actual data (measured profile) deviates from a best-fit (modeled profile) of the data (McGhee and Flintsch, 2003).

Friction Indices

Friction indices have been in use for a long time. In 1965, ASTM started the use of the Skid Number (*SN*) (ASTM E 274) as an alternative to the coefficient of friction. In later years, AASHTO adopted the ASTM E 274 as AASHTO T 242 test method and changed the terminology from Skid Number to Friction Number (*FN*). In the early 1990s, PIARC developed the International Friction Index (IFI),

based on the PIARC international harmonization study. A refined IFI model was developed shortly thereafter as part of a Ph.D. thesis (Rado, 1994).

The use of friction indices has allowed for harmonization of the different sensitivities of the various friction measurement principles to micro-texture and macro-texture. Provided below are brief discussions of these primary friction indices.

Friction Number

The Friction Number (*FN*) (or Skid Number (*SN*)) produced by the AASHTO T 242 locked-wheel testing device represents the average coefficient of friction measured across a test interval. It is computed as follows:

$$FN = 100 \times \mu = 100 \times (F/W) \quad (2-5)$$

where:

- FN* = Friction number at the measured speed,
- μ = Coefficient of friction,
- F* = Tractive horizontal force applied to the tire, lb, and
- W* = Vertical load applied to the tire, lb.

The reporting values range from 0 to 100, with 0 representing no friction and 100 representing complete friction.

FN values are generally designated by the speed at which the test is conducted and by the type of tire used in the test. For example, *FN40R* = 36 indicates a friction value of 36, as measured at a test speed of 40 mi/h (64 km/h) and with a ribbed (*R*) tire. Similarly, *FN50S* = 29 indicates a friction value of 29, as measured at a test speed of 50 mi/h (81 km/h) and with a smooth (*S*) tire.

International Friction Index

Traditionally, pavement friction has been reported as a single number representing the amount of friction available at the pavement–tire interface for a given pavement surface condition (micro-texture and macro-texture) and test speed. The fundamental reason for measuring pavement friction, however, is to estimate how much friction is available for performing expected driving maneuvers under different speed conditions. In other words, how much friction is available as the vehicle wheel rotation is gradually reduced from free rolling to a locked state (i.e., as the slip speed of the wheel increases).

The International Friction Index (IFI), computed using ASTM E 1960, reflects the average pavement friction over the typical range of vehicle tire free rolling and slip speeds. IFI is based on the PIARC international harmonization study conducted in 1992 and is composed of two numbers: a friction number, *F(60)*, and a speed constant, *SP*. The designation and reporting of this index is *IFI(F(60),SP)*.

F(60) indicates the friction at a slip speed of 37 mi/h (60 km/h) measured using any standardized friction test method. It is a harmonized friction value, which adjusts for the speed at which a

particular friction test method is performed, as well as the type of measurement device used. Note that $F(60)$ is the friction level for a test measurement at 37 mi/h (60 km/h), which is close to the speed of the standard $FN40$ test measurement.

The speed constant S_P defines the relationship between measured friction and vehicle tire free rotation or slip speed. It is calculated using the pavement macro-texture measured using any standardized texture measurement method. The PIARC experiment strongly confirmed that S_P is a measure of the macro-texture influence on friction.

The IFI can be estimated (in Metric form, as outlined in ASTM E 1960) by following the steps below.

1. *Measure Pavement Friction and Macro-texture*—Using a selected friction device, measure pavement friction $FR(S)$ at a given slip speed S (in km/h). Also, using a selected texture measuring device, measure pavement macro-texture and compute MPD (ASTM E 1845) or MTD (ASTM E 965) (in millimeters).

2. *Estimate the IFI speed constant S_P* —Using the computed MPD or MTD , calculate S_P (in km/h) as follows:

$$S_P = 14.2 + 89.7 \times MPD \quad (2-6)$$

$$S_P = -11.6 + 113.6 \times MTD \quad (2-7)$$

3. *Convert Friction Measurement $FR(S)$ at Slip Speed S to Friction at 60 km/h*—Adjust the friction $FR(S)$ measured by the selected friction device at slip speed S using the following equation:

$$FR(60) = FR(S) \times e^{\left(\frac{S-60}{S_P}\right)} \quad (2-8)$$

where:

$FR(60)$ = Adjusted value of friction measurement $FR(S)$ at a slip speed of S to a slip speed of 60 km/h,

$FR(S)$ = Friction value at selected slip speed S , and

S = Selected slip speed, km/h.

4. *Calculate the IFI Friction Number $F(60)$* —Using the speed-adjusted friction value $FR(60)$ and the following equation, compute $F(60)$:

$$F(60) = A + B \times FR(60) + C \times TX \quad (2-9)$$

where:

A, B, C = Calibration constants for the selected friction measuring device. The values of A , B , and C for various devices are given in ASTM E 1960.

TX = The value of MPD or MTD , as determined in Step 1.

The IFI model describes friction experienced by a driver in emergency braking using conventional brakes and deals with the friction from wheel lock-up to stop. The improved IFI model developed by Rado considers the friction experienced by a driver in emergency braking using an anti-lock braking system (ABS). This model takes the following form (Henry, 2000):

$$\mu(S) = \mu_{\max} \times e^{-\left(\frac{\ln\left(\frac{S}{S_{MAX}}\right)}{\hat{C}}\right)^2} \quad (2-10)$$

where:

- $\mu(S)$ = Friction at slip speed S ;
- S = Slip speed of the measurement tire;
- $\mu_{\max}$ = Maximum friction value (a function of surface and tire properties, measuring speed, and slip speed);
- S_{MAX} = Slip speed at maximum friction value (also known as the critical slip speed, which is when the tire is slipping on the pavement with S_{MAX} slip speed while it develops $\mu_{\max}$ friction); and
- $\hat{C}$ = Shape factor which is closely related to the speed number SP in the original IFI equation ($\hat{C}$ determines the skewed shape of the full friction curve).

Figure 2-11 presents graphically friction computed using $IFI(F(60), Sp)$ and the Rado IFI models.

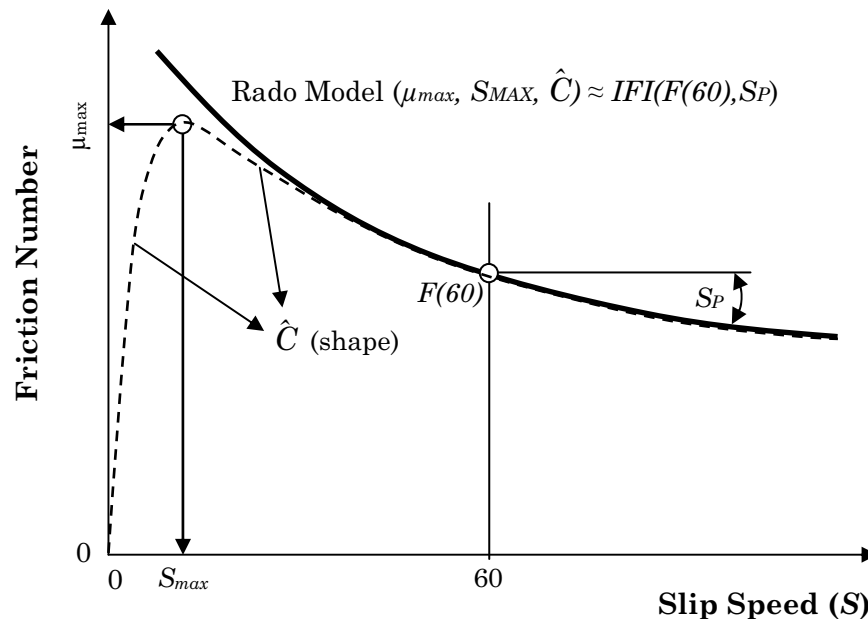


Figure 2-11. The IFI and Rado IFI Models (Rado, 1994).

Index Relationships

Over the years, many studies have been performed to correlate the different friction and texture measurement techniques. The established correlations are important in determining how micro-texture and macro-texture affect pavement–tire friction performance over a range of pavement conditions. Discussed below are some of the key relationships.

- **Micro-Texture**—Currently, there is no direct way to measure micro-texture in the field. Even in the laboratory, it has only been done with very special equipment. Because of this and because micro-texture is related to low slip speed friction, a surrogate device is used for micro-texture.

In the past, the most common device was the BPT (AASHTO T 278), which produces the low-speed wet friction number *BPN*. A newer testing device is the DFT (ASTM E 1911), which measures friction as a function of slip speed from 0 to 55 mi/h (0 to 90 km/h). The DFT at 20 km/h (*DFT(20)*) is now being used more and more around the world as a replacement for the *BPN*. Testing at the NASA Wallops Friction Workshops has shown *DFT(20)* to be more reproducible than the *BPN* (Henry, 2000).

- **Macro-Texture**—The primary indices used to characterize macro-texture are the *MTD* and the *MPD*. While it was found in the international PIARC experiment that the best parameter for determining the speed constant (*Sp*) of the IFI is *MPD*, good predictive capabilities were also observed for *MTD* (Henry, 2000). To allow for conversions to either of these macro-texture indices, the following relationships (given in both English and Metric form, respectively) have been developed (PIARC, 1995):

For estimating *MTD* from profiler-derived measurements of *MPD* (ASTM E 1845):

$$\begin{aligned} \text{Estimated } MTD \text{ (or } EMTD) &= 0.79 \times MPD + 0.009 && \text{English (in.)} \\ EMTD &= 0.79 \times MPD + 0.23 && \text{Metric (mm)} \end{aligned} \quad (2-11)$$

For estimating *MTD* from CTM-derived measurements of *MPD* (ASTM E 2157):

$$\begin{aligned} EMTD &= 0.947 \times MPD + 0.0027 && \text{English (in.)} \\ EMTD &= 0.947 \times MPD + 0.069 && \text{Metric (mm)} \end{aligned} \quad (2-12)$$

For estimating *MTD* from outflow time (*OFT*), as measured with the OFM device (ASTM E 2380) (PIARC, 1995):

$$\begin{aligned} EMTD &= (0.123/OFT) + 0.026 && \text{English (in.)} \\ EMTD &= (3.114/OFT) + 0.656 && \text{Metric (mm)} \end{aligned} \quad (2-13)$$

- **Friction (Micro-Texture and Macro-Texture)**—It has been shown that, using a combination of smooth (AASHTO M 286) and ribbed tires (AASHTO M 261) at highway speeds (i.e., >40 mi/h [64 km/h]), *FN* can be predicted from micro-texture and macro-texture. The relationships (Equations 2-14 through 2-16) are based on macro-texture measured using the SPM (ASTM E 965) and on *BPN* (AASHTO T 278), as a surrogate for micro-texture. Similar equations can be determined from other macro-texture measurement methods (such as *MPD* [ASTM E 1845]) and a surrogate for micro-texture (such as *DFT(20)* [ASTM E 1911]). The IFI provides a method to do this through the following equations (Wambold et al., 1984):

$$BPN = 20 + 0.405 \times FN40R + 0.039 \times FN40S \quad (2-14)$$

$$MTD = 0.039 - 0.0029 \times FN40R + 0.0035 \times FN40S \quad (2-15)$$