ENGINEERING SAFER ROAD SURFACES TO HELP ACHIEVE U.S. HIGHWAY SAFETY GOAL

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ABSTRACT

In recent years, there has been a major increase in activities related to improving highway safety in the United States (U.S.). This is emphasized by the publications by the American Association of State Highway and Transportation Officials (AASHTO) of the 2008 *Guide for Pavement Friction* and the 2010 *Highway Safety Manual* (first edition), by the NCHRP 500-series reports (Guidance for Implementation of the AASHTO Strategic Highway Safety Plan), and by the updated FHWA regulations and guidance regarding the Highway Safety Improvement Program. These and many other recent or ongoing research and technology development activities are beginning to have a positive impact on the nation's crash fatalities; a number that in 2008 dipped below 40,000 for the first time since 1962.

Much emphasis has been placed on improving highway safety from the standpoints of driver behavior (e.g., addressing aggressive, distracted, and impaired driving and the neglected use of seat belts) and roadway design (e.g., geometrics, roadside, and traffic control features). However, an important but often overlooked aspect of the road—the pavement surface—has been shown to be a significant factor in highway safety and thus has become a major area of focus at the FHWA, the National Cooperative Highway Research Program (NCHRP), and many state highway agencies (SHAs).

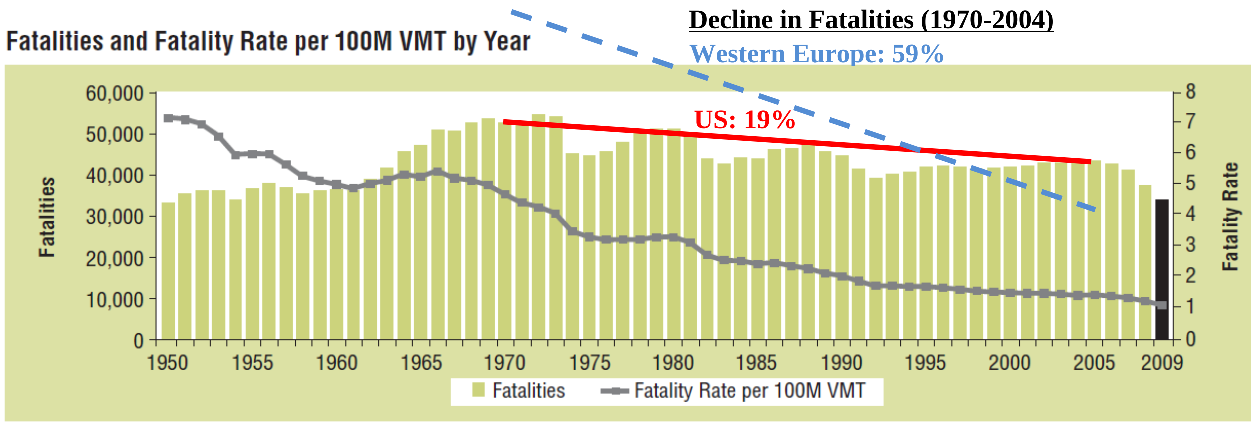
This paper provides a detailed and up-to-date look at how safety is being addressed in the U.S. from the realm of the pavement surface. It presents basic information on the more significant national studies and events involving pavement surface characteristics and their impacts on highway safety. It gives special focus to the topic of pavement friction and texture, describing the traditional approaches and state-of-the-practice for testing and ensuring pavement friction at the network level and discussing the primary shortcomings of those practices. More importantly, it presents the latest efforts to cultivate new and improved methods and technologies for minimizing the effects of friction and texture on highway crashes and the devastating number of fatalities and injuries stemming from those crashes. Such efforts are intended to help FHWA and AASHTO achieve its current highway safety goal of reducing fatalities by half in 20 years.

Key words: pavement surface characteristics, pavement friction, surface texture, microtexture, macrotexture, safety, crashes, friction testing, texture testing, pavement friction design, pavement friction management, friction demand, friction number (FN), international friction index (IFI).

INTRODUCTION

Background

Highway safety is a critical transportation issue in the United States (U.S.), which is now getting increased emphasis. As figure 1 shows, after years of having annual fatalities over 42,000, there was a slight reduction in 2007 to 41,257, followed by significant declines in 2008 to 37,262, in 2009 to 33,808, and in 2010 to 32,788. Higher fuel prices and the recession undoubtedly contributed to the decline in the number of fatalities; however, recent safety-related engineering activities are believed to be making significant contributions.



1950-1974: National Center for Health Statistics, HEW, and State Accident Summaries (Adjusted to 30-Day Traffic Deaths by NHTSA); FARS 1975-2008 (Final), 2009 Annual Report File (ARF); Vehicle Miles Traveled (VMT): Federal Highway Administration.

Figure 1. Fatality and fatality rate trends in the U.S.—1950 through 2009 (adapted from NHTSA 2010).

While steady improvement in the fatality rate has been made since the 1970s corresponding to the U.S. goal of 1 fatality per 100 million vehicle miles traveled (VMT), the total number of fatalities has become of greater concern, based on the gains that other countries have made. For instance, as figure 1 shows, the countries of western Europe experienced a 59 percent reduction in fatalities between 1970 and 2004 (from 80,093 to 33,158), compared to the U.S. reduction of 19 percent (from 52,627 to 42,636) over this same time frame. Over a more recent time period (2001-2009), Europe reduced annual fatalities by 36 percent, while the U.S. reduced annual fatalities by 20 percent. It is clear that, from this perspective, the U.S. can and should be doing much more to reduce crashes and the fatalities and injuries associated with crashes.

Recently, the U.S. safety goal has been revised from the fatality rate-based goal to fatality number goal. The new goal is to reduce the number of fatalities in half in 20 years (2010-2030).

