GUIDE FOR PAVEMENT FRICTION
# TABLE OF CONTENTS

LIST OF FIGURES ......................................................................................... ii

LIST OF TABLES ......................................................................................... iii

ACKNOWLEDGMENTS ................................................................................ iv

ABSTRACT ..................................................................................................... v

1. INTRODUCTION ......................................................................................... 1
   1.1 BACKGROUND ..................................................................................... 1
   1.2 PURPOSE AND SCOPE OF GUIDE ..................................................... 1
   1.3 GUIDE ORGANIZATION AND USE .................................................... 2

2. PAVEMENT FRICTION OVERVIEW ......................................................... 3
   2.1 IMPORTANCE OF PAVEMENT FRICTION .......................................... 3
   2.2 PAVEMENT FRICTION PRINCIPLES .................................................. 6

3. PAVEMENT FRICTION MANAGEMENT .................................................. 21
   3.1 DEVELOPING PAVEMENT FRICTION MANAGEMENT POLICIES .... 22
   3.2 ESTABLISHING THE PAVEMENT FRICTION MANAGEMENT PROGRAM.. 24

4. PAVEMENT FRICTION DESIGN ............................................................. 39
   4.1 INTRODUCTION ................................................................................... 39
   4.2 DEVELOPING FRICTION DESIGN POLICIES .................................... 39
   4.3 PROJECT-LEVEL DESIGN GUIDELINES ............................................. 52

REFERENCES ............................................................................................... 60

APPENDIX A. TERMINOLOGY

APPENDIX B. STANDARDS RELEVANT TO PAVEMENT FRICTION
LIST OF FIGURES

Figure 1. Total crashes (from all vehicle types) on U.S. highways from 1990 to 2003 (NHTSA, 2004)........................................................................................ 3
Figure 2. Total fatalities (from all vehicle types) on U.S. highways from 1990 to 2003 (NHTSA, 2004)........................................................................................ 4
Figure 3. Relationship between wet-weather crash rates and pavement friction (Rizenbergs et al., 1973)...................................................................................... 5
Figure 4. Mean crash risk for roadway network in the United Kingdom (Viner et al., 2004) ............................................................................................... 5
Figure 5. Simplified diagram of forces acting on a rotating wheel ................................... 6
Figure 6. Pavement longitudinal friction versus tire slip (Henry, 2000).......................... 7
Figure 7. Dynamics of a vehicle traveling around a constant radius curve at a constant speed, and the forces acting on the rotating wheel ..................... 8
Figure 8. Key mechanisms of pavement–tire friction...................................................... 9
Figure 9. Simplified illustration of the various texture ranges that exist for a given pavement surface (Sandburg, 1998) ................................................................. 11
Figure 10. Texture wavelength influence on pavement–tire interactions (adapted from Henry, 2000 and Sandburg and Ejsmont, 2002)............................................. 12
Figure 11. The IFI and Rado IFI models (Rado, 1994)................................................. 18
Figure 12. Example PFM program ..................................................................................... 23
Figure 13. Conceptual relationship between friction demand, speed, and friction availability........................................................................................................ 27
Figure 14. Setting of investigatory and intervention levels for a specific friction demand category using time history of pavement friction ................................ 32
Figure 15. Setting of investigatory and intervention levels for a specific friction demand category using time history of friction and crash rate history.......... 32
Figure 16. Setting of investigatory and intervention levels for a specific friction demand category using pavement friction distribution and crash rate–friction trend......................................................................................................................... 33
Figure 17. Determination of friction and/or texture deficiencies using the IFI ............... 34
Figure 18. Example illustration of matching aggregate sources and mix types/texturing techniques to meet friction demand .............................................. 52
Figure 19. Example of determining DFT(20) and MPD needed to achieve design friction level.............................................................................................................. 55
Figure 20. Flowchart illustration of asphalt pavement friction design methodology (Sullivan, 2005).................................................................................... 56
Figure 21. Illustration of vehicle response as function of PSV and MTD (Sullivan, 2005).................................................................................................................. 56
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Table 1. Factors affecting available pavement friction (Wallman and Astrom, 2001)</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Table 2. Summary of key issues to be considered in standardizing test conditions</td>
<td>29</td>
</tr>
<tr>
<td>3</td>
<td>Table 3. Assessment of hydroplaning potential based on vehicle speed and water film thickness</td>
<td>36</td>
</tr>
<tr>
<td>4</td>
<td>Table 4. Test methods for characterizing aggregate frictional properties</td>
<td>41</td>
</tr>
<tr>
<td>5</td>
<td>Table 5. Typical range of test values for aggregate properties</td>
<td>46</td>
</tr>
<tr>
<td>6</td>
<td>Table 6. Asphalt pavement surface mix types and texturing techniques</td>
<td>48</td>
</tr>
<tr>
<td>7</td>
<td>Table 7. Concrete pavement surface mix types and texturing techniques</td>
<td>50</td>
</tr>
<tr>
<td>8</td>
<td>Table 8. Pairs of MPD and DFT(20) needed to achieve design friction level of 40</td>
<td>55</td>
</tr>
</tbody>
</table>
ACKNOWLEDGMENTS

The research described herein was performed under NCHRP Project 1-43 by the Transportation Sector of Applied Research Associates (ARA), Inc. Dr. Jim W. Hall, Jr., was the Principal Investigator for the study.

Dr. Hall was supported in the research and in developing this Guide by ARA Research Engineers Mr. Leslie Titus-Glover, Mr. Kelly Smith, and Mr. Lynn Evans, and by three project consultants—Dr. James Wambold (President of CDRM, Inc. and Professor Emeritus of Mechanical Engineering at Penn State University), Mr. Thomas Yager (Senior Research Engineer at the NASA Langley Research Center), and Mr. Zoltan Rado (Senior Research Associate at the Pennsylvania Transportation Institute).

The authors gratefully acknowledge all of the individuals with state departments of transportation (DOTs) who responded to the pavement friction survey conducted for this project. The authors also express their gratitude for the valuable input provided by knowledgeable representatives of DOTs, paving associations, academia, and manufacturers of friction measuring equipment, vehicle tires, and trucks.
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 ensure 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 the primary factors determining highway safety and, in particular, the probability of wet skidding crashes. Highway agencies have recognized this fact since the 1920’s (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, 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.
- 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.
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 1 and 2 present summaries of the total number of crashes and resulting fatalities in the U.S. between 1990 and 2003. 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.

Figure 1. Total crashes (from all vehicles types) on U.S. highways from 1990 to 2003 (NHTSA, 2004).
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 U.S. 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 3, crash and measured pavement friction data obtained from mostly rural interstates and parkway roads in Kentucky (Rizenbergs et al., 1973) showed increased wet crash rates at pavement friction values \( SN40 \), skid/friction number determined with a locked-wheel friction tester operated at 40 mi/hr [64 km/hr] less than 40 for low and moderate traffic levels.

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/hr (80 km/hr). 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 4 provides the relationships determined in that study for tangent alignments in both wet and dry conditions (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,
Figure 3. Relationship between wet-weather crash rates and pavement friction (Rizenbergs et al., 1973).

Figure 4. Mean crash risk for roadway network in the United Kingdom (Viner et al., 2004) (Note: dual carriageway = 4-lane divided highway, single carriageway = undivided highway, non-event = segments with no junctions, crossings, or notable bends or gradients).
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 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 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, \( \mu \), which as expressed in equation 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 \( F_w \).

\[
\mu = \frac{F}{F_w}
\]

Eq. 1

Figure 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):
\[ S = V - V_p = V - (0.68 \times \omega \times r) \]  

Eq. 2

where:  
- \( S \) = Slip speed, mi/hr.  
- \( V \) = Vehicle speed, mi/hr.  
- \( V_p \) = Average peripheral speed of the tire, mi/hr.  
- \( \omega \) = Angular velocity of the tire, radians/sec.  
- \( r \) = Average radius of the tire, 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 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 6. Pavement longitudinal friction versus tire slip (Henry, 2000).](image-url)
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 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, 2001):

\[ F_s = \frac{V^2}{15R} - e \]  

Eq. 3

where:  
\( F_s \) = Side friction.  
\( V \) = Vehicle speed, mi/hr.  
\( R \) = Radius of the path of the vehicle’s center of gravity (also, the radius of curvature in a curve), ft.  
\( e \) = Pavement superelevation, ft/ft.

Figure 7. Dynamics of a vehicle traveling around a constant radius curve at a constant speed, and the forces acting on the rotating wheel.
Combining 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. 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). The degree of ellipse or circle depends on the tire and pavement properties.

2.2.2 Mechanisms (of Pavement Friction)

Pavement friction is the result of a complex interplay between two principal frictional force components—adhesion and hysteresis (figure 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:

\[ F = F_A + F_H \quad \text{Eq. 4} \]

![Figure 8. Key mechanisms of pavement–tire friction.](image)

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 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 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 1. Factors affecting available pavement friction (Wallman and Astrom, 2001).

<table>
<thead>
<tr>
<th>Pavement Surface Characteristics</th>
<th>Vehicle Operating Parameters</th>
<th>Tire Properties</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Micro-texture</td>
<td>• Slip speed</td>
<td>• Foot Print</td>
<td>• Climate</td>
</tr>
</tbody>
</table>
| • Macro-texture                 | ➢ vehicle speed             | • Tread design and condition
| • Mega-texture/unevenness       | ➢ braking action            | ➢ Rubber composition and hardness |
| • Material properties          | • Driving maneuver          | • Inflation pressure |
| • Temperature                   | ➢ turning                   | • Load          |
|                                 | ➢ overtaking                | • Temperature   |

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
(PIARC) (1987), are as follows:
• Micro-texture \((\lambda < 0.02 \text{ in } [0.5 \text{ mm}], A = 0.04 \text{ to } 20 \text{ mils } [1 \text{ to } 500 \text{ µm}])\)—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 \((\lambda = 0.02 \text{ to } 2 \text{ in } [0.5 \text{ to } 50 \text{ mm}], A = 0.005 \text{ to } 0.8 \text{ in } [0.1 \text{ to } 20 \text{ mm}])\)—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 \((\lambda = 2 \text{ to } 20 \text{ in } [50 \text{ to } 500 \text{ mm}], A = 0.005 \text{ to } 2 \text{ in } [0.1 \text{ to } 50 \text{ mm}])\)—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 \((20 \text{ in } [500 \text{ mm}])\) of mega-texture are defined as roughness or unevenness (Henry, 2000). Figure 9 illustrates the three texture ranges, as well as a fourth level—roughness/unevenness—representing wavelengths longer than the upper limit \((20 \text{ in } [500 \text{ mm}])\) of mega-texture (Sandburg, 1998).

It is widely recognized that pavement surface texture influences many different pavement–tire interactions. Figure 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 9. Simplified illustration of the various texture ranges that exist for a given pavement surface (Sandburg, 1998).
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/hr (105 km/hr) 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

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

Temperature

Friction of natural rubber tires has a large dependence on temperature, especially when going through the freezing point. Modern rubber compounds are formulated to remove the effect of temperature on friction. Since hysteresis is affected by the visco-elastic property of the tire, friction is reduced at high temperatures where the rubber becomes soft. However, these temperatures are above the normal running speeds and temperatures. When a lot of braking is performed, these higher temperatures can be reached, however the brakes would fade first. 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/hr [32 km/hr]) and quite pronounced at higher speeds (>40 mi/hr [64 km/hr]). 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 Buhmann, 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

Ice and snow 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/hr (161 km/hr), 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 be still superseding 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/hr [64 km/hr] 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/hr (20, 40, 60, and 80 km/hr), 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 [0.5 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 OFTs indicating smooth macro-texture and low OFTs 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:

\[ FN = 100 \times \mu = 100 \times \left( \frac{F}{W} \right) \]

Eq. 5

where:
- \( FN \) = Friction number at the measured speed.
- \( \mu \) = Coefficient of friction.
- \( F \) = Tractive horizontal force applied to the tire, lb.
- \( W \) = 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/hr (64 km/hr) and with a ribbed (R) tire. Similarly, \( FN50S = 29 \) indicates a friction value of 29, as measured at a test speed of 50 mi/hr (81 km/hr) 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 number or speed gradient, $S_p$. The designation and reporting of this index is $IFI(F(60), S_p)$.

$F(60)$ indicates the friction at a slip speed of 37 mi/hr (60 km/hr) 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/hr (60 km/hr), which is close to the speed of the standard $FN40$ test measurement.

The speed number $S_p$ 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/hr). 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 Number $S_p$—Using the computed $MPD$ or $MTD$, calculate $S_p$ (in km/hr) as follows:

   \[ S_p = 14.2 + 89.7 \times MPD \]  
   \[ S_p = -11.6 + 113.6 \times MTD \]

   Eq. 6  
   Eq. 7

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

   \[ FR(60) = FR(S) \times e^{\left(\frac{S-60}{S_p}\right)} \]  
   \[ \text{Eq. 8} \]

   where:  
   - $FR(60)$ = Adjusted value of friction measurement $FR(S)$ at a slip speed of $S$ to a slip speed of 60 km/hr.  
   - $FR(S)$ = Friction value at selected slip speed $S$.  
   - $S$ = Selected slip speed, km/hr.

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

   \[ F(60) = A + B \times FR(60) + C \times TX \]  
   \[ \text{Eq. 9} \]

   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.
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):

\[
\mu(S) = \mu_{\text{max}} \times e^{-\frac{\ln \left( \frac{S}{S_{\text{MAX}}} \right)^2}{C}} \quad \text{Eq. 10}
\]

where:

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

Figure 11 presents graphically friction computed using \( \text{IFI}(F(60), S_{p}) \) and the Rado IFI models.
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/hr (0 to 90 km/hr). The DFT at 20 km/hr ($DFT(20)$) 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 ($S_p$) 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):
  \[
  \text{Estimated } MTD \text{ (or } EMTD) = 0.79 \times MPD + 0.009 \quad \text{English (in)} \quad \text{Eq. 11} \\
  EMTD = 0.79 \times MPD + 0.23 \quad \text{Metric (mm)}
  \]

  For estimating $MTD$ from CTM-derived measurements of $MPD$ (ASTM E 2157):
  \[
  EMTD = 0.947 \times MPD + 0.0027 \quad \text{English (in)} \quad \text{Eq. 12} \\
  EMTD = 0.947 \times MPD + 0.069 \quad \text{Metric (mm)}
  \]

  For estimating $MTD$ from outflow time ($OFT$), as measured with the OFM device (ASTM E 2380) (PIARC, 1995):
  \[
  EMTD = (0.123/OFT) + 0.026 \quad \text{English (in)} \quad \text{Eq. 13} \\
  EMTD = (3.114/OFT) + 0.656 \quad \text{Metric (mm)}
  \]
• 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/hr [64 km/hr]), FN can be predicted from micro-texture and macro-texture. The relationships (equations 14 thru 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):

\[
\begin{align*}
BPN &= 20 + 0.405 \times FN_{40R} + 0.039 \times FN_{40S} \quad \text{Eq. 14} \\
MTD &= 0.49 - 0.029 \times FN_{40R} + 0.43 \times FN_{40S} \quad \text{Eq. 15}
\end{align*}
\]

where:

- \( BPN \) = British pendulum number.
- \( FN_{40R} \) = Friction number using ribbed tire at 40 mi/hr.
- \( FN_{40S} \) = Friction number using smooth tire at 40 mi/hr.
- \( MTD \) = Mean texture depth, in.

The set of equations show that \( BPN \) (micro-texture) is an order of magnitude more dependent on the ribbed tire than on the smooth tire. The reverse is true of \( MTD \) (macro-texture). It should also be noted that these equations can be solved for as follows:

\[
FN_{40R} = 1.19 \times FN_{40S} - 13.3 \times MTD + 13.3 \quad \text{Eq. 16}
\]

So that a smooth tire friction and texture measurement made to determine IFI can still be used to predict \( FN_{40R} \) for reference. However, the \( BPN \) is not very reproducible and the equations are only valid for the BPT used in the correlation. For this reason, the following correlations with \( DFT(20) \) and the MPD (from the CTM) were developed using NASA Wallops Friction Workshops data:

\[
\begin{align*}
FNS &= 15.5 \times MPD + 42.6 \times DFT(20) - 3.1 \quad \text{Eq. 17} \\
FNR &= 4.67 \times MPD + 27.1 \times DFT(20) + 32.8 \quad \text{Eq. 18}
\end{align*}
\]

And, the correlation of \( FN_{40R} \), as a function of \( FN_{40S} \) and MPD is as follows:

\[
FN_{40R} = 0.735 \times FN_{40S} - 1.78 \times MPD + 32.9 \quad \text{Eq. 19}
\]
CHAPTER 3. PAVEMENT FRICTION MANAGEMENT

Successful control of pavement friction suggests strategies at both the management and design levels of a highway pavement program. On the management end, policies and practices can be developed and administered that result in sufficient monitoring of friction and/or crashes, and proper and timely responses to potentially unsafe roadway surfaces. Where restorative treatments are needed, an evaluation of friction supply versus demand may be performed.

On the design end, policies and practices that focus on the provision of adequate levels of micro-texture and macro-texture and ensures texture durability throughout the pavement life should be encouraged. Using the established policies, an analysis of friction supply versus demand should also be performed to design and construct the roadway.

Managing and designing for pavement friction within an agency should consider the following (Austroads, 2005):

- **Policy.**
  - Defining objectives and responsibilities.
  - Developing policies regarding friction demand and friction supply.
  - Developing materials standards (i.e., frictional and durability properties).
  - Developing standards for selection and construction of restoration activities.
  - Developing policies regarding investigatory and intervention friction levels, as well as testing equipment and protocols (including calibration and maintenance).

- **Management.**
  - Collection and processing of friction and/or crash data.
  - Identification and prioritization of sites for investigation and/or restoration.
  - Performance of detailed site investigation.

- **Design.**
  - Determination of friction demand and optimum levels of micro-texture and macro-texture to match friction demand and durability requirements.
  - Selection of remedial actions to restore pavement friction.

- **Research.**
  - Monitoring, review, and improvement of policies.

Although these issues are considered key in the development of an agency strategy for managing and designing for friction, they are neither comprehensive nor mandatory.

Friction management and friction design entail a host of different issues and are therefore discussed in separate chapters (3 and 4) of this Guide. This chapter discusses the concept of a pavement friction management (PFM) program and provides guidance in the development of PFM policies and practices that could enhance highway safety. Section 3.1 covers the policy aspects of PFM, while section 3.2 describes a process that could be used to establish a PFM program.
3.1 DEVELOPING PAVEMENT FRICTION MANAGEMENT POLICIES

A PFM program is a systematic approach to measuring and monitoring the friction qualities and wet crash rates of roadways, identifying those pavement surfaces and roadway situations that are or will soon be in need of remedial treatment, and planning and budgeting for treatments and reconstruction work that will ensure appropriate friction characteristics.

The development of PFM policies within a highway agency requires a good understanding of the agency's current management/operational practices and resources (people, equipment, materials). Detailed discussions of these items and how they might be used in developing a customized PFM program follows.

It is important that a PFM program is practically achievable and that its implementation is demonstrable. In other words, a PFM program should not create an unachievable goal that cannot be reached and must provide a means of documenting the successful implementation of the program. Anything less will create an atmosphere where potential liability outweighs any possible benefits of the program. To the extent possible, it should be integrated with roadway safety and other highway management programs.

3.1.1 Federal Advisories Regarding Highway Safety

The FHWA has published technical advisories regarding skid-crash reduction and texturing of asphalt and concrete pavements. Brief summaries of these are presented below.

FHWA Technical Advisory T 5040.17—Skid-Accident Reduction Program

This advisory (FHWA, 1980) presents a comprehensive guide for state and local highway agencies in conducting skid-crash reduction programs. The purpose of the Skid-Accident Reduction Program was to minimize wet-weather skidding crashes through (1) identifying and correcting sections of roadway with a high or potentially high incidence of skid-crashes, (2) ensuring that the new surfaces have adequate and durable friction properties, and (3) utilizing resources available for crash reduction in a cost-effective manner.

FHWA Technical Advisory T 5040.36—Surface Texture for Asphalt and Concrete Pavements

This advisory (FHWA, 2005) includes (a) information on state-of-the-practice for providing surface texture/friction on pavements and (b) guidance for selecting techniques that will provide adequate wet pavement friction and low-tire/surface noise characteristics. This document replaced the 1979 Technical Advisory T 5140.10 on concrete pavement texturing and friction.

3.2.2 Pavement Friction Management Approach and Framework

To develop PFM policies, an agency should identify an overall approach for managing pavement friction and a process for implementing it. The comprehensive PFM program
shown in figure 12 may be used. This program is comprised of the following key components:

- **Network Definition**—Subdivide the highway network into distinct pavement sections and group the sections according to levels of friction need.
  - Define pavement sections.
  - Establish friction demand categories.

- **Network-Level Data Collection**—Gather all the necessary information.
  - Establish field testing protocols (methods, equipment, frequency, conditions, etc.) for measuring pavement friction and texture.
  - Collect friction and texture data and determine overall friction of each section.
  - Collect crash data.

- **Network-Level Data Analysis**—Analyze friction and/or crash data to assess overall network condition and identify friction deficiencies.
  - Establish investigatory and intervention levels for friction. Investigatory and intervention levels are defined, respectively, as levels that prompt the need for a detailed site investigation or the application of a friction restoration treatment.
  - Identify pavement sections requiring detailed site investigation or intervention.

- **Detailed Site Investigation**—Evaluate and test deficient pavement sections to determine causes and remedies.
  - Evaluate non-friction-related items, such as alignment, the layout of lanes, intersections, and traffic control devices, the presence, amount, and severity of pavement distresses, and longitudinal and transverse pavement profiles.
  - Assess current pavement friction characteristics, both in terms of micro-texture and macro-texture.
  - Identify deficiencies that must be addressed by restoration.
  - Identify uniform sections for restoration design over the project length.

- **Selection and Prioritization of Short- and Long-Term Restoration Treatments**—Plan and schedule friction restoration activities as part of overall pavement management process.
  - Identify candidate restoration techniques best suited to correct existing pavement deficiencies.
  - Compare costs and benefits of the different restoration alternatives over a defined analysis period.
  - Consider monetary and non-monetary factors and select one pavement rehabilitation strategy.
Define Pavement Network & Identify Sites (Re-assess Site Categories Periodically)

Perform Routine Friction Testing and Collect Crash Data

Is Friction At or Below Investigatory Level?

No

For all Sections Above Investigatory Level, Process and Evaluate Crash Data. Conduct Detailed Investigation of Sections with High Crash Rates to Determine if High Crash Rates are Due to (1) Setting of Inadequate Investigatory Levels or (2) Non-Friction Related Causes. Develop Appropriate Recommendations Based on Investigation Results

Yes

Process Crash Data for all Sections at or Below Investigatory Level

Is Friction At or Below Intervention Level?

No

Are Wet Crash Rates High?

No

Yes

Are Wet Crash Rates High?

No

Yes

Assess Risk

Lower

Higher

Perform Detailed Site Investigation

Does Site Need Restoration

Yes

No

1. Shortlist Sites Requiring Restoration in Order of Priority
2. Perform Short-Term Remedial Works, if Needed
3. Identify Preferred Restoration Design Strategy
4. Develop Schedules for Restoration Activities

Review Pavement Friction Testing Frequency

Figure 12. Example of a Possible PFM program.
3.2 Establishing the Pavement Friction Management Program

The PFM program should consist of practical, well-defined work activities and be based on reliable information. This section describes issues relevant to each PFM program component and provides guidance on determining implementation approaches and defining activities and procedures.

3.2.1 Defining the Network

Pavement Section Definition

Section definition for a PFM network involves identifying a basic set of pavement characteristics to help make informed management decisions. Without these characteristics, a pavement friction number is virtually meaningless. To put an pavement friction number in context, you must have information relating to the below described characteristics. The main characteristic of interest is friction demand, which is defined as the level of friction (micro- and macro-texture) needed to safely perform braking, steering, and acceleration maneuvers. PFM sections can be established by reviewing the sectioning in the PMS and identifying where changes in friction demand occur. A friction demand category can then be assigned to serve as basis for monitoring friction adequacy throughout the network.

Factors that affect friction demand can be grouped into four basic categories: highway alignment, highway features/environment, highway traffic characteristics, and driver/vehicle characteristics. Another category includes driver skills and age, vehicle tire characteristics, and vehicle steering capabilities, not discussed herein. The specific factors involved in the first three categories are discussed below.

Highway Alignment

Friction demand is significantly influenced by both the horizontal and vertical alignment of a highway. The following are key considerations:

- **Horizontal Alignment**—The horizontal alignment of a highway is defined by tangents and curves (simple, compound, and spiral). The amount of friction required on highway curves increases with increasing complexity of the curve (i.e., as the alignment changes from a tangent to a horizontal curve). To counter increasing friction demand in horizontal curves, highway designers increase the horizontal radius of curvature and super-elevate the highway cross-section.

  The lateral friction developed at the pavement–tire interface along a curve is directly related to the square of the vehicle’s speed. As the speed increases, the force required to maintain a circular path eventually exceeds the force that can be developed at the pavement–tire interface and super-elevation. At this point, the vehicle begins to slide in a straight line tangential to the highway alignment. The
relationship between side-force friction for horizontal curves (the most critical horizontal alignment), vehicle speed, radius of curvature, and highway cross-section (super-elevation) is defined by the AASHTO Green Book equation (AASHTO, 2001).

- Vertical Alignment—Vertical alignment consists of a series of gradients (grades) connected by vertical curves. It controls how the highway follows existing terrain and its properties are mainly controlled by terrain, horizontal alignment, and sight distance.

The friction demand for vehicles traversing a highway is highly influenced by the highway’s vertical alignment. This is because vertical alignment design policy is based on the need to provide drivers with adequate stopping sight distance to enable them to see an obstacle soon enough to perform evasive maneuvers. The ability to perform evasive maneuvers successfully is highly dependent on friction availability.
Highway Features/Environment

Highway features/environment is an important characteristic of traffic flow that can influence pavement friction. This characteristic of traffic flow is defined largely by the level of interacting traffic situations (e.g., entrance/exit ramps, access drives, unsigned/unsignalized intersections), the presence of controlled (signed/signalized) intersections, the presence of specially designated lanes (e.g., separate turn lanes at intersections, center left-turn lanes, through versus local traffic lanes), the presence and type of median barriers, and the setting (urban versus rural) of the roadway facility. In general, as the highway environment becomes more difficult and complex, significantly higher levels of friction are required to help drivers perform the necessary maneuvers (e.g., sudden braking). Understanding the various features of this characteristic provides the basis for determining how a friction number might provide useful information regarding safety at a particular location.

Highway Traffic Characteristics

Traffic characteristics that influence friction demand include traffic volume, composition, and speed. Key aspects of these factors are as follows:

- Traffic Volume—As traffic volume increases, the number of driving maneuvers taking place along any given segment increases. The risk associated with these increased maneuvers is elevated, especially in high-speed areas. When traffic volume is increased to the point that congestion occurs, the possibility of crashes is aggravated if a highway facility is undivided and traffic speed is high (Page and Butas, 1986; Mahone and Runkle, 1972).

- Traffic Composition—For the same traffic volume, the composition of traffic vehicles (i.e., the percentage of trucks in the traffic stream) can significantly affect highway safety and thus friction demand for the following reasons:
  - Stopping distances of trucks are significantly longer than stopping distances of passenger cars (AASHTO, 2001).
  - Trucks have inferior steering capability compared to passenger cars.
  - Truck tires produce less friction than passenger car tires.

Hence, for highway segments where a high percentage of trucks is anticipated, friction demand will typically be higher than a corresponding highway having predominantly passenger cars or lower percentage of trucks.

- Traffic Speed—Vehicle speed is the most important factor influencing friction demand. For wet pavement surfaces, for instance, an increase in truck speed on tangents from 20 to 70 mi/hr (32 to 113 km/hr) results in an increase in truck stopping distance from 50 to 1,200 ft (15 to 366 m) (Radlinski and Williams, 1985). Such an increase in stopping distance significantly increases the risk of a crash.

Figure 13 shows the conceptual relationship between friction demand and friction availability for wet pavements. This figure indicates that an increase in speed...
results in an increase in friction demand and a decrease in available surface friction (Glennon, 1996).

Figure 13. Conceptual relationship between friction demand, speed, and friction availability.

Speed also contributes to the severity of impact when a collision occurs. For passenger cars colliding with an impact speed of 65 mi/hr (105 km/hr), the likelihood of death is 20 times greater than that associated with an impact speed of 20 mi/hr (30 km/hr) (WHO, 2004). Finally, increasing speed (above 40 mi/hr [64 km/hr]) increases the likelihood of hydroplaning, which is a major cause of wet-weather crashes (Glennon, 1996).

The speed of vehicles on the highway must therefore be considered in determining friction demand. Highways with higher posted speed limits and overall travel speeds (85th percentile of vehicle speed) require higher levels of pavement surface friction than lower speed facilities.

Establishing Friction Demand Categories

Pavement friction demand categories should be established logically and systematically based on highway alignment, highway features/environment, and highway traffic characteristics. Ideally, friction demand categories should be established for individual highway classes, facility types, or access types. Also, 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 and intervention friction levels.

3.2.2 Network-Level Data Collection

Collection of Friction Data
Measurements of pavement friction should consider (1) testing protocol and equipment, (2) testing frequency, (3) testing conditions, and (4) equipment calibration and maintenance.

**Testing Protocol**

At the network level, the locked-wheel friction tester (AASHTO T 242 is the most appropriate method of testing. The method is standardized (e.g., test speed, water flow rate), can be performed quickly and at high speeds, and is generally quite repeatable. The method can assess friction and texture by performing tests with both smooth and ribbed tires or with a properly mounted texture laser.

**Frequency of Testing**

For a network-level evaluation, it is desirable to test all pavement sections annually because of the year-to-year variation in pavement friction. However, the testing frequency for each agency is determined by the length of network to be tested and available resources. A practical approach is a rolling or cyclical testing regime, whereby portions of the network are tested once every few years (e.g., for a rolling 3-year program, one-third of the network is tested each year). Statistical sampling of pavement sections for network level analysis is an acceptable option, as many agencies cannot test 100 percent of their pavement network due to budgetary and/or other constraints.

**Testing Conditions**

Because pavement friction is influenced by various factors, such as pavement surface temperature, test speed, and ambient weather conditions, testing should be performed under standardized conditions to control the effect of these factors on test results. Controlling testing conditions will minimize variability in test results and produce repeatable measurements. The factors presented in table 2 should be considered along with other relevant factors in establishing testing conditions (Highways Agency, 2005).

**Equipment Calibration and Maintenance**

Proper calibration and maintenance of the friction testing equipment is essential to the collection of reliable friction data. To this end, agencies should follow the manufacturer-specified regime or guidance for calibration and routine maintenance.

**Collection of Crash Data**

Crash data are generally available from an agency’s crash database or from other sources, such as law enforcement agencies and statistical bureaus. Inputs to classify and describe crashes may include (1) the location (route, milepost, direction) of each crash, (2) vehicles involved along with their characteristics, (3) drivers and passengers involved along with their characteristics, (4) ambient weather conditions at the time of the crash, and (5) injury levels and property damage as a result of the crash.
Table 2. Summary of issues relating to standardized test conditions.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Consideration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Season for testing</td>
<td>Because significant variations in measured friction may occur across seasons within a given year, friction testing should be limited to a specific season or time of year when friction is typically lowest. This will help maintain some consistency in year-to-year measurements and reduce variability in measured data. For agencies that cannot perform all testing requirements within a given season, the following can be considered to reduce test variability:</td>
</tr>
<tr>
<td></td>
<td>• Develop correction factors, as needed, to normalize raw friction test data to a common baseline season.</td>
</tr>
<tr>
<td></td>
<td>• For a given pavement section, initial and subsequent testing must be done within a specific season (e.g., pavement sections originally tested in fall should subsequently be tested in fall).</td>
</tr>
<tr>
<td>Test speed</td>
<td>The standard speed recommended by AASHTO T242 for pavement friction tests is 40 mi/hr (64 km/hr). However, since most agencies conduct friction tests without traffic control and because posted or operational speeds vary dramatically throughout a network, it is very difficult for the operator to conduct testing at just this speed. For such situations, the operator typically adjusts test speeds to suit traffic conditions and to assure a safe operation. Thus, it is recommended that friction values corresponding to testing done at speeds other than 40 mi/hr (64 km/hr) be adjusted to the baseline 40-mi/hr (64-km/hr) value to make friction measurements comparable and useful.</td>
</tr>
<tr>
<td></td>
<td>To do this requires the establishment of correlations between friction measurements taken at 40 mi/hr (64 km/hr) and those taken at other speeds (i.e., speed gradient curves). The following equation can be used to adjust friction measurements to FN40:</td>
</tr>
</tbody>
</table>
|                          | \[
|                          | FN(S) = FN_v \times e^{S_p} \frac{S_p}{S_v}
|                          | \]                                                                                                                                           |
|                          | where: \( FN(S) \) = Adjusted value of friction for a speed \( S \). \( FN_v \) = Measured friction value at speed \( V \). \( S_p \) = Speed number. |
|                          | In order to produce accurate estimates of \( FN(S) \), \( S_p \) must be established for a broad range of pavement macro-textures and texture measuring devices. |
| Test lane and line       | Friction measurements must be done in the most heavily trafficked lane, as this lane usually carries the heaviest traffic and is, therefore, expected to show the highest rate of friction loss (worst case scenario). For 2-lane highways with a near 50-50 directional distribution of traffic, testing a single lane will suffice; otherwise, the lane in the direction with heavier traffic should be tested. For multilane highways, the outermost lane in both directions is typically the most heavily trafficked and should be tested. Where the outermost lane is not the most heavily trafficked, a different lane or more than one lane should be tested. Test measurements must be carried out within the wheelpath, as this is the location where friction loss is greatest. Note that it is important to test along the same lane and wheelpath to maintain some consistency between test results and to reduce variability. If it is necessary to deviate from the test lane and wheelpath (e.g., to avoid a physical obstruction or surface contamination), the test data should be marked accordingly. |
| Ambient conditions       | Because ambient conditions can have an effect on pavement friction, it is important to standardize ambient test conditions to the extent possible and document ambient test conditions so the measurements can be corrected as needed. The following should be noted when setting ambient conditions for testing: |
|                          | • Testing in extremely strong side winds must be avoided because these can affect the measurements by creating turbulence under the vehicle that causes the water jet to be diverted from the correct line. |
|                          | • Testing must be avoided in heavy rainfall or where there is standing water on the pavement surface. Excess water on the surface can affect the drag forces at the pavement–tire interface and influence the measurements. |
|                          | • Measurements shall not be undertaken where the air temperature is below 41°F (5°C). |
| Contamination            | Contamination of the pavement surface by mud, oil, grit, or other contaminants must be avoided. |
3.2.3 Network-Level Data Analysis

Establishing Investigatory and Intervention Friction Threshold Levels

As pointed out in chapter 2, a general relationship exists between pavement friction and crashes. Because conditions and circumstances (previously defined as highway characteristics) along a highway change, there is no one “magic” friction number that defines the threshold between “safe” and “potentially unsafe.”

The ideal situation would be to identify a specific friction number that would meet or exceed friction demand for the entire system. Such a practice would be prohibitively expensive (as well as largely unnecessary) and would not generate the cost-benefits associated with a better-targeted strategy. A more practical approach, would be to maintain an appropriate level of pavement friction for pavement sections within the highway network, based on each section’s friction demand. This approach seeks to provide adequate friction levels for a variety of roadway (intersections, approaches to traffic signals, tight curves) and traffic conditions.

The establishment of investigatory and intervention friction levels requires detailed analyses of micro-texture and macro-texture data, and crash data, if available. Such analyses should be carried out separately for each friction demand category established by the agency.

Presented in the sections below are three feasible methods for setting investigatory and intervention friction levels, either in terms of $FN$ or in terms of $IFI(F(60),Sp)$. These example methods are derived from many years of discussions at national and international meetings and workshops on pavement friction (e.g., ASTM E 17, TRB AFD90, PIARC TC 1 [now T4.2], and the NASA Wallops Friction Workshops).

Establishing Thresholds Using Historical Pavement Friction Data Only (Method 1)

This method uses historical trends of friction loss determined by plotting friction loss against pavement age or time for a specific friction demand category. An investigatory level is set at the pavement friction value where friction loss begins to increase at a significantly faster rate. An intervention level may then be set at a certain amount (e.g., five $F(60),Sp$ points or five $FN$ points) or percentage (e.g., 10 percent) below the investigatory level.

The friction value at which friction loss begins to increase rapidly can be determined graphically or through the use of analytical/statistical methods. An example graphical based method includes the following steps:

- Step 1—Plot pavement friction versus age/time for a given friction demand category (figure 14).
- Step 2—Develop a friction loss deterioration curve based on the measured data.
- Step 3—Graphically determine the slopes of the three stages of the S-shaped friction loss versus pavement age/time relationship.
- Step 4—Set the investigatory level as the friction value where there is a significant increase in the pavement friction loss.
• Step 5—Set intervention level at a certain value or percentage below the investigatory level.

*Establishing Thresholds Using Both Historical Pavement Friction Data and Crash Data (Method 2)*

This method compares historical pavement friction and crash data for the given friction demand category for which levels are being set. Figure 15 shows a plot of friction and wet-to-dry crash trends for a specific friction demand category. An investigatory level may be set corresponding to a large change in friction loss rate while the intervention level may be set where there is a significant increase in crashes.

*Establishing Thresholds Using Pavement Friction Distribution and Crash Rate–Friction Trend (Method 3)*

This method uses the distribution of friction data versus the crash rates that correspond with the friction for the category of roadway for which the levels are being set. An example of using this method includes the following steps:

• Step 1—Plot a histogram of pavement friction for a given friction demand category, based on current history. On the same graph, plot the current wet-to-dry crash ratio for the same sections as the friction frequency distribution (figure 16).

• Step 2—Determine the mean pavement friction and standard deviation for the pavement friction frequency distribution.

• Step 3—Set the investigatory level as the mean friction value minus “X” standard deviations (say, 1.5 or 2.0) of the distribution of sections and adjust to where wet-to-dry crashes begin to increase considerably.

• Step 4—Set intervention level as the mean friction value minus “Y” standard deviations (say, 2.5 or 3.0) of the distribution of sections and adjust the level to a minimum satisfactory wet-to-dry crash rate or by the point where the amount of money is available to repair that many roadway sections.
Figure 14. Setting of investigatory and intervention levels for a specific friction demand category using time history of pavement friction.

Figure 15. Setting of investigatory and intervention levels for a specific friction demand category using time history of friction and crash rate.
Figure 16. Setting of investigatory and intervention levels for a specific friction demand category using pavement friction distribution and crash rate–friction trend.

Method 3 is the most detailed approach. It has the advantage of discerning the number of roadway sections below a certain level.

As in any engineering decision, a transportation agency considers the financial implications of maintaining highway safety through managing pavement friction levels. Thus, an agency should consider the effects of using different investigatory and intervention levels in terms of the improvement in safety and the cost to achieve the level. Levels can be adjusted to optimize the increase in safety within the agency’s budget.

Regardless of the method used, the investigatory and intervention levels selected should be reviewed periodically and revised as needed. Improvements in highway safety guidelines may require changes in the levels set by an agency.

**Identifying Pavement Sections Requiring Detailed Site Investigation or Intervention**

Once a section has been identified as being at or below a friction threshold level, steps should be taken to identify the cause(s) of the deficiency. An agency should consider caution highway users by installing appropriate warning signs (e.g., slippery when wet, reduced speed) and then proceed with plans for a detailed investigation of the section.

If the IFI is being used, a quick assessment can be made of the friction and texture measurements to determine if micro-texture or macro-texture, or both, are inadequate and in need of improvement. A graph similar to figure 17 can be developed and used, not only as an aid to the detailed investigation, but for selecting the type of warning that should be posted.
3.2.4 Detailed Site Investigation

A detailed site investigation of pavement sections at or below the investigatory or intervention level is necessary to (a) identify other factors besides friction that are adversely impacting safety and (b) determine specific causes of inadequate micro-texture and/or macro-texture. The detailed investigation involves at a minimum two steps, described below or of similar nature.

**Step 1—Conduct Visual/Video Survey**

Each identified section should be evaluated for highway characteristics (as previously described) that may contribute to the safety issue, both in terms of available friction and friction demand. Such items include the horizontal and vertical alignment, the layout of lanes, intersections, and traffic control devices, the presence, amount, and severity of pavement distresses (e.g., potholes, rutting, bleeding, deteriorated patches), longitudinal pavement smoothness, and transverse pavement profile. Also of importance in the detailed investigation are the issues of glare (as caused by the pavement or the lack of appropriate traffic aids), splash and spray, and hydroplaning potential (often linked to rutting or inadequate cross-slope). Discussion of these issues are provided below.
Splash and Spray

The occurrence of splash and spray is influenced by the drainage condition at the pavement surface. Providing positive drainage that quickly removes standing water from the pavement surface will reduce the occurrence of splash/spray significantly. Pavement surface drainage is enhanced by providing adequate amounts of macro-texture and cross-slope.

Suggestion here is to eliminate the entire section on hydroplaning as it is not directly related to the Guide on Friction

Hydroplaning Potential

As discussed earlier in chapter 2, hydroplaning refers to the separation of the tire contact from the pavement surface by a layer of water. It is a complex phenomenon that is affected by (1) the water film thickness ($WFT$) on the pavement surface, (2) pavement macro-texture, (3) tire tread depth, (4) tire inflation pressure, (5) tire contact area, and (6) vehicle speed.

For a vehicle to experience hydroplaning, two things must occur simultaneously: there must be a sufficient buildup of water on the pavement surface and the vehicle must be traveling at a speed high enough to cause hydroplaning. Thus, the potential for hydroplaning for a given highway segment can be assessed by determining (1) the frequency of water buildup from precipitation (rainfall only) on the pavement surface and (2) whether the traveling speeds of vehicles is high enough to result in hydroplaning for the water buildup conditions.

A three-step procedure for determining hydroplaning potential is presented below.

- Step 1—Estimate Critical Hydroplaning Speed ($HPS$): An approximate relationship between the vehicle speed (in mi/hr) at which hydroplaning for both asphalt and concrete pavements will occur and the tire inflation pressure (in lb/in²) is as follows (Ong and Fwa, 2006):

$$HPS = 10.35 \sqrt{\text{tire pressure}}$$

Eq. 20

This equation assumes that $WFT$ on the pavement surface exceeds the combined capability of the surface macro-texture and tire design (i.e., tread depth) to remove water from the pavement surface.

- Step 2—Compute $WFT$ using agency-established models or procedures or the $WFT$ prediction models (and accompanying software) developed in NCHRP Project 1-29 (Anderson et al., 1998).
• Step 3—Determine Hydroplaning Potential: An example scheme for determining hydroplaning potential according to four categories (none, low, moderate, and high) is provided in table 3.

Table 3. Assessment of hydroplaning potential based on vehicle speed and water film thickness.

<table>
<thead>
<tr>
<th>Average Vehicle Speed (85th Percentile of Traveling Speed) minus Critical Hydroplaning Speed (HPS), mi/hr</th>
<th>WFT, in</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.02</td>
<td>None</td>
</tr>
<tr>
<td>0.02 to 0.06</td>
<td>None</td>
</tr>
<tr>
<td>&gt; 0.06</td>
<td>None</td>
</tr>
<tr>
<td>Less than –5</td>
<td>None</td>
</tr>
<tr>
<td>Between +5</td>
<td>Low</td>
</tr>
<tr>
<td>Greater than 5</td>
<td>Moderate</td>
</tr>
<tr>
<td>1 mi/hr = 1.61 km/hr, 1 in = 25.4 mm</td>
<td></td>
</tr>
</tbody>
</table>

* Guidelines for determining design speed based on highway functional classification, location (i.e., rural versus urban), and terrain type (i.e., level, rolling, and mountainous) can be found in the AASHTO Green Book (AASHTO, 2001).

Step 2—Evaluate Micro-Texture and Macro-Texture

The second step in the detailed site investigation involves testing the pavement surface for micro-texture and macro-texture. These two properties can be evaluated using various types of equipment, including:

- Micro-texture, which can be evaluated using any of the following:
  - Locked-wheel friction tester.
  - British Pendulum Tester (BPT).
  - Dynamic Friction Tester (DFT).
- Macro-texture, which can be evaluated using any of the following:
  - High-speed laser.
  - Circular Texture Meter (CTM).
  - Sand Patch Method (SPM).

Testing must be done in a manner that produces results that are representative of the entire pavement section.

In addition to the micro-texture and macro-texture data, the following information must be obtained from the records or through field testing:

- Traffic applications, including truck percentages.
- Pavement surface age.
- Surface material type and/or finishing method.
- Data on all materials used in the surface pavement (e.g., fine/coarse aggregate type), including polishing/wear characteristics, structure, hardness, and so on, if available.
- Other information, such as data from laboratory tests.
Using the micro-texture and macro-texture results and the data listed above, the exact cause of friction loss can be determined. Common causes of friction loss include polishing of coarse aggregates and excessive wearing of the pavement surface resulting in a loss of macro-texture.

### 3.2.5 Selection and Prioritization of Friction Restoration Treatments

A next step in a PFM program could be to analyze the collected data to identify sites suggesting more frequent monitoring or forensic investigation, and sites that might be considered for friction restoration. Highway agencies may use pavement friction, other identified highway characteristic data and condition data to identify and prioritize sites to be included in a program for:

- Short-term remedial (maintenance) works.
- Comprehensive restoration treatment (e.g., diamond grinding, cold milling, thin overlays, chip seals) aimed directly at improving friction.

In analyzing pavement friction data, a desirable outcome is to ensure that the appropriate sites are detected and given reasonable priority. The extent of the analysis and use of pavement friction and other data is determined locally by the agency. Analysis can be restricted to identifying all sites where the measured pavement friction is at or below any investigatory or intervention level that has been set, followed by a detailed site investigation to identify actions that might include:

1. Continuing to monitor the site: Such a decision typically would be reached where (a) current crash rates are sufficiently low and an increase is not expected to significantly impact safety and (b) the pavement surface does not require maintenance because of other factors.
2. Listing the site for remedial action to improve pavement friction (e.g., resurface, retexture), where such an increase in pavement friction would significantly impact safety.
This page intentionally left blank.
CHAPTER 4. PAVEMENT FRICTION DESIGN

4.1 INTRODUCTION

Although the design of pavement friction is a relatively small component of the overall pavement design process, it is critical because of its impact on highway safety. Its importance and complexity have increased over the years due to increased demands for safer roads and the desire for greater highway user comfort, which sometimes contradicts friction.

Friction design requires a thorough understanding of the factors that influence friction and knowledge of the materials and construction techniques (including equipment) that ultimately dictate initial and long-term friction. It also requires an understanding of the economic and engineering tradeoffs associated with different materials and techniques, such as the costs/benefits of utilizing one friction strategy over another and how each strategy impacts structural design and other functional aspects (e.g., noise, splash/spray).

This chapter provides guidance on the design of pavement friction, as determined by surface micro-texture and macro-texture. The information provided can be used to (a) develop and implement useful, effective friction design policies at the network level and (b) formulate feasible, cost-conscious friction design strategies at the project level. This guidance is intended to supplement and not replace existing agency standards and procedures.

4.2 DEVELOPING FRICTION DESIGN POLICIES

Friction design policies must focus on the selection and use of (a) aggregates for micro-texture and (b) paving mixtures and surface texturing techniques for macro-texture. The policies should effectively reduce occurrences of wet-weather friction hazards and vehicle crashes. Specifically, they should be geared towards overcoming deficiencies in materials and construction techniques through improvements in aggregate testing protocols and standards, mix design methods and formulations, and construction specifications and special provisions.

4.2.1 Aggregate Testing and Characterization

Aggregate properties are the predominant factor that determines frictional performance of asphalt and concrete pavement surfaces. Aggregate makes up the bulk of both asphalt and concrete mixtures, and therefore, for the surface of either pavement type, aggregate is the primary contact medium with the vehicle tires.

Aggregate generally is viewed as two distinct fractions—coarse aggregate and fine aggregate. Coarse aggregate pieces are greater than the No. 4 sieve (0.19 in [4.75 mm]), with most pieces between 0.375 and 1.5 in (9.5 and 38 mm). Fine aggregate, on the other hand, is the collection of natural or crushed/manufactured particles less than 0.19 in (4.75 mm), but greater than the No. 200 sieve (0.003 in [75 µm]).
Aggregate testing and characterization must be targeted to the fraction(s) of aggregate in a mix that will control the frictional performance. In general, coarse aggregate controls the frictional properties of asphalt mixtures, while fine aggregate controls the frictional properties of concrete mixes. Exceptions include fine-graded asphalt mixes, where fine aggregates are in greater abundance, and concrete mixes in which coarse aggregates are either intentionally exposed at the time of construction (exposed aggregate concrete, porous concrete) or will become exposed in the future (diamond grinding, surface abrading).

In terms of friction design and performance, the important aggregate properties are:

- **Mineralogical and Petrographic Properties.**
  - Aggregate composition/structure and mineral hardness.
- **Physical and Geometrical properties.**
  - Angularity, shape, and texture.
- **Mechanical Properties.**
  - Abrasion/wear resistance.
  - Polish characteristics.
- **Durability Properties.**
  - Soundness.

Several test methods are available for characterizing aggregate frictional properties, whether as part of a standard mix design process or an aggregate source rating program. The extent of aggregate testing and characterization required as part of the friction design process will vary from agency to agency, based on the types of aggregates available, the variability of aggregate properties, the quality and historical performance of available aggregates, and the anticipated applications (e.g., mix types, roadway functional class). Laboratory material testing does not guarantee friction performance in the field. Thus, it is essential that testing be used in conjunction with field performance history to identify acceptable aggregate types.

The aggregate tests described in table 4 are considered the most relevant in characterizing frictional properties. The test methods shown in this table are recommended for consideration as part of agency construction and materials specifications pertaining to pavement surface mixtures. Agencies are encouraged to establish test criteria corresponding to varying levels of friction design. Such criteria should be based on a correlation between (a) aggregate characteristics obtained from standardized laboratory tests and actual field performance and/or (b) aggregate geologic type or petrography and field performance.

A brief discussion of each important aggregate property, and its influence and impact on pavement friction, is provided in the following subsections.

**Aggregate Composition/Structure and Mineral Hardness**

One of the most important properties of aggregate used in pavement surfaces is the composition of the minerals that comprise the aggregate particles. Aggregates that exhibit the highest levels of polish resistance and resistance to wear typically are composed of
Table 4. Test methods for characterizing aggregate frictional properties.

<table>
<thead>
<tr>
<th>Aggregate Property</th>
<th>Aggregate Type</th>
<th>Test Name</th>
<th>Test Protocol</th>
<th>Test Description</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fine</td>
<td>Scratch Hardness test</td>
<td>Mohs</td>
<td>Rough measure of the resistance of a mineral’s surface to scratching. Expressed using a 1-to-10 scale (1 being very soft, 10 being very hard), Mohs hardness is determined by observing whether its surface is scratched by minerals of a known or defined hardness.</td>
<td>• New concrete surfacings.</td>
</tr>
<tr>
<td></td>
<td>Coarse</td>
<td>Scratch Hardness test</td>
<td>Mohs</td>
<td>Same as above.</td>
<td>• New asphalt surfacings and asphalt mixes used for friction restoration. • New concrete surfacings (conventional and innovative).</td>
</tr>
<tr>
<td></td>
<td>Fine</td>
<td>Descriptive Nomenclature for Constituents of Concrete Aggregates</td>
<td>ASTM C 294</td>
<td>Provides brief descriptions of commonly occurring natural or artificial aggregates from which mineral aggregates are derived. The descriptions provide a basis for understanding the potential effects on pavement friction of using different aggregate materials.</td>
<td>• New concrete surfacings.</td>
</tr>
<tr>
<td></td>
<td>Coarse</td>
<td>Descriptive Nomenclature for Constituents of Concrete Aggregates</td>
<td>ASTM C 294</td>
<td>Same as above.</td>
<td>• New asphalt surfacings and asphalt mixes used for friction restoration. • New concrete surfacings (conventional and innovative).</td>
</tr>
<tr>
<td></td>
<td>Petrographic Analysis</td>
<td>ASTM C 295</td>
<td>Used to assess aggregate (1) constituent minerals and structure, (2) surface texture, and (3) mineralogy, and to develop a petrographic database for aggregate sources to serve as a basis for linking aggregate sources to pavement field performance (Pollard and Smith, 2003).</td>
<td>• New concrete surfacings.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Petrographic Analysis</td>
<td>ASTM C 295</td>
<td>Same as above.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* For conventional PCC surfaces, where coarse aggregates are expected to be exposed, and innovative surfaces, such as porous concrete and exposed aggregate concrete.
Table 4. Test methods for characterizing aggregate frictional properties (continued).

<table>
<thead>
<tr>
<th>Aggregate Property</th>
<th>Aggregate Type</th>
<th>Test Name</th>
<th>Test Protocol</th>
<th>Test Description</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angularity, Shape, &amp; Texture</td>
<td>Fine</td>
<td>Uncompacted Voids (UV) test for fine aggregates</td>
<td>AASHTO T 304</td>
<td>Fine aggregate of prescribed gradation is allowed to flow through orifice of a funnel and fill a 6.1-in³ (100-cm³) cylinder. Excess material is struck off and cylinder with aggregate is weighed. Uncompacted void content is computed using this weight and the bulk dry specific gravity of the aggregate (Kandhal et al., 1997). Higher uncompacted void contents are generally the result of more fractured faces and rougher textures, which are desirable for pavement friction.</td>
<td>• New concrete surfacings.</td>
</tr>
<tr>
<td>Coarse</td>
<td>UV test for coarse aggregates</td>
<td>AASHTO T 326b</td>
<td>Coarse aggregate angularity, shape, and texture can be determined using principles similar to those described above for fine aggregates. Again, higher uncompacted void contents are generally the result of more fractured faces and rougher textures, which are desirable for pavement friction.</td>
<td>• New asphalt surfacings and asphalt mixes used for friction restoration. • New concrete surfacings (conventional and innovative).a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fractured-Face Particles test</td>
<td>ASTM D 5821 (or AASHTO TP 61)</td>
<td>Determines the amount (percent) of fractured-faced (an angular, rough, or broken surface of an aggregate particle) aggregate particles, by visual inspection. The fractured face of each aggregate particle must meet a minimum cross-sectional area.</td>
<td>• New asphalt surfacings and asphalt mixes used for friction restoration. • New concrete surfacings (conventional and innovative).a</td>
<td></td>
</tr>
<tr>
<td>Abrasion/Wear Resistance</td>
<td>Fine</td>
<td>Micro-Deval test for fine aggregates</td>
<td>Canadian Standards Association (CSA) A23.2-23A</td>
<td>A fine aggregate sample is subjected to wet attrition by placing it in a steel jar with 0.375-in (9.5-mm) diameter steel balls and water. The jar is rotated at 100 rpm for 15 minutes, after which aggregate damage is assessed by mass loss using a No. 200 (75 μm) sieve. Higher percentages of loss indicate greater potential for aggregate breakdown (Folliard and Smith, 2003).</td>
<td>• New concrete surfacings (conventional).</td>
</tr>
<tr>
<td>Coarse</td>
<td>LA Abrasion test</td>
<td>AASHTO T 96 ASTM C 535 (for large-sized coarse aggregates)</td>
<td>A dry aggregate sample is placed in a steel drum with six to twelve 420-gram steel balls, and the drum is rotated for 500 to 1,000 revolutions. Degradation by impact of the aggregate sample is determined by the percentage passing the No. 12 (1.7-mm) sieve.</td>
<td>• New asphalt surfacings and asphalt mixes used for friction restoration. • New concrete surfacings (conventional and innovative)a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Micro-Deval test for coarse aggregates</td>
<td>AASHTO T 327</td>
<td>A coarse aggregate sample is subjected to wet attrition by placing it in a steel jar with 0.375-in (9.5-mm) diameter steel balls and water. The jar is rotated at 100 rpm for 2 hours, after which aggregate damage is assessed by mass loss using a No. 16 (1.18-mm) sieve.</td>
<td>• New asphalt surfacings and asphalt mixes used for friction restoration. • New concrete surfacings (conventional and innovative)a</td>
<td></td>
</tr>
</tbody>
</table>

a For conventional PCC surfaces, where coarse aggregates are expected to be exposed, and innovative surfaces, such as porous concrete and exposed aggregate concrete.

b Formerly AASHTO TP 56.
Table 4. Test methods for characterizing aggregate frictional properties (continued).

<table>
<thead>
<tr>
<th>Aggregate Property</th>
<th>Aggregate Type</th>
<th>Test Name</th>
<th>Test Protocol</th>
<th>Test Description</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polish Resistance</td>
<td>Fine</td>
<td>Acid Insoluble Residue (AIR) test</td>
<td>ASTM D 3042</td>
<td>Estimates the percent by weight of insoluble, hard, non-carbonate residue in carbonate aggregates (e.g., limestone, dolomite), using hydrochloric acid solution to react the carbonates. Higher acid insoluble residue (AIR) values indicate larger percentages of siliceous minerals, which are considered more polish resistant than carbonate materials (Kandhal et al., 1997).</td>
<td>• New concrete surfacings.</td>
</tr>
</tbody>
</table>
|                   | Coarse         | Polished Stone Value (PSV) test   | AASHTO T 278 & T 279 | Aggregate coupons (aggregates embedded in epoxy resin) are fabricated, subjected to accelerated polishing (using British polish wheel) for a specified time (usually 9 hrs), and then tested for frictional resistance (expressed as British Pendulum Number [BPN]) using the British Pendulum Tester. The BPN value associated with accelerated polishing is defined as the polished stone value (PSV), which is a quantitative representation of the aggregate’s terminal frictional characteristics. Higher values of PSV indicate greater resistance to polish. | • New asphalt surfacings and asphalt mixes used for friction restoration.  
  • New concrete surfacings (conventional and innovative)\(^a\) |
|                   |                | Acid Insoluble Residue (AIR) test | ASTM D 3042  | Same as above.                                                                                                                                                                                               | • New asphalt surfacings and asphalt mixes used for friction restoration.  
  • New concrete surfacings (conventional and innovative)\(^a\) |
| Soundness         | Fine           | Magnesium Sulfate Soundness test  | AASHTO T 104 | An aggregate sample is immersed in a solution of magnesium sulfate for a period of 16 to 18 hours at a temperature of 70°F (21°C). The sample is then removed, drained for 15 minutes, and oven-dried to a constant weight (5 cycles of immersion and drying is typical). During the immersion process, the salt solution penetrates the permeable pore spaces of the aggregate. Oven drying dehydrates the sulfate salt precipitated in the pores. The internal expansive force of the re-hydration upon re-immersion simulates the expansion of water upon freezing. Upon completion of the final cycle, the sample is sieved over various sieves and the maximum weighted average loss is reported as the sulfate soundness loss. Higher percentages of loss indicate less sound or durable aggregate (Khandal et al., 1997). | • New concrete surfacings.          |
|                   | Coarse         |                                   |              |                                                                                                                                                                                                           | • New asphalt surfacings and asphalt mixes used for friction restoration.  
  • New concrete surfacings (conventional and innovative)\(^a\) |

\(^a\) For conventional PCC surfaces, where coarse aggregates are expected to be exposed, and innovative surfaces, such as porous concrete and exposed aggregate concrete.
hard, strongly bonded, interlocking mineral crystals (coarse grains) embedded in a matrix
of softer minerals (Folliard and Smith, 2003; Liang, 2003). The differences in grain size
and hardness provide a constantly renewed abrasive surface because of differential wear
rates and the breaking off of the harder grains from the softer matrix of softer minerals.

The Mohs scratch hardness test is recommended for determining mineral hardness. While
a visual inspection (using the descriptive nomenclature in ASTM C 294) of the aggregate
can provide a basic understanding of mineral composition and structure, more detailed
information can be obtained through advanced testing using petrographic analysis (ASTM
C 295). Some caution is advised with mineralogical tests due to the high variability
observed in the behavior of aggregates with similar mineralogy from different locations.

Aggregates made up of hard minerals (Mohs hardness > 6) alone typically resist wear and
other forms of degradation, yet may polish easily when subjected to traffic. Aggregates
made up of moderately soft minerals (Mohs hardness of 3 to 6) alone resist polishing, but
wear quickly when subjected to traffic. Agencies typically consider the ideal coarse
aggregate to consist of 50 to 70 percent coarse-grained and hard minerals embedded in a
matrix of 30 to 50 percent softer minerals. Coarse aggregates that contain larger and more
angular mineral grains or crystals exhibit higher levels of micro-texture and have a higher
frictional resistance.

The information presented in this section represents typical aggregate frictional properties
observed and reported through laboratory and field studies. However, because of the high
variability exhibited by aggregates frictional properties, it is recommended that agencies
guidance on the use of local aggregate sources be based on extensive laboratory testing
and/or field studies. This is the only way in which the recommendations provided will be
reliable and useful for pavement friction design.

Aggregate Angularity, Shape, and Texture

Aggregate angularity, shape, and texture are important parameters for defining pavement
surface micro-texture and macro-texture. Fine aggregates that exhibit angular edges and
cubical or irregular shapes generally provide higher levels of micro-texture, whereas those
with rounded edges or elongated shapes generally produce lower micro-texture. For coarse
aggregates, sharp and angular particles interlock and produce a deep macro-texture as
compared to more rounded, smooth particles. Moreover, in asphalt mixes, platy (i.e., flat
and elongated) aggregate particles tend to orient themselves horizontally, resulting in
lower macro-texture depth.

Recommended test methods for assessing angularity, shape, and texture are provided in
table 5. The uncompacted voids (UV) test (AASHTO T 304) is the most commonly used test
for assessing fine aggregate angularity, sphericity, and texture (Folliard and Smith, 2003).
As noted by Meininger (1994), this test does not require performing detailed petrographic
evaluations of shape and texture.

Two options are given for assessing coarse aggregates; the fractured-face particles test
(ASTM D 5821), which is very commonly used, and the UV test (AASHTO T 326 [formerly
AASHTO TP 56]), which is similar to the UV test for fine aggregate but is conducted with
proportionally larger equipment (Kandhal and Parker, 1998).
 Abrasion/Wear Resistance

The use of abrasion-resistant aggregates is important for avoiding breakdown when subjected to traffic shear forces or during handling, stockpiling, mixing, placing, and compaction. The breakdown of fine and/or coarse aggregate particles can alter gradation significantly, thereby affecting asphalt mix volumetric properties, concrete mix strength, and overall mix porosity and macro-texture.

Table 4 lists the recommended test methods for both fine and coarse aggregates. While the Micro-Deval test (AASHTO T 327, formerly AASHTO TP 58) for coarse aggregates have been reported (Folliard and Smith, 2003; Kandhal and Parker, 1998) in recent years to be a better indicator of the potential for aggregate breakdown, the LA Abrasion test is commonly used with good success.

Polish Resistance

The resistance of fine and coarse aggregates to polishing under traffic wear is a major factor in long-term frictional performance. Polish-resistant aggregates are those that retain their harsh micro-texture under the grinding and shearing effects of repeated traffic loadings. Polish-susceptible aggregates must be limited for use or blended with more polish-resistant aggregates.

Recommended tests for aggregate polish resistance are provided in table 4. There are no direct tests for assessing fine aggregate polish characteristics. Hence, the acid insoluble residue (AIR) test (ASTM D 3042), which indicates the amount of softer polishing carbonate material in an aggregate, is used.

For coarse aggregates, both the AIR test and the polished stone value (PSV) test (AASHTO T 278 & T 279) have been used with good success and are recommended. It should be noted, however, that other non-standard polish susceptibility tests exist and may be worthy of further examination.

Soundness

Soundness refers to an aggregate’s ability to resist degradation caused by climatic/environmental effects (i.e., wetting and drying, freezing and thawing). Similar to abrasion/wear resistance, sound aggregate properties are important for avoiding breakdown, particularly when used in harsh climates.

The test method considered to best characterize aggregate soundness is the sulfate soundness test (AASHTO T 104). This widely used test was developed to simulate, without the need for refrigeration equipment, the effects of freeze-thaw water action on aggregate particles (Khandal and Parker, 1998).

Two options for sulfate solution are given in this test—sodium sulfate and magnesium sulfate. The preferred option is the latter, as it has been reported to produce less variation in mass loss (Folliard and Smith, 2003) and provide a better indication of good versus poor aggregates (Kandhal and Parker, 1998).
Aggregate Test Criteria

Table 5 provides a range of typical test values for aggregate properties that will enhance pavement friction and friction durability (aggregate wear resistance). These values were obtained from various studies that related aggregate properties to frictional performance (Liang, 2003; Liang and Chyi, 2000; Dahir and Henry, 1978; FHWA, 2005; Kandhal and Parker, 1998; Wu et al., 1998; Prowell et al., 2005). The information presented pertains to typical virgin aggregates and may not apply to lightweight, heavyweight, or recycled aggregates.

Table 5. Typical range of test values for aggregate properties.

<table>
<thead>
<tr>
<th>Aggregate Property</th>
<th>Aggregate Fraction</th>
<th>Test Type</th>
<th>Typical Property Range for Good Friction Performance&lt;sup&gt;a,b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness</td>
<td>Fine</td>
<td>Mohs Scratch Hardness</td>
<td>≥ 6</td>
</tr>
<tr>
<td></td>
<td>Coarse</td>
<td>Mohs Scratch Hardness</td>
<td>Hard minerals: ≥ 6  Soft minerals: 3 to 5  Differential hardness (hard minus soft): 2 to 3</td>
</tr>
</tbody>
</table>
|                    | Fine               | Visual Examination (Constituents of Concrete Aggregates) and Petrographic Analysis | Hard siliceous mineral aggregate  
|                    | Coarse             | Visual Examination (Constituents of Concrete Aggregates) and Petrographic Analysis | Percent of Hard Fraction  
| Aggregate Composition & Structure | | | Natural Aggregate: 50 to 70  Artificial Aggregate: 20 to 40  
| | | | Hard Grain or Crystal Size  
| | | | 150 to 300 µm, average 200 µm  
| | | | Hard Grain or Crystal Shape  
| | | | Angular Tips  
| Angularity, Shape, & Texture | Fine               | Uncompacted Voids content, % | ≥ 45  |
| | Coarse             | Uncompacted Voids content, % | ≥ 45  |
| Abrasion/Wear Resistance | Fine               | Uncompacted Voids content, % | ≥ 45  |
| | Coarse             | Uncompacted Voids content, % | ≥ 45  |
| Polish Resistance   | Fine               | Fractured-Face Particles | Agg. Particle Size: 0.12 to 0.5 in (3 to 13 mm)  
| | Coarse             | Fractured-Face Particles | Agg. Particle Shape: Conical, Angular  
| | | | At least 90 percent by weight of the combined aggregates retained on No. 4 (4.75 mm) sieve should have two or more mechanically fractured faces.  
| Soundness           | Fine               | Micro-Deval, % Loss | ≤ 17 to 20  |
| | Coarse             | Micro-Deval, % Loss | ≤ 17 to 20  |
| |                  | LA Abrasion, % Loss | ≤ 35 to 45  |
|                | Fine               | Acid Insoluble Residue (AIR), % | ≥ 50 to 70  |
| | Coarse             | AIR, % | ≥ 50 to 70  |
| |                  | Polished Stone Value (PSV) | ≥ 30 to 35  |
|                | Fine               | Magnesium Sulfate Soundness (5 cycles), % Loss | ≤ 10 to 20  |
| | Coarse             | Magnesium Sulfate Soundness (5 cycles), % Loss | ≤ 10 to 20  |

<sup>a</sup> Based on Liang, 2003; Liang and Chyi, 2000; Dahir and Henry, 1978; FHWA, 2005; Kandhal and Parker, 1998; Wu et al., 1998; Prowell et al., 2005.

<sup>b</sup> Property range descriptions given for Mohs Scratch Hardness and Visual Examination and Petrographic Analysis pertain to individual aggregate particles.
4.2.2 Surface Mix Types and Texturing Techniques

Pavement surface drainage is in part a function of the surface macro-texture, which is defined largely by the aggregate gradation characteristics and finish quality of the surface mix. Surfaces with greater amounts of macro-texture provide greater resistance to sliding via hysteresis, and they help facilitate drainage, thereby reducing the potential for vehicle hydroplaning.

Several different surface mix types and finishing/texturing techniques are available for use in constructing new pavements and overlays, or for restoring friction on existing pavements. Tables 6 and 7 describe the more commonly used mix types and texturing techniques, respectively, and they present the typical macro-texture levels achieved. Pavement–tire considerations, such as noise, splash/spray, and hydroplaning, and general considerations, such as constructability, cost, and structural performance, are not discussed here, but they must be an integral part of any policies developed for these mixes and texturing techniques.

4.2.3 Friction Design Categories

State highway agencies (SHAs) are encouraged to develop or update policies concerning the friction design of new and restored pavements. Such policies should clearly define the aggregate friction testing protocol (i.e., test types and criteria) and surface mix/texturing techniques that are applicable for the friction demand categories established in the PFM program.

As conceptually illustrated in figure 18, friction design categories should be established that link combinations of rated aggregate sources and agency mix types/texturing techniques with PFM sections having different levels of friction demand (defined by investigatory/intervention level). Each category should include a design friction level that takes into consideration expected friction loss over time due to aggregate polishing and/or macro-texture erosion.

As a minimum, friction design categories should be established according to highway design speed and traffic (or design loadings in terms of equivalent single axle loads [ESALs]), since these factors largely determine micro-texture and macro-texture needs. Other factors that could be used in establishing categories include roadway facility type (i.e., functional or highway class, access type), facility setting (rural, urban), climate (e.g., wet, dry), number of lanes, and truck percentages.

Although several factors can be used in establishing friction design categories, the number of categories should be limited to between three and five. When developing aggregate source–texture options for a given design category, economics should be considered from the standpoint that, if the local sources contain only low-polish aggregate, it may be justifiable to use such aggregate for low friction demand situations. In addition, agencies should be mindful of any existing classification schemes set forth in their wet-weather crash reduction programs, materials and/or construction specifications, or other pavement-related policies and systems, as they may by and large reflect the desired friction priorities.
Table 6. Asphalt pavement surface mix types and texturing techniques.

<table>
<thead>
<tr>
<th>Application</th>
<th>Mix/Texture Type</th>
<th>Description</th>
<th>Macro-texture Depth&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>New AC or AC Overlay</td>
<td>Dense Fine-Graded HMA</td>
<td>Dense-graded HMA is a dense, continuously graded mixture of coarse and fine aggregates, mineral filler, and asphalt cement (5 to 6 percent). It is produced in a hot-mix plant, delivered, spread, and compacted on site. Dense-graded HMA can be modified with polymers or crumb rubber&lt;sup&gt;b&lt;/sup&gt;, and may include recycled materials. Nominal maximum sizes for surfacing applications can range from 0.38 in (9.5 mm) to 0.75 in (19.0 mm). Fine HMA mixes contain gradations that pass above the maximum density line (MDL) at the No. 8 (2.36-mm) sieve (WSDOT, 2005).</td>
<td>Typically ranges from 0.015 to 0.025 in (0.4 to 0.6 mm)</td>
</tr>
<tr>
<td>Dense Coarse-Graded HMA</td>
<td>Coarse HMA mixes have gradations that pass below the MDL at the No. 8 sieve (2.36-mm) (WSDOT, 2005).</td>
<td></td>
<td>Typically ranges from 0.025 to 0.05 in (0.6 to 1.2 mm)</td>
</tr>
<tr>
<td>Gap-Graded HMA or Stone Matrix Asphalt (SMA)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>SMA is a gap-graded mixture of course aggregate (typically, 0.4 to 0.6 in [10 to 15 mm]), filler, fibers and polymer-modified asphalt (typically, between 6 and 9 percent) produced in a hot-mix plant. Its primary advantage is resistance to deformation, but its relatively coarse surface yields good frictional characteristics.</td>
<td></td>
<td>Typically exceeds 0.04 in (1.0 mm)</td>
</tr>
<tr>
<td>Open-Graded HMA or Open-Graded Friction Course (OGFC)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>OGFC is an open-graded mixture of mostly coarse aggregate, mineral filler, and asphalt cement (3 to 6 percent). It is produced in a hot-mix plant, contains a high percentage of air voids (17-22 percent) in the mix, and is spread and compacted on site. Friction, texture, and drainage properties can be controlled by the aggregate gradation, size, angularity, and type. Open-graded HMA can be modified with polymers, fibers, and/or crumb rubber&lt;sup&gt;c&lt;/sup&gt;.</td>
<td></td>
<td>Typically ranges from 0.06 to 0.14 in (1.5 to 3.0 mm)</td>
</tr>
</tbody>
</table>

<sup>a</sup> Based in part on Hanson and Prowell, 2004; Meegoda et al., 2002; FHWA, 1996; FHWA, 2005; Richardson, 1999.

<sup>b</sup> Fine- and coarse-graded SMAs and OGFCs are being developed and increasingly used.

<sup>c</sup> Crumb rubber asphalt is a blend of 5 to 10 percent asphalt cement, reclaimed tire rubber, and additives in which the rubber component is 15 to 20 percent by weight of the total blend. The rubber must react in the hot asphalt cement sufficiently to cause swelling of the rubber particles.
Table 6. Asphalt pavement surface mix types and texturing techniques (continued).

<table>
<thead>
<tr>
<th>Application</th>
<th>Mix/Texture Type</th>
<th>Description</th>
<th>Macro-texture Depth(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friction Restoration of Existing AC Pavement</td>
<td>Chip Seal</td>
<td>Thin surface treatment containing single-sized, high-quality, angular aggregates (0.38 to 0.63 in [9.5 to 15 mm]), spread over and rolled into a liquid asphalt or asphalt emulsion binder. Aggregates are sometimes pre-coated with asphalt emulsion prior to spreading. Completed surface is somewhat course, yielding good frictional characteristics.</td>
<td>Typically exceeds 0.04 in (1 mm).</td>
</tr>
<tr>
<td></td>
<td>Slurry Seal</td>
<td>Slurry mixtures of fine aggregate, mineral filler, and asphalt emulsion. They are similar to micro-surfacing, without interlocking aggregates. Polymers are not always used in the emulsion. Their surface is typically gritty.</td>
<td>Typically range from 0.01 to 0.025 in (0.3 to 0.6 mm).</td>
</tr>
<tr>
<td></td>
<td>Micro-Surfacing (polymer-modified slurry seal)</td>
<td>A slurry mixture containing high-quality crushed, dense-graded aggregate, mineral filler, and polymer-modified asphalt emulsion. It is placed over a tack coat and is capable of being spread in variable thickness layers for rut-filling, correction courses, and wearing course applications.</td>
<td>Typically range from 0.02 to 0.04 in (0.5 to 1 mm).</td>
</tr>
<tr>
<td></td>
<td>HMA Overlay</td>
<td>See HMA surface mixes above.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ultra-Thin Polymer-Modified Asphalt (e.g., NovaChip)</td>
<td>Thin gap-graded asphalt surfaces placed using specialized equipment immediately over a thick polymer-modified asphalt emulsion membrane. Following slight compaction the surface provides a semi-porous texture.</td>
<td>Typically exceeds 0.04 in (1 mm).</td>
</tr>
<tr>
<td></td>
<td>Epoxied Synthetic Treatment (e.g., Italgrip)</td>
<td>A very thin surface treatment consisting of a two-part polymer resin placed on an existing pavement and covered with a man-made aggregate of re-worked steel slag (0.12 to 0.16 in [3 to 4 mm]). The surface is designed to substantially improve the frictional characteristics of pavements.</td>
<td>Typically exceeds 0.06 in (1.5 mm).</td>
</tr>
<tr>
<td>Retexturing of Existing AC Pavement</td>
<td>Micro-Milling</td>
<td>Milling equipment, consisting of a self-propelled machine with carbide teeth mounted on a rotating drum, typically removes 0.75 to 1.25 in (19 to 32 mm) from the asphalt surface. Spacing of cuts is approximately 0.2 in (5 mm) versus 0.62-in (6-mm) cut of conventional cold-milling machines. Resulting surface has a fine, smooth pattern that gives smoother ride.</td>
<td>Typically exceeds 0.04 in (1 mm)</td>
</tr>
</tbody>
</table>

\(^a\) Based in part on FHWA, 1996; FHWA, 2005; Hanson and Prowell, 2004; Mockensturm, 2002; Wade et al., 2001; McNerney et al., 2000; HITEC, 2003; Gransberg and James, 2005; Yaron and Nesichi, 2005.
Table 7. Concrete pavement surface mix types and texturing techniques.

<table>
<thead>
<tr>
<th>Application</th>
<th>Mix/Texture Type</th>
<th>Description</th>
<th>Macro-texture Depth&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>New PCC or PCC Overlay</td>
<td><strong>Broom Drag</strong> (longitudinal or transverse)</td>
<td>A long-bristled broom is mechanically or manually dragged over the concrete surface in either the longitudinal or transverse direction. Texture properties are controlled by adjusting the broom angle, bristle properties (length, strength, density), and delay behind the paver. Uniform striations approximately 0.06 to 0.12 in (1.5 to 3.0 mm) deep are produced by this method.</td>
<td>Typically ranges from 0.008 to 0.016 in (0.2 to 0.4 mm).</td>
</tr>
<tr>
<td></td>
<td><strong>Artificial Turf Drag</strong> (longitudinal)</td>
<td>An inverted section of artificial turf is dragged longitudinally over a concrete surface following placement. Texture properties are controlled by raising/lowering the support boom, adding weight to the turf, and delaying application to allow surface hardening. This method produces uniform 0.06 to 0.12 in (1.5 to 3.0 mm) deep surface striations.</td>
<td>Typically ranges from 0.008 to 0.016 in (0.2 to 0.4 mm), but a deep texture (min depth of 0.04 in [1.0 mm]) has been specified&lt;sup&gt;b&lt;/sup&gt;.</td>
</tr>
<tr>
<td></td>
<td><strong>Burlap Drag</strong> (longitudinal)</td>
<td>One or two layers of moistened coarse burlap sheeting are dragged over the concrete surface following placement. Texture properties are controlled by raising/lowering the support boom and adjusting the delay following concrete placement. This method produces uniform 0.06 to 0.12 in (1.5 to 3.0 mm) deep striations in the surface.</td>
<td>Typically ranges from 0.008 to 0.016 in (0.2 to 0.4 mm).</td>
</tr>
<tr>
<td></td>
<td><strong>Longitudinal Tine</strong></td>
<td>A mechanical assembly drags a wire comb of tines (~ 5 in [127 mm] long and 10 ft [3 m] wide) behind the paver (and usually following a burlap or turf drag). Texture properties are controlled by the tine angle, tine length, tine spacing, and delay for surface curing. Grooves from 0.12 to 0.25 in (3 to 6 mm) deep and 0.12 in (3 mm) wide are produced by this method, typically spaced at 0.75 in (19 mm).</td>
<td>Typically ranges from 0.015 to 0.04 in (0.4 to 1.0 mm).</td>
</tr>
<tr>
<td></td>
<td><strong>Transverse Tine</strong></td>
<td>Accomplished using methods similar to longitudinal tining, however, the mechanical assembly drags the wire comb perpendicular to the paving direction. Variations include skewing the tines 9 to 14° from perpendicular and using random or uniform tine spacing from 0.5 to 1.5 in (12 to 38 mm).</td>
<td>Typically ranges from 0.015 to 0.04 in (0.4 to 1.0 mm).</td>
</tr>
</tbody>
</table>

<sup>a</sup> Based in part on Hoerner et al., 2003; Hoerner and Smith, 2002; FHWA, 1996; FHWA, 2005.

<sup>b</sup> Minnesota Department of Transportation.
Table 7. Concrete pavement surface mix types and texturing techniques.

<table>
<thead>
<tr>
<th>Application</th>
<th>Mix/Texture Type</th>
<th>Description</th>
<th>Macro-texture Depth$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>New PCC or PCC Overlay</td>
<td>Diamond Grinding</td>
<td>A self-propelled grinding machine with a grinding head of gang-mounted diamond sawing blades removes 0.12 to 0.75 in (3 to 19 mm) of cured concrete surface, leaving a corduroy-type surface. Blades are typically 0.08 to 0.16 in (2 to 4 mm) wide and spaced 0.18 to 0.25 in (4.5 to 6 mm) apart, leaving 0.08 to 0.16 in (2 to 4 mm) high ridges. This method is most commonly used to restore surface characteristics of existing pavements, however, in recent years, it has been used to enhance the surface qualities of new PCC pavements or PCC overlays.</td>
<td>Typically ranges from 0.03 to 0.05 in (0.7 to 1.2 mm).</td>
</tr>
<tr>
<td>Porous PCC</td>
<td>Gap-graded, small-diameter aggregate are combined with cement, polymers, and water to form a drainable surface layer (typically 8 in [200 mm] thick). That surface layer is bonded to the underlying wet or dry dense concrete layer. Texture properties are controlled by aggregate sizes and gradations. Air voids range from 15 to 25 percent.</td>
<td>Typically exceeds 0.04 in (1 mm).</td>
<td></td>
</tr>
<tr>
<td>Exposed Aggregate PCC</td>
<td>HMA Overlay</td>
<td>A set retarder is applied to the wet concrete surface and the surface is protected for curing. After 12 to 24 hours, the unset mortar is removed to a depth of 0.04 to 0.08 in (1 to 2 mm) using a power broom. The large diameter aggregate is exposed by this process leaving a uniform surface.</td>
<td>Typically exceeds 0.055 in (0.9 mm).</td>
</tr>
<tr>
<td>Friction Restoration of Existing PCC Pavement$^b$</td>
<td>HMA Overlay</td>
<td>See HMA surface mixes above.</td>
<td></td>
</tr>
<tr>
<td>Retexturing of Existing PCC Pavement$^b$</td>
<td>Diamond Grinding</td>
<td>See diamond grinding above.</td>
<td></td>
</tr>
<tr>
<td>Longitudinal Diamond Grooving</td>
<td>A self-propelled grooving machine saws longitudinal grooves in the road surface about 0.12 to 0.25 in (3 to 6 mm) deep and spaced 0.5 to 1.5 (13 to 38 mm) apart. This method adds macro-texture for drainage but relies on the original surface for micro-texture.</td>
<td>Typically ranges from 0.035 to 0.055 in (0.9 to 1.4 mm).</td>
<td></td>
</tr>
<tr>
<td>Transverse Diamond Grooving</td>
<td>Completed in a manner similar to longitudinal diamond grooving, except the grooves are sawn transverse to the travel direction. This method also adds macro-texture and positive drainage for surface water. It relies on the original surface for micro-texture.</td>
<td>Typically ranges from 0.035 to 0.055 in (0.9 to 1.4 mm).</td>
<td></td>
</tr>
<tr>
<td>Shot Abrading</td>
<td>An automated machine hurls recycled round steel abrasive material at the pavement surface, abrading the surface and/or removing the mortar and sand particles surrounding the coarse aggregate to a depth of up to 0.25 in (6 mm). Texture properties are controlled by adjusting the steel abrasive material velocity and approach angle and by modifying the forward equipment speed.</td>
<td>Typically ranges from 0.025 to 0.05 in (0.6 to 1.2 mm).</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Based in part on Hoerner et al., 2003; Hoerner and Smith, 2002; FHWA, 1996; FHWA, 2005; HITEC, 2003; Rao et al., 1999.

$^b$ Other treatments, such as micro-surfacing, ultra-thin polymer-modified asphalt, epoxy-bonded laminates, and thin-bonded PCC overlays, have been used but often have structural performance and/or cost issues.
Once the design categories have been set, aggregate test protocols and mix/texture type options can be developed for each category, along with design friction levels. The test protocol should list the specific tests to be performed and the criteria/parameters to be used. The criteria should be based on established links between historical friction performance and laboratory test data.

### 4.3 Project-Level Design Guidelines

This section provides information on state-of-the-practice for providing friction on new and restored asphalt and concrete pavements. Although safety over the established pavement design life is the paramount concern, the design process should target a surface that most economically satisfies the following criteria:

- Adequate levels of micro-texture over the life of the pavement, as produced by sharp, gritty aggregate with low polish and high wear-resistance characteristics.
- Adequate levels of macro-texture over the life of the pavement for efficient displacement of water on the pavement surface.
- Low levels of splash/spray, noise generation, glare, tire wear, and rolling resistance.

Project-level friction design entails selecting aggregates and mix types/texturing techniques that satisfy both initial and long-term friction requirements. A five-step process for designing surfaces for new asphalt or concrete pavement, as well as restoration treatments of existing asphalt or concrete pavement, is as follows:
1. Determine design friction level.
2. Select aggregates.
3. Establish surface mix types and/or texturing techniques.
4. Develop construction specifications.
5. Formulate design strategies.

These design steps are described in detail in the sections below.

4.3.1 Determining Design Friction Level (Step 1)

For each new construction or restoration project, a design friction level (expressed as $F(60)$ if IFI is used or as $FN$) must be selected to satisfy agency policy requirements. The selected design level must ensure that adequate amounts of micro-texture and macro-texture are available throughout the design period.

The selected design level should take into consideration the design levels of individual PFM sections. Either one overall level can be established for the project corresponding to the PFM section with the highest demand, or multiple levels can be used. In the latter case, care must be taken such that the multiple levels do not result in an excessive number of mix types and/or surface textures to be used along the project.

Once an agency sets the goal for friction for a particular project, the process of selecting aggregates and mix types/texturing techniques that satisfy the design friction level can begin. An initial list of aggregate source–texture options can be derived from the feasible combinations identified previously for each design category (e.g., B-X, A-X, and A-Y for design category I in figure 18). These, and other potential combinations, can be evaluated more thoroughly for adequacy using the IFI model, as described below in step 3.

4.3.2 Selecting Aggregates (Step 2)

The most important factor in achieving long-lasting friction is aggregate selection. Aggregates should have the physical, chemical, and mechanical properties needed to satisfy both initial friction design levels and long-term friction requirements.

Aggregates must comply with the testing requirements established by the agency. Aggregate samples should be tested early in a project to determine their suitability and compliance with specifications. Frequently, two or more aggregate sources must be combined in appropriate percentages to meet project gradation requirements.

As stated earlier, aggregates comprised of a matrix of both hard and soft minerals will ensure friction durability. Aggregates not meeting the specified test parameters should be rejected (prior to any mix design effort) and either new materials should be considered and tested or a suitable blend of high- and low-polish susceptible aggregates should be identified.

Micro-texture in asphalt surface mixes is provided by the coarse aggregate surface texture. Coarse aggregates that exhibit “rough sandpaper” surface textures provide higher levels of micro-texture than those with smooth “fine sandpaper” textures.
Micro-texture in concrete surfaces is generally provided by the fine aggregates in the cement mortar/paste (for concrete mixes with exposed aggregates, the surface properties of the coarse aggregate will dictate micro-texture). Fine aggregates that exhibit angular edges and cubical or irregular shapes generally provide higher levels of micro-texture, whereas those with rounded edges or elongated shapes generally produce lower micro-texture.

### 4.3.3 Establishing Surface Mix Types and/or Texturing Techniques (Step 3)

**Framework for Achieving Design Friction Level**

As discussed earlier in step 1, potential combinations of aggregate source and mix type/texturing technique can be evaluated in detail using the IFI model (equations 6 through 9). Using \( DFT(20) \) as a surrogate for micro-texture and the CTM to get \( MPD, FR(S) \) in equation 8 can be set to \( DFT(20) \) at \( S \) equal to 20 km/hr. Furthermore, substituting equation 6 into equation 8, one gets the following:

\[
FR(60) = DFT(20) \times e^{\left(\frac{20-60}{14.2+89.7\times MPD}\right)}
\]

Eq. 21

Inserting equation 21 into equation 9, adding in the \( A, B, \) and \( C \) calibration constants (0.081, 0.732, and 0, respectively) for \( DFT(20) \) as given in ASTM E 1960, and re-arranging to solve for \( DFT(20) \), the following equation is obtained:

\[
DFT(20) = \left[\left(F(60) - 0.081 - 0 \times MPD\right) / 0.732\right] \times e^{\left(\frac{60-20}{14.2+89.7\times MPD}\right)}
\]

Eq. 22

Figure 19 is a plot of the above equation. As an example application, consider a project where it is desired that a locked-wheel smooth-tire friction test give a friction number of 40 at a speed limit of 60 km/hr. Then \( F(60) \) becomes is 40 and equation 22 becomes as follows:

\[
DFT(20) = \left[\left(40 - 0.081\right) / 0.732\right] \times e^{\left(\frac{40}{14.2+89.7\times MPD}\right)}
\]

Eq. 23

To achieve the design friction level of 40, the pairs of \( DFT(20) \) and \( MPD \) given in table 8 are needed. The first pair includes a rather high \( DFT(20) \) and the last two pairs include high \( MPD \) values. Therefore, the second and third pairs containing \( MPD \) values of 0.813 and 1.524 mm would need to be selected to give the \( F(60) \) or \( FN \) needed.

If the polishing characteristics have been measured or are already known, higher levels of micro-texture and/or macro-texture should be selected to meet the required levels at the end of the design life. For example, if the polished \( DFT(20) \) (i.e., \( PSV \)) and the \( MPD \) are satisfactory, then the initial \( DFT(20) \) from the test would need to be specified. If the polished \( DFT(20) \) is too low and thus requires a \( MPD \) that is too high to meet, then a higher \( DFT(20) \) or different aggregate is needed to get the required polished \( DFT(20) \) at the end of the design life.
Figure 19. Example of determining $DFT(20)$ and MPD needed to achieve design friction level.

<table>
<thead>
<tr>
<th>$MPD$, mm</th>
<th>0.457</th>
<th>0.813</th>
<th>1.524</th>
<th>2.921</th>
<th>4.343</th>
</tr>
</thead>
<tbody>
<tr>
<td>$DFT(20)$</td>
<td>112.5</td>
<td>86.3</td>
<td>71.1</td>
<td>63.0</td>
<td>60.2</td>
</tr>
</tbody>
</table>

Table 8. Pairs of $MPD$ and $DFT(20)$ needed to achieve design friction level of 40.

This method is then a guide for evaluating the levels of micro-texture ($DFT(20)$) and macro-texture ($MPD$) needed to achieve the design friction level established for a project. It can be used directly in identifying a suitable combination(s) of aggregate and mix type/texturing technique for a project or it can serve as a framework for agencies interested in developing their own customized procedure. It should also be noted that a similar process utilizing the combination of $BPN$ (micro-texture) and $MTD$ (macro-texture) could be established and used.

During the mix design stage of an asphalt project, there may become the need to “fine-tune” the gradation of a mix to satisfy the friction design requirement. A method for doing this was developed by Sullivan (2005). This method, illustrated in figure 20, uses $PSV$ and $MPD$ to compute $IFI$ (as given in ASTM E 1960) and subsequently determine the design vehicle stopping distance. Figure 21 shows an example vehicle response chart for a selected speed of 50 mi/hr (80 km/hr).
Figure 20. Flowchart illustration of asphalt pavement friction design methodology (Sullivan, 2005).

Figure 21. Illustration of vehicle response as function of PSV and MPD (Sullivan, 2005).
The Sullivan method uses an equation for computing the MPD based on key asphalt mix characteristics (maximum aggregate size, gradation, binder content). While historical data on asphalt surface mix textures can be used in this process, the MPD equation (derived using comprehensive mix design and surface texture data from the NCAT test track) gives the mix designer greater flexibility in establishing a mix design that will meet friction requirements.

Although a similar process for conventional concrete mixes could be developed, it is not as important, since the macro-texture is designed separately from the micro-texture. However, agencies are encouraged to quantify the macro-texture (MPD or MTD) of both newly applied and in-service surface texturings (e.g., tined, grooved, or ground surfaces with different groove dimensions, spacings, and orientations), so as to ensure the right supplement for the chosen fine aggregate,

**Asphalt Mix Design**

Mix design requirements for asphalt mixes may vary depending on the nature of the mix type (dense-graded, OGFC, SMA, etc.). The standard agency procedures for mix design should be followed for a given mix type and design requirement.

During the mix design process, the agency must ascertain the aggregate micro-texture, either through aggregate source historical PSV test data or through testing of the chosen aggregate. The agency must also ascertain the expected in-place macro-texture of the mix, so that a determination can be made as to whether the mix will meet the friction design requirements. Historical mean texture/profile depths (MTD/MPDs), theoretical MTD/MPDs using established relationships, or laboratory-derived MTD/MPDs (using molded samples and performing texture tests) are all possible means for identifying the mix macro-texture.

**Concrete Mix Design and Texturing Selection**

The strength/abrasion properties of the cement mortar/paste largely determine the wearing characteristics of new concrete surfaces, while the coarse aggregate polishing characteristics define restored concrete macro-texture durability. Increasing the cement content (or decreasing the water cement ratio) and implementing sound construction practices maximizes cement paste/mortar strength and, thus, abrasion resistance.

Concrete surface macro-texture is determined by the texturing type applied. Designers must select feasible surface types that meet macro-texture design requirements. Extensive recommendations for applying the finishing methods listed in table 7 have been presented in several references, including FHWA Technical Advisory T 5040.36 (FHWA, 2005). The recommendations provided can be used to enhance macro-texture for the texturing method selected.

**4.3.4 Development of Construction Specifications (Step 4)**

All agencies have standard specifications for construction of pavement surfaces that provide guidance on requirements for aggregates, mixes, handling, placement, compaction, curing,
and protection of new surfaces. For some agencies, these specifications do not specifically address friction properties of the wearing surface. To ensure quality friction on new or rehabilitated pavement surfaces, requirements for aggregate properties and test methods presented in this section may be included in project specifications, as needed.

Special Provisions

Each project has unique requirements because of the design and construction constraints and special demands. Items such as aggregate blending, noise mitigation, and QA should be clarified in the special provisions of the construction documents and specifications.

Blending

Frequently, aggregates from two or more sources must be blended to meet the specification limits. Several studies have reported that the blended aggregate properties tend to be the same as the weighted average of the properties of the individual aggregates (Liang, 2003). Thus, the goal of blending aggregate is to set the percentages of each aggregate used such that the final blend has properties that lies within the specification limits of the tests to be performed.

Quality Assurance

Among other things, a QA program often stipulates the frequency of testing aggregate sources. While no specific guidance on the extent and frequency of testing is provided in this Guide, it is strongly suggested that an aggregate source be tested extensively whenever substantially new aggregate deposits are to be used for pavement surfacing. The extent and frequency can be reduced as the agency becomes more familiar with the aggregate source and there is a history of performance for aggregates from the given source (Folliard and Smith, 2003).

Construction Issues

Construction deficiencies and poor construction practices can contribute to inadequate friction. Construction issues involve control of aggregate and mix quality during production, handling, stockpiling, mixing, placing, and finishing. Friction restoration treatments in particular, such as chip seals, slurry seals, micro-surfacing, and proprietary surfaces, are susceptible to providing less than expected friction, if poor construction practices are employed.

4.3.5 Formulation of Design Strategies (Step 5)

Both monetary and non-monetary factors are considered in selecting preferred pavement design strategy the various feasible alternatives. The main inputs required are (a) estimates of costs, (b) estimates of benefits (if the benefit cost option is selected, not that benefit cost analysis is required only if there is a significant difference in benefits between alternatives, and (c) non-monetary factors.
Important cost elements related to the inclusion of surface friction in the design strategy are:

- **Agency costs.**
  - Additional design and engineering costs.
  - Aggregate materials with required frictional properties.
  - Additives, including polymers, to improve surface properties and performance.
  - Frequency/duration of restoration activities.
    - Design strategies involving frequent M&R are typically more costly overall because of the effects of highway user delay costs, traffic control, and so on.
    - Timing of M&R can significantly escalate costs if M&R to restore surface friction does not coincide with M&R to restore structural capacity.

- **User costs**
  - Travel delays (time/delay) for friction restoration impact life cycle cost.
  - Friction can adversely influence pavement–tire factors such as tire wear, rolling resistance, and fuel consumption.
  - Safety associated factors that impact crash costs.
    - Frequency of crashes.
    - Value of crashes.

Benefits from ensuring adequate levels of friction throughout the pavement life are quantified through:

- Improved highway safety (i.e., reduction in crash costs).
  - Value of lives saved.
  - Value of injuries avoided (medical, loss income, psychological damage).
  - Savings in pain and suffering of crash victims and their families due to a reduction in crashes.
  - Reductions in property damage due to reduction in crashes.

Non-monetary factors can be included in the decision matrix and addressed through (a) agency policies and criteria on these factors and (b) appropriate weights to these factors to reflect the importance assigned to them by the agency. The non-monetary design considerations include (AASHTO, 1993):

- Service life.
- Duration of construction.
- Traffic control problems.
- Reliability, constructability, and maintainability of design.

Non-monetary considerations associated with pavement friction include:

- Pavement–tire noise.
- Splash and spray.
- Fuel consumption/rolling resistance.
- Tire wear.
- Reflectance and glare.
REFERENCES


This page intentionally left blank.
APPENDIX A. TERMINOLOGY
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS</td>
<td>Anti-lock Braking System</td>
</tr>
<tr>
<td>AC</td>
<td>Asphalt Concrete</td>
</tr>
<tr>
<td>ADT</td>
<td>Average Daily Traffic</td>
</tr>
<tr>
<td>AIR</td>
<td>Acid Insoluble Residue test</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>BPN</td>
<td>British Pendulum Number</td>
</tr>
<tr>
<td>BPT</td>
<td>British Pendulum Tester</td>
</tr>
<tr>
<td>CEN</td>
<td>European Committee for Standardization</td>
</tr>
<tr>
<td>CSA</td>
<td>Canadian Standards Association</td>
</tr>
<tr>
<td>CTM</td>
<td>Circular Texture Meter</td>
</tr>
<tr>
<td>DFT</td>
<td>Dynamic Friction Tester</td>
</tr>
<tr>
<td>ETD</td>
<td>Estimated Mean Texture Depth</td>
</tr>
<tr>
<td>FARS</td>
<td>Fatality Analysis Reporting System</td>
</tr>
<tr>
<td>FN</td>
<td>Friction Number</td>
</tr>
<tr>
<td>HMA</td>
<td>Hot-Mix Asphalt</td>
</tr>
<tr>
<td>HPS</td>
<td>(Critical) Hydroplaning Speed</td>
</tr>
<tr>
<td>ICM</td>
<td>Integrated Climatic Model</td>
</tr>
<tr>
<td>IFI</td>
<td>International Friction Index</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standards Organization</td>
</tr>
<tr>
<td>IVS</td>
<td>Intelligent Vehicle System</td>
</tr>
<tr>
<td>LCCA</td>
<td>Life-Cycle Cost Analysis</td>
</tr>
<tr>
<td>MPD</td>
<td>Mean Profile Depth</td>
</tr>
<tr>
<td>MTD</td>
<td>Mean Texture Depth</td>
</tr>
<tr>
<td>MUTCD</td>
<td>Manual on Uniform Traffic Control Devices</td>
</tr>
<tr>
<td>M&amp;R</td>
<td>Maintenance and Rehabilitation</td>
</tr>
<tr>
<td>OFM</td>
<td>Outflow Meter</td>
</tr>
<tr>
<td>OPT</td>
<td>Outflow Time</td>
</tr>
<tr>
<td>OGFC</td>
<td>Open-Graded Friction Courses</td>
</tr>
<tr>
<td>PCC</td>
<td>Portland Cement Concrete</td>
</tr>
<tr>
<td>PFM</td>
<td>Pavement Friction Management</td>
</tr>
<tr>
<td>PMS</td>
<td>Pavement Management System</td>
</tr>
<tr>
<td>PSV</td>
<td>Polished Stone Value</td>
</tr>
<tr>
<td>QA</td>
<td>Quality Assurance</td>
</tr>
<tr>
<td>QC</td>
<td>Quality Control</td>
</tr>
<tr>
<td>ROSANv</td>
<td>Road Surface Analyzer</td>
</tr>
<tr>
<td>SFT</td>
<td>Surface Friction Tester</td>
</tr>
<tr>
<td>SMA</td>
<td>Stone Matrix Asphalt</td>
</tr>
<tr>
<td>SPM</td>
<td>Sand Patch Method</td>
</tr>
<tr>
<td>SSD</td>
<td>Stopping Sight Distance</td>
</tr>
<tr>
<td>TDG</td>
<td>Texture Depth Gauge</td>
</tr>
<tr>
<td>WCR</td>
<td>Wet Crash Rate</td>
</tr>
<tr>
<td>WFT</td>
<td>Water Film Thickness</td>
</tr>
<tr>
<td>WSR</td>
<td>Wet Skidding Rate</td>
</tr>
</tbody>
</table>
TERM DEFINITIONS

Adhesion—Frictional forces that result from the small-scale bonding/interlocking of the vehicle tire rubber and the pavement surface as they come in contact with each other.

Anti-lock Braking System (ABS)—A collection of sensing and control hardware installed on a vehicle to prevent wheel lock-up during brake application.

Braking Force Coefficient—The ratio of tire braking force to normal force.

Braking Force Coefficient, Peak—The maximum value of tire braking force coefficient that occurs prior to wheel lockup as the braking torque is progressively increased.

Braking Force Coefficient, Slide—The value of tire braking force coefficient obtained on a locked wheel.

Coefficient of Friction—The ratio of the value of the tangential force between the tire tread rubber and the horizontal traveled surface to the absolute value of normal force attainable on a given traveled surface on a given rolling or locked wheel at specified test conditions.

Contact Area—The gross tire contact area that is loaded under static conditions against a smooth flat surface.

Cornering Force—The horizontal force acting perpendicularly to the instantaneous motion vector of the center of contact for a tire operating at a slip angle.

Critical Slip Angle—The value of the tire slip angle at the peak cornering force coefficient.

Friction Number (sometimes referred to as Skid Number)—The number that is used to report the results of a pavement friction test conducted in accordance with ASTM Test Method E 274; usually expressed as the friction coefficient multiplied by 100.

Hydroplaning—Phenomenon in which a vehicle tire is separated from the pavement surface by the water pressure that builds up at the pavement–tire interface.

Hysteresis—Frictional forces resulting from the energy loss due to bulk deformation of the vehicle tire.

International Friction Index ($IFI$)—Friction index defined by two parameters, a calibrated friction value at 37 mi/hr (60 km/hr), $F(60)$, and the speed gradient, $S_P$.

Intervention Level—The point in a friction deterioration curve where an agency must either take immediate corrective action, such as applying a restorative treatment, or provide proper cautionary measures, such as posting “Slippery When Wet” signs and/or reduced speed signs.
Investigatory Level—The point in a friction deterioration curve where an agency should start more carefully monitoring the friction and/or crash levels at a particular site and begin the process of planning for some sort of restorative action.

Pavement Friction Management (PFM)—A systematic approach to minimizing skid-crashes through friction and/or crash rate monitoring, timely application of friction restoration treatments, and utilization of good friction design and construction practices.

Pavement–Tire Friction (or Pavement Friction)—The force that resists the relative motion between a vehicle tire and a pavement surface. A measure of this resistive force is the non-dimensional friction coefficient, $\mu$.

Side-Force Friction—The friction that develops as a vehicle changes direction or compensates for pavement cross-slope and/or wind effects.

Skid Resistance—The ability of the traveled surface to prevent the loss of tire traction.

Slip Angle—The angle between the X-axis and the direction of travel at the center of tire contact.

Slip Speed—The difference between the speed of the axis of the measuring wheel, which is equal to the traveling speed of the measuring device, and the tangential velocity of measuring wheel with unloaded radius.

Splash—The large droplets of water that are thrown off the tire or squeezed out from pavement–tire contact area. Splash is associated with large water depths or low vehicle speeds.

Spray—The mist that is carried alongside and thrown behind a moving vehicle by the turbulent airflow created by the vehicle, other nearby vehicles, and wind. Spray is associated with shallow water depths or high vehicle speeds.

SYMBOLS

$A$ Surface texture amplitude.

$BPN$ British Pendulum Number

$C_D$ Coefficient of displacement drag.

$COV$ Coefficient of variation.

$\hat{C}$ Shape factor in the Rado friction model (log normal).

$DFT$ Dynamic Friction Test index.

$EMTD$ Estimated mean texture depth.

$F$ Friction force between vehicle tire and pavement surface.

$F_A$ Adhesion component of pavement friction.

$F_H$ Hysteresis component of pavement friction.
$F_S$ Side-force friction.

$F_W$ Applied vertical force on a wheel axle, equal to the device mass multiplied by the gravity constant, or a controlled vertically applied force.

$F_x$ Brake force.

$F_y$ Lateral force.

$FN(##)$ Friction number

$FN##R$, $SN##R$ Friction number/skid number determined at ## mi/hr using a ribbed tire.

$FN##S$, $SN##S$ Friction number/skid number determined at ## mi/hr using a smooth tire.

$FN(##)R$, $SN(##)R$ Friction number/skid number determined at ## km/hr using a ribbed tire.

$FN(##)S$, $SN(##)S$ Friction number/skid number determined at ## km/hr using a smooth tire.

$F(60)$ Friction number of the International Friction Index (IFI).

$HPS$ Critical hydroplaning speed.

$IR$ Excess rainfall (rainfall intensity minus pavement surface permeability).

$IFI$ International Friction Index.

$L$ Drainage path length.

$M$ Mass of vehicle.

$MPD$ Mean profile depth.

$MTD$ Mean texture depth.

$P$ Centripetal force (horizontal).

$R$ Radius of curvature of highway curve.

$S$ Slip speed.

$S_{MAX}$ Critical slip speed value in Rado friction model (log normal friction model).

$SP$ Speed number of the International Friction Index (IFI).

$V$ Travel speed.

$VP$ Average peripheral speed of tire.

$W$ Weight of vehicle.

$WFT$ Water film thickness.

$e$ Pavement super-elevation

$i$ Rainfall intensity.

$m$ Mass of vehicle.

$n$ Manning’s roughness coefficient.

$r$ Average tire radius.

$\alpha$ Angle of super-elevation.

$\lambda$ Surface texture wavelength.

$\mu$ 1) Friction coefficient as the ratio of a horizontal force to a vertical force in the pavement–tire contact area.

2) A reported friction value.

$\mu_{max}$ Maximum friction value.

$\omega$ Angular velocity of tire.
APPENDIX B. STANDARDS RELEVANT TO PAVEMENT FRICTION
This page intentionally left blank.
AASHTO TP 61 Standard Method of Test for Determining the Percentage of Fracture in Coarse Aggregate
AASHTO T 96 Standard Method of Test for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
AASHTO T 104 Standard Method of Test for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate
AASHTO T 261 Standard Method of Test for Measuring Texture Depth of Portland Cement Concrete Using a Tire Tread Depth Gauge
AASHTO T 278 Standard Method of Test for Surface Frictional Properties Using the British Pendulum Tester
AASHTO T 279 Standard Method of Test for Accelerated Polishing of Aggregates Using the British Wheel
AASHTO T 304 Standard Method of Test for Uncompacted Void Content of Fine Aggregate
AASHTO T 327 (formerly TP 58) Standard Method of Test for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus
AASHTO T 326 (formerly TP 56) Standard Method of Test for Uncompacted Void Content of Coarse Aggregates (as influenced by particle shape, surface texture, and grading)
ASTM C 88 Standard Test Method for Soundness of Aggregate of Use of Sodium Sulfate or Magnesium Sulfate
ASTM C 294 Standard Descriptive Nomenclature for Constituents of Concrete Aggregates
ASTM C 295 Standard Guide for Petrographic Examination of Aggregates for Concrete
ASTM C 1252 Standard Test Method for Uncompacted Void Content of Fine Aggregate (as Influenced by Particle Shape, Surface Texture, and Grading)
ASTM D 3042 Standard Test Method for Insoluble Residue in Carbonate Aggregates
ASTM D 3319 Standard Practice for the Accelerated Polishing of Aggregates Using the British Wheel
ASTM D 5821 Standard Test Method for Determining the Percentage of Fractured Particles in Coarse Aggregate
ASTM E 303 Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester
ASTM E 965 Standard Test Method for Measuring Pavement Macro-texture Depth Using a Volumetric Technique
ASTM E 1845 Standard Practice for Calculating Pavement Macro-texture Mean Profile Depth (Laser Profiler Method)
<table>
<thead>
<tr>
<th>Standard Test Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM E 1960</td>
<td>Standard Practice for Calculating International Friction Index of a Pavement Surface</td>
</tr>
<tr>
<td>ASTM E 2157</td>
<td>Standard Test Method for Measuring Pavement Macro-texture Properties Using the Circular Track Meter</td>
</tr>
<tr>
<td>ASTM E 2341</td>
<td>Standard Test Method for Determining the Stopping Distance Number by Initial Speed and Stopping Distance at Traffic Incident Site</td>
</tr>
<tr>
<td>ASTM E 2380</td>
<td>Standard Test Method for Measuring Pavement Texture Drainage Using an Outflow Meter</td>
</tr>
<tr>
<td>ASTM WK 364</td>
<td>Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus</td>
</tr>
<tr>
<td>CSA A23.2-23A</td>
<td>Resistance of Fine Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus</td>
</tr>
</tbody>
</table>