In addition, the American Association of State Highway and Transportation Officials (AASHTO) have endorsed the Global Safety Initiative to reduce fatalities in half in 10 years (2010 to 2020). Both New York State and the United Kingdom (U.K.) are examples where annual fatalities have actually been reduced in half during the last 20 years. However, safety efforts throughout the U.S. will need to be dramatically increased to reach this revised goal.

There are a number of factors that contribute to the high number of traffic fatalities. The factors fall under three broad categories, as follows:

- Driver behavior—Factors include aggressive, distracted, and impaired driving and the neglected use of seat belts.
- Vehicle design/condition—Factors include mechanical deficiencies, such as steering or braking failures and inoperative safety restraint/impact systems.
- Roadway design/condition—Factors include roadway geometry (horizontal and vertical curves, lane configurations and widths), roadside design (e.g., shoulders and slopes, guardrails and median barriers), traffic control features (e.g., signs, signals, and striping) and pavement surface characteristics (e.g., friction, texture, profile, and roughness).

Of the $500+ billion in total crash costs estimated by Miller and Zoloshnja (2009), more than one-third were noted as being related to poor roadway conditions, as shown below:

- Seat Belt Non-Use: $59.6 billion.
- Speeding-Related: $97.1 billion.
- Alcohol-Related: $129.7 billion.
- Road Condition-Related: $217.5 billion.

Poor roadway conditions have been identified as a contributing factor in about 30 percent of the annual highway fatalities in the U.S. (Larson 2005). An evaluation of U.S. traffic crashes in 2006 indicated that roadway condition was a contributing factor in 31.4 percent of the total crashes, 52.7 percent of the 42,642 fatalities, and 38 percent of the 5,746,231 non-fatal crashes (Miller and Zoloshnja 2009).

Wet-pavement crashes, in particular, have plagued highway safety efforts for many years. A 1980 report by the National Transportation Safety Board (NTSB) concluded that, in the U.S., fatal accidents occur on wet pavements at a rate of between 3.9 and 4.5 times the rate of occurrence on dry pavements. The NTSB and the Federal Highway Administration (FHWA) have reported that 13.5 percent of fatal crashes and 18.8 percent of all crashes occur when the pavement surface is wet (Dahir and Gramling 1990; FHWA 1990). The literature also supports that up to 70 percent of the wet-pavement crashes can be prevented or minimized by improved pavement friction and texture (Henry 2000).

Most past safety improvement efforts in the U.S. have focused on driver behavior and vehicle design factors, as well as roadway geometric design and traffic safety features. The regulations and guidance put forth in the FHWA Highway Safety Improvement Program (HSIP), the NCHRP 500-series reports (*Guidance for Implementation of the AASHTO Strategic Highway Safety Plan*), and AASHTO *Highway Safety Manual* represent major advancements in the latter category of safety improvements. However, because of liability concerns and complexity, an important but often overlooked aspect of the road—the pavement surface—has been shown to be a significant factor in highway safety and thus has become a major area of focus at the FHWA, NCHRP, and many state highway agencies (SHAs).

This paper provides a detailed and up-to-date look at how safety is being addressed in the U.S. from the realm of the pavement surface. It presents basic information on the more significant national studies and events involving pavement surface characteristics and their impacts on highway safety. It gives special focus to the topic of pavement friction and texture, since these surface characteristics have much greater influence on safety and crash mitigation than other surface characteristics. It describes the traditional approaches and state-of-the-practice for testing and ensuring pavement friction at the network level and discusses the primary shortcomings of those practices. More importantly, it presents the latest efforts to cultivate new and improved methods and technologies for minimizing the effects of friction and texture on highway crashes and the devastating number of fatalities and injuries stemming from those crashes. Such efforts are intended to help FHWA and AASHTO achieve its current highway safety goal of reducing fatalities by half in 20 years.

PAVEMENT SURFACE CHARACTERISTICS

Pavement surface characteristics are a vital, yet often overlooked component of highway roadway pavement structure (Pierce et al. 2010). While physically representing only a tiny percentage of the total pavement structure, the top 0.5 in (13 mm) or less of the pavement surface has a tremendous impact on the safety and comfort of the highway users. Durable pavements that are built and maintained to have good surface friction, surface drainage, smoothness, and visibility typically exhibit fewer crashes and improved rideability.

Pavement surface characteristics include both physical attributes and dynamic attributes (Pierce et al. 2010). Physical attributes represent the stand-alone physical features of the pavement surface, such as transverse and longitudinal profile, surface texture, and porosity. Dynamic attributes represent the dynamic interaction properties that occur as a result of a vehicle traversing over the pavement surface. They include friction, hydroplaning potential, splash/spray, smoothness, tire-pavement noise, as well as several other ancillary characteristics (e.g., rolling resistance, tire wear, light reflectance/luminance).

Physical attributes directly affect many of the dynamic attributes, as summarized in table 1 (Pierce et al. 2010). Dynamic attributes, in turn, have certain impacts on the safety and comfort of highway users and the economic impacts on society (i.e., crash costs, time-delay costs, and vehicle operating costs), as shown in table 2 (Pierce et al. 2010).

Physical Attributes

Basic definitions for the four physical attributes are provided below.

Table 1. Effects of physical attributes on dynamic attributes.

Dynamic Attribute	Physical Attributes			
	Transverse Profile	**Longitudinal Profile**	**Surface Texture**	**Surface Porosity**
Friction			✓[1]	✓
Hydroplaning Potential	✓	✓	✓	✓
Splash/Spray	✓	✓	✓	✓
Smoothness		✓	✓[2]	
Noise (Interior)		✓	✓	✓
Noise (Exterior)		✓	✓	✓
Rolling Resistance		✓	✓	
Tire Wear		✓	✓	
Light Reflectance/Luminance			✓	✓

[1] Microtexture and macrotexture.

[2] Megatexture

Table 2. Effects of pavement surface dynamic attributes on highway users.

Dynamic Attribute	**Safety**	**Comfort**	**Economics**
Friction	✓ (driving control – braking and steering)		✓
Hydroplaning Potential	✓ (driving control – high-speed grip)	✓	✓
Splash/Spray	✓ (roadway visibility)	✓	✓
Smoothness	✓ (driving control – high-speed grip)	✓	✓
Noise (Interior)		✓	
Noise (Exterior)		✓[1]	
Rolling Resistance			✓
Tire Wear			✓
Light Reflectance/Luminance	✓ (pavement and roadway visibility)	✓	✓

[1] Impact on adjacent highway receptors, not users.

- Transverse and Longitudinal Pavement Profile—Profile is defined as a two-dimensional "slice" of the road surface, taken along an imaginary line and defined by the surface elevation points along that line (adapted from Pierce et al. 2010)." The "slices" can be taken either transversely across the roadway or longitudinally along the roadway length.
    - Transverse profile encompasses both cross-slope and evenness in the vertical plane perpendicular to traffic flow. Cross-slope is the rate of elevation drop across the pavement surface, while evenness is the degree of straightness in the profile (i.e., lack of deviations in the profile). Cross-slope must be developed as a compromise between the need for adequate surface drainage (i.e., steeper slopes) and the need to provide adequate driver comfort and safety (i.e., flatter slopes) (Pierce et al. 2010). As a pavement develops distresses over time due to traffic loadings and environmental forces, its transverse profile can become altered by those distresses, often to the point that water flow across the pavement is impeded and water ponds on the pavement surface. Hence, critical distresses, such as wheelpath rutting, heaving/shoving, and lane or shoulder drop-off, can present serious safety hazards for motorists during significant rainfall events.
    - Longitudinal profile refers to both grade and evenness in the vertical plane parallel to traffic flow. Grade is a measure of the incline or slope of a roadway (usually expressed as a percentage), while evenness is again the degree of straightness in the profile. Overall grade is largely governed by terrain, but to the extent possible, grades are specifically designed to account for the safety of highway users and the operating characteristics of their vehicles. Minimum allowable grades are necessary for drainage concerns, while maximum allowable grades must be specified for safety reasons (i.e., sight distance, stopping distance on downgrade) and to control traffic flow (truck speed loss on upgrade, truck control and braking on downgrades) (Anderson et al. 1998). As a pavement develops distresses (e.g., potholes/spalls, heaving/shoving, settlements/depressions, joint faulting, curled/warped slabs) over time, its longitudinal profile can become altered by those distresses, leading to decreased smoothness and increased noise, among other things.

- Texture—Texture is defined by the deviations of a pavement surface from a true planar surface (AASHTO 2008). The deviations occur at three distinct levels of scale (megatexture, macrotexture, and microtexture), each defined by the wavelength (λ) and peak-to-peak amplitudes (A) of its components. The definitions of these texture subcomponents are provided below, with the differences illustrated in figure 2.
    - Microtexture is defined by wavelengths of 0.0004 in to 0.02 in (1 µm to 0.5 mm) and vertical amplitudes less than 0.008 in (0.2 mm). The relative roughness of the aggregate particles and the cementing agent determine the microtexture of the pavement, which is mainly responsible for pavement friction at low speeds.
    - Macrotexture is defined by wavelengths of 0.02 to 2 in (0.5 mm to 51 mm) and vertical amplitudes between 0.004 to 0.8 in (0.1 mm and 20 mm) (Henry 2000). It helps (1) reduce the potential for separation of tire from pavement surface due to hydroplaning and (2) induce friction for vehicles travelling at high speeds. In hot-mix asphalt (HMA) pavements, adequate macrotexture stems from a proper asphalt mix aggregate gradation, whereas macrotexture in Portland cement concrete (PCC) pavements is most commonly produced through small surface channels, grooves, or

indentations that are intentionally formed (plastic concrete) or cut (hardened concrete) to allow water to escape from beneath a vehicle's tires.

- Megatexture is the texture which has wavelengths in the same order of size as the pavement-tire interface (AASHTO 2008) (2 to 20 in [50 to 500 mm]) and vertical amplitude between 0.005 and 2 in (0.1 to 50 mm) (AASHTO 2008). Largely defined by the distress, defects, or waviness on the pavement surface, its primary influences are on interior vehicle noise, rolling resistance, and smoothness.

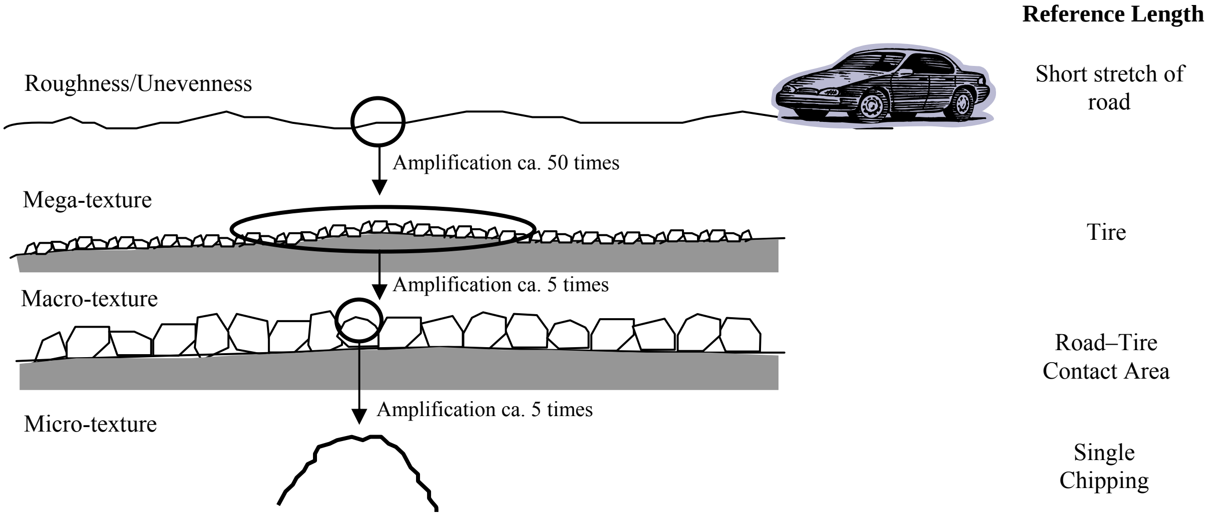


Figure 2. Illustration of megatexture, macrotexture, and microtexture for road surface (AASHTO 2008).

- Porosity—The amount of void spaces that exist within a pavement material, typically expressed as a percentage of the volume of the voids to the total material volume. Because not all air voids in pavement material mixtures are interconnected, the porosity of the mix is generally slightly less than the total percentage of air voids. Increased porosity yields increased permeability, which can expedite surface drainage (consequently improving friction and reducing hydroplaning potential and splash/spray) and, in the case of full-depth porous pavement design, significantly reduce storm water runoff. However, higher porosity has the negative effects of reduced strength/stiffness and durability of a pavement material mixture.

Dynamic Attributes

Basic definitions for the dynamic attributes affecting highway safety are provided below.

- Friction—The retarding force developed at the pavement-tire interface that resists longitudinal sliding when braking forces are applied to the vehicle tires (see figure 3) or sideways sliding when a vehicle corners around a curve (AASHTO 2008, Pierce et al. 2010). Friction is usually measured in terms of the non-dimensional coefficient of friction (μ), which is the ratio of (a) the friction force between the tire tread rubber and the horizontal traveled surface to (b) the perpendicular force or vertical load. The higher the coefficient, the more control the driver usually has over a vehicle. Friction is influenced by many factors relating to vehicle operating characteristics (e.g., speed, type of driving maneuver), tire properties (e.g., tire tread characteristics, inflation pressure), pavement surface characteristics (e.g., microtexture, macrotexture), and environment (e.g., water, temperature). While adequate surface friction generally exists on dry pavements (although there are exceptions), the presence of water reduces the direct contact between the pavement surface and the tire.

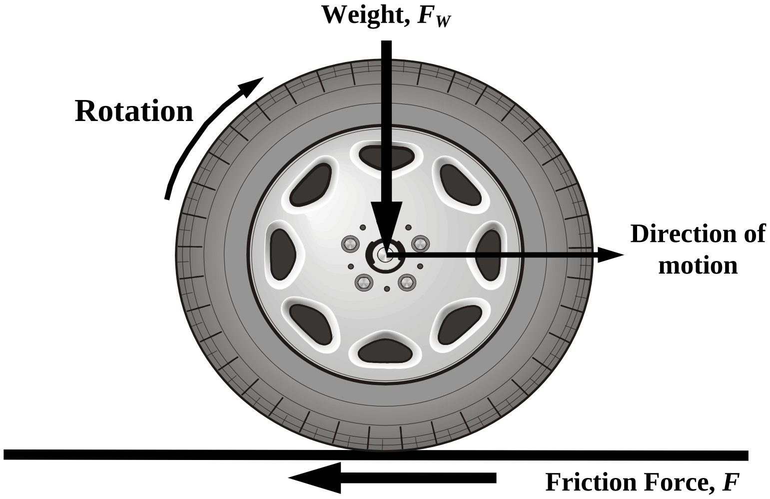


Figure 3. Simplified diagram of forces acting on a rotating wheel (AASHTO 2008).

- Hydroplaning Potential—The potential for a highway vehicle to lose complete directional control due to the tires riding on a film of water and losing contact with the pavement (Pierce et al. 2010). In addition to vehicle speed, hydroplaning potential is largely governed by water film thickness, which is influenced by the longitudinal and transverse profile of the roadway and by pavement macro-texture.
- Splash/Spray—Water from a wet road that is thrown from the tire tread and/or squeezed out from the pavement-tire contact patch, resulting in either an airborne mist of tiny water droplets (spray) or an airborne jet of large water droplets (splash) (Pierce et al. 2010). Like hydroplaning, splash/spray is influenced by the longitudinal and transverse profile of the roadway and by pavement macro-texture.
- Smoothness—Lack of roughness or lack of significant bumps, dips, holes, and other surface irregularities that can cause discomfort to motorists and, in severe cases, safety hazards. Smoothness is primarily influenced by large-scale deviations (wavelengths longer than the upper limit (20 in [500 mm]) of mega-texture in the longitudinal and transverse directions of the roadway (Pierce et al. 2010).

HISTORICAL OVERVIEW OF PAVEMENT SAFETY-RELATED ACTIVITIES

Figure 4 shows a timeline of some of more significant pavement safety-related studies and events. Several years after the First International Skid Prevention Conference (Charlottesville, Virginia) in 1958 and 1 year after the historic Highway Safety Act of 1966 (which authorized states to use federal funds to develop and strengthen their traffic safety programs), the first major guidance in the U.S. on pavement surface friction was published in NCHRP Report 37 (Larson and Smith 2010). Although responsibility for highway safety was given to the states in 1971, a considerable amount of work on pavement skid resistance and friction was conducted in the early 1970's, culminating in various Highway Research Board (HRB) workshops and syntheses, a symposium on skid resistance sponsored by the American Society for Testing and Materials (ASTM), and the publication of AASHTO's *Guidelines for Skid Resistant Pavement Design* (Larson and Smith 2010).

In the late 1970s and early 1980s, the FHWA produced several valuable resource documents on pavement friction and safety, including a report on *Pavement Texture and Available Skid Resistance* and two technical advisories on *Texturing and Skid Resistance of Concrete Pavements and Bridge Decks* (1979) and *Skid Accident Reduction Program* (1980) (Larson and Smith 2010).

Although Section 1034 of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 required states to have a safety management system (SMS) by October 1, 1994, the National Highway System (NHS) Designation Act of 1995 (Section 205) made the SMS requirement optional. Over half the states subsequently dropped their efforts to develop an SMS, despite the FHWA's 1996 published guidance on *Safety Management Systems: Good Practices for Development and Implementation* (Larson and Smith 2010).

The development in 2000 of NCHRP Synthesis 291 on *Evaluation of Pavement Friction Characteristics* precipitated a slew of national studies on pavement surface characteristics in the last decade or so. Some of these studies are completed and have produced major policy or technical guideline materials. These include the *Guide for Pavement Friction*, produced under NCHRP Project 1-43 and published by AASHTO in 2008, the FHWA's 2008 *Updated Position Paper: Asset Management and Safety*, the FHWA's technical advisories on *Surface Texture for Asphalt and Concrete Pavements* (2005) and *Pavement Friction Management* (2010), and the soon-to-be-published FHWA report on the *Relationship between Pavement Surface Characteristics and Crashes* (Larson and Smith 2010).

Several on-going studies are helping to further define and shape the way pavement surface characteristics are measured and analyzed with respect to safety and other highway performance goals. These studies are indicated by the shaded text boxes in figure 4.

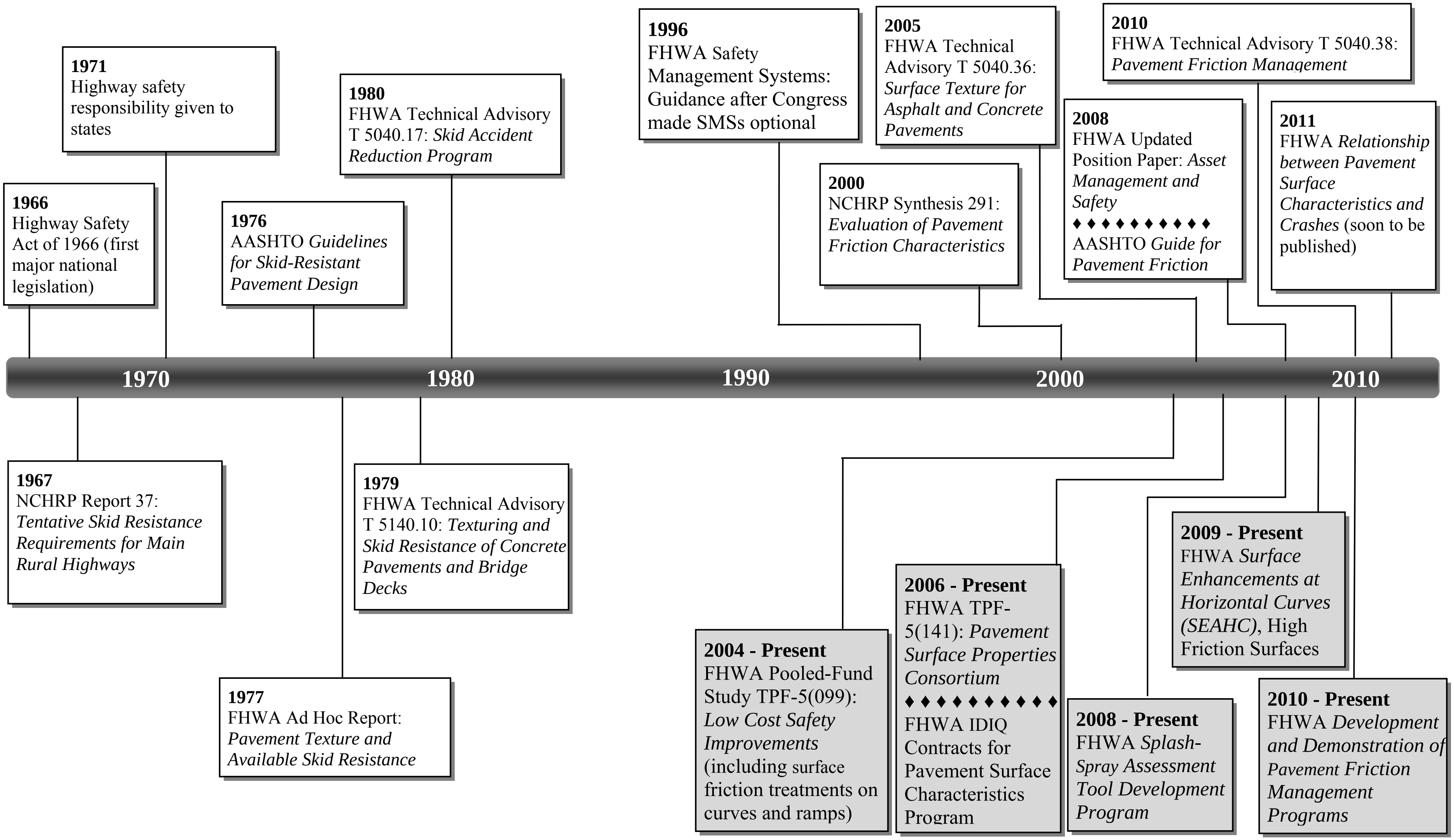


Figure 4. Historical timeline of significant pavement safety-related activities.

FRICTION AND TEXTURE MEASUREMENT PRACTICES

Equipment and Methods

Many different types of equipment have been developed and used over the years to measure pavement surface friction and texture properties. Their differences, in terms of measurement principles and procedures and the way measurement data are processed and reported, can be quite significant.

Friction and texture testing devices can be 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 (AASHTO 2008). Although the resolution and accuracy of the acquired data for low-speed or stationary measurement devices still supersede those of the high-speed devices, new technologies in data acquisition and the improved processing power of computers are helping to close the gap.

<u>Friction</u>

There are several commercially available friction testing devices. These devices use one of three main principles to measure the friction of pavements:

- Rubber pads or sliders attached to a falling pendulum or rotating feet that are slowed upon contact with the pavement surface. Devices using this technology test in a stationary position.
- Friction-measuring tires attached to or pulled by a vehicle, to obtain a coefficient of <u>longitudinal</u> friction between the pavement surface and the tire. The test tire is forced to rotate slower than the test vehicle pulling it, causing it to slip or skid.
- Friction-measuring tires attached to or pulled by a vehicle, to obtain a coefficient of <u>transverse</u> friction between the pavement surface and the tire. The test tire rotates freely, but since it is angled to the direction of travel of the vehicle, this causes it to also slip.

Two devices commonly used to measure pavement friction characteristics in the field in a stationary position are the British Pendulum Tester (BP Tester) and the Dynamic Friction Tester (DF Tester). Both of these devices measure frictional properties by determining the loss in kinetic energy of a sliding pendulum or rotating disc when in contact with the pavement surface.

There are four basic types of full-scale friction measurement devices that involve dragging a test tire over a wetted pavement surface while traveling at speeds up to 100 mi/hr (161 km/hr). These devices are categorized as follows (Hall et al. 2009):

- Locked-wheel—Measures <u>longitudinal</u> friction by completely locking the brake of the measuring tire, regardless of the speed of the test vehicle.
- Fixed-slip—Measures <u>longitudinal</u> friction while braking the test tire in such a way that it rotates at a fixed fraction, or slip-speed, of the speed of the test vehicle.

- Variable-slip—Measures longitudinal friction by braking the test tire at different slip-speeds, or variable rotational speeds, of the tire.
- Side-force—Measures transverse friction with a test tire angled with respect to the direction of travel, causing it to also measure under slip-speed conditions.

Each method of measuring friction has its specific advantages. The locked-wheel method, for instance, simulates emergency braking without anti-lock brakes. The side-force method measures the ability to maintain control during curves and has the ability for continuous friction measurement throughout a stretch of road. The fixed- and variable-slip methods allow for assessing the effects of anti-lock braking systems (ABS).

Today, most SHAs measure pavement friction with a locked-wheel trailer (see figure 5) using either a standard ribbed or smooth (blank) test tire and typically operating at speeds between 40 and 60 mi/hr (64 and 96 km/hr). A recent survey of testing practices indicated that 41 of 45 responding state agencies use the locked-wheel tester, either for network-level testing, site-specific investigations, or both. Of those 41 agencies, 23 use the ribbed tire exclusively, six of them use the smooth tire exclusively, and 12 of them use both tires (Hall et al. 2009). The ribbed tire is more sensitive to microtexture, while the smooth tire is more sensitive to macrotexture.

Figure 5. Locked-wheel friction testing trailer (Hall et al. 2009).

Emerging technologies are evaluating the computation of the pavement friction based on data from the vehicle (deceleration, slipping information for the traction control systems, etc.) and/or non-contact technologies (e.g., laser-based systems).

Texture

The measurement of pavement surface macrotexture has been a common practice in Europe for many years. The U.K., for instance, has specified macrotexture depth on new construction since 1976. Recognition of the importance of the role of pavement macrotexture in providing adequate surface friction has been increasing in recent years in the U.S. (Larson and Smith 2010).

Measurement of macrotexture can be performed using a variety of stationary, low-speed, or high-speed devices (Hall et al. 2009). Stationary equipment includes the volumetric-based Sand Patch Method (SPM), which determines macro-texture through the spreading of a known volume of glass beads or sand in a circle onto a cleaned pavement surface and measuring the diameter/area of the resulting circle (the volume divided by the area of the circle yields an estimate of the texture depth); the Outflow Meter (OF Meter), which measures the drainage rate of a specified volume of water released through the pavement surface texture and interior voids; and the Circular Texture Meter (CT Meter), a non-contact laser device that measures the surface profile along an approximate 11-in (286-mm) diameter circular path of the pavement surface and computes an average texture depth from the measured profile.

One low-speed texture measurement device is the Robotic Texture (RoboTex) Measurement System. This system uses the LMI-Selcom RoLine Line Laser to measure a continuous three-dimensional texture profile in both the transverse and longitudinal directions. The resulting profile is then used to compute texture depth and other texture parameters that are important in addressing safety, ride, and noise issues (Larson and Smith 2010).

High-speed texture measuring equipment includes laser profilers, such as the FHWA Road Surface Analyzer (ROSAN_V) (AASHTO 2008). 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 at very short intervals. From these elevations, the profiler systems can calculate the average texture depth.

Combination Friction and Texture

In recent years, some SHAs have started to retrofit macrotexture measurement capabilities to their friction measuring equipment (e.g., high-speed lasers incorporated onto locked-wheel friction testers). The macro-texture measurements are used to determine the change of friction with speed—pavement with high macrotexture presents less reduction of friction with speed and is less probable to contribute to skidding and hydroplaning.

An on-going study sponsored by the FHWA is examining all commercially available friction and texture equipment and developing recommendations as to the specific devices that would best support the pavement friction management concepts presented in the 2008 AASHTO *Guide for Pavement Friction*. The study, entitled Development and Demonstration of Pavement Friction Management Programs, seeks to identify a continuous friction measurement (CFM) device that produces friction and texture data highly correlated to crash data and that can be used by SHAs for network-level testing and deficiency monitoring.

Reporting Parameters

Friction

A number of quantitative friction indices have been developed since the late 1940s, when the skid number (SN) measurement index was first introduced (Larson and Smith 2010). The preferred term is now friction number (FN), and it is currently the most common measure of pavement friction in the U.S., given that it is the index used with locked-wheel testers.

FN is computed as 100 times the force required to slide a locked tire (at the stated speed, usually 40 mi/hr [64 km/hr]) divided by the effective wheel load. It is reported in the form of "FN" followed by the "test speed" in English or metric units (mi/hr or km/hr) followed by an "R" if a ribbed test tire was used or an "S" if a smooth-tread tire was used. Typically, FN40R (or FN(64)R for the metric designation) values in the range of 30 to 40 are targeted for major highways, while lower friction numbers are generally acceptable for low-speed and low-volume pavements with daily traffic less than 3,000 vehicles/day (Hoerner and Smith 2002).

In 1992, the Permanent International Association of Road Congresses (PIARC, now known as the World Road Association) proposed the international friction index (IFI) as a method of incorporating simultaneous measurements of friction and macrotexture into a single index representative of a pavement's frictional characteristics (Henry 2000). The IFI is dependent on two parameters that describe the pavement surface friction: a speed constant (S_P) derived from the macrotexture measurement that indicates the speed dependence of the friction, and a friction number (F(60)) that indicates the friction at a slip speed of 37 mi/hr (60 km/hr) measured using any standardized friction test method.

F(60) 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 (i.e., different makes of locked-wheel, fixed-slip, variable-slip, and side-force friction devices with different test tires) (AASHTO 2008). 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.

Although much historical FN data exists among the U.S. states, and the data have been quite useful in monitoring safety and effecting safety improvements, the FN statistic represents only a small sampling of the friction along a roadway and does not reflect the friction experienced by vehicles with ABS, the percentage of which continues to grow. With regard to the IFI, while it provides a valuable and viable means for reporting friction results from different devices on a standard scale, it is still somewhat imprecise for practical use in its current form.

Texture

The two most common macro-texture parameters are the mean texture depth (MTD) and the mean profile depth (MPD). The MTD is determined using the traditional volumetric-based sand patch test, while the MPD statistic is the typical output of today's laser-based devices (e.g., CT Meter, RoboTex, high-speed laser profilers). A highly correlated relationship between these two parameters has been developed and is often used in estimating MTD from MPD values.

To provide adequate surface friction, it is generally recommended that the average MTD be 0.03 in (0.8 mm) with a minimum of 0.02 in (0.5 mm) for any individual test (Hibbs and Larson 1996). Few agencies in the U.S. specify minimum levels of texture, whereas such practices are quite common in several European and other countries.

Use of Friction and Texture Data

Friction and texture data are collected and used by SHAs in various ways (Larson and Smith 2010). Recent surveys of state practices indicate that a few states do not test for friction at all and a few other states test friction for winter maintenance. A little more than half of the states perform network surveys for pavement management and about the same number perform friction testing at sites identified as having high crash levels or potentially low friction. About half the states also use friction data on a regular basis to develop improved materials and construction specifications.

Recent surveys indicate much less usage of texture data among SHAs (Larson and Smith 2010). Although interest seems to be slowly growing, only a few states currently collect and use texture data to help evaluate the high-speed friction characteristics of their road surfaces, whether as part of network-level pavement management or site-specific investigations. A few agencies also incorporate texture depth requirements in their construction specifications.

PAVEMENT FRICTION DESIGN

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. To build a pavement surface with adequate friction, consideration must be given to material and construction activities that influence the microtexture and macrotexture characteristics of the surface.

Pavement friction design encompasses both network policy and project-level engineering aspects. Friction design policies represent a highway agency's overall framework and procedural manner for ensuring that all pavement projects fully and properly account for friction needs (Hall et al. 2009). Project-level friction design entails selecting aggregates and mix types/texturing techniques that satisfy both initial and long-term friction requirements.

Friction Design Policy

Friction design policies establish network standards for (a) the selection and use of aggregates for micro-texture and (b) paving mixtures and surface texturing techniques for macro-texture. Successful policies effectively reduce the occurrences of wet-weather friction hazards and vehicle crashes. They are 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 (AASHTO 2008).

Aggregate Properties and Tests

Aggregate properties are the predominant factor that determines the frictional performance asphalt and concrete pavement surfaces (AASHTO 2008). Aggregate makes up the bulk of both

HMA and PCC mixtures, and therefore, for the surface of either pavement type, aggregate is the primary contact medium with the vehicle tires.

Aggregate testing and characterization must be targeted to the fraction(s) of aggregate in a mix that will control the frictional performance (AASHTO 2008). In general, coarse aggregate controls the frictional properties of asphalt mixtures, while fine aggregate controls the frictional properties of concrete mixes.

A key part of friction design is the selection of aggregates that have good, durable microtexture. Aggregates that exhibit the highest levels of long-term friction are typically composed of hard, strongly bonded, interlocking mineral crystals (coarse grains) embedded in a matrix of softer minerals (Larson and Smith 2010). 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 (AASHTO 2008).

Aggregate polishing and wear characteristics largely determine the long-term frictional performance of HMA and PCC pavement surfaces. Two tests for evaluating the polish susceptibility of aggregates in the U.S. are the polished stone value (PSV) test and the acid insoluble residue (AIR) test (Larson and Smith 2010). The PSV test, which is used only for coarse aggregates, consists of two steps: (1) polishing of the aggregate using an accelerated polishing machine, and (2) determining the resulting friction using the BPT. The higher the PSV for an aggregate, the less susceptible it is to polishing under traffic. The AASHTO-recommended minimum values of PSV are 30 to 35 (AASHTO 2008); other countries specify somewhat higher minimum values.

The AIR test uses a hydrochloric acid solution to estimate the amount of insoluble, hard, non-carbonate residue in carbonate aggregates such as limestone and dolomite (AASHTO 2008). Higher AIR values indicate higher percentages of siliceous minerals, which are considered more polish resistant that carbonate materials. The AASHTO-recommended minimum values of AIR are 50 to 70 percent (AASHTO 2008).

Research and development of other tests for evaluating aggregate polish susceptibility is on-going. One particular test shown to have potential in Europe is the German Wehner Schulze test, which subjects laboratory-prepared asphalt samples or cores extracted from the roadway to simulated traffic and measures the change in skidding resistance with time.

Surface Mix Types and Texturing Techniques

In addition to defining aggregate friction testing protocol (i.e., test types and criteria), friction design policies must set forth guidelines as to the surface mix and/or texturing techniques appropriate for different categories of friction demand. 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, and each mix type/texturing technique provides a certain range of macrotexture depth. For instance, the macrotexture depth of dense coarse-graded HMA typically ranges between 0.025 and 0.05 in (0.6 to 1.2 mm), while the macrotexture of tined PCC pavement typically ranges between 0.015 and 0.04 in (0.4 to 1.0 mm) (AASHTO 2008).

As conceptually illustrated in figure 6, friction design categories should be established that link combinations of rated aggregate sources and agency mix types/texturing techniques with pavement sections having different levels of friction demand (defined by investigatory/ intervention level) (AASHTO 2008). As a minimum, friction design categories should be established according to highway design speed and traffic, since these factors largely determine micro-texture and macro-texture needs (AASHTO 2008). 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.

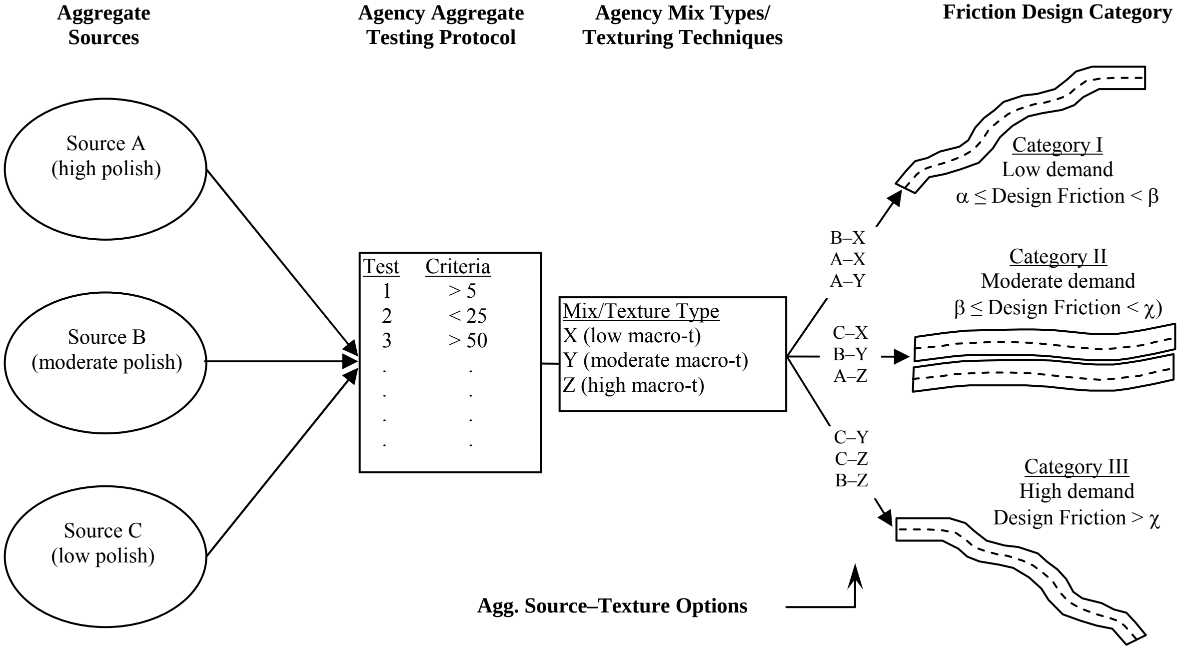


Figure 6. Example illustration of matching aggregate sources and mix types/texturing techniques to meet friction demand (AASHTO 2008).

Project-Level Friction Design

Project-level friction design entails selecting aggregates and mix types/texturing techniques that satisfy both initial and long-term friction requirements. AASHTO's 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 (AASHTO 2008, NCHRP 2009):

1. Determining design friction level required to provide adequate microtexture and macrotexture during the design period.

2. Selecting aggregates with the physical, chemical, and mechanical properties that will provide both the initial and long-term friction requirements.
3. Establishing the combinations of aggregate source, mixture type and proportions, texturing method, etc. that will provide the desired friction levels.
4. Developing construction specifications to provide guidance on the requirements for aggregates, mixtures, handling, placement, compaction, curing, other factors that influence the surface.
5. Formulating and evaluating with consideration to monetary and nonmonetary factors, potential design strategies to identify the preferred pavement design option.

Essentially, the process involves defining the long-term friction level (in terms of IFI) for the project given the geometric conditions and driving environment, and identifying combinations of microtexture (based on the selected aggregate) and macrotexture (based on mix type/texturing technique) that will satisfy the long-term friction requirement. The IFI model is used to drive the computations, with aggregate microtexture defined through tests using the DF Tester or BP Tester and pavement macrotexture defined through tests using the SPM, the CT Meter, or other laser-based texture devices. Again, while the IFI provides a valuable and viable means for reporting friction results from different devices to a standard scale, it is still somewhat imprecise and needs to be refined for more reliable use as a friction design technique.

Many SHAs use the Superpave mix design procedure to establish the requirements of HMA mixes used in pavement projects. Unfortunately, friction design is not specifically addressed in the Superpave procedure (Larson and Smith 2010). Although the procedure includes certain source property (aggregate toughness and soundness) and consensus property (aggregate shape and texture) requirements that can enhance the friction properties of the mix, no assessment of microtexture, polish susceptibility, and macrotexture is included which would help ensure the long-term friction needs of a particular project are met. Research is underway to incorporate friction and texture considerations during the HMA mix design process.

PAVEMENT FRICTION MANAGEMENT

Pavement friction management is another critical component in the effort to ensure highway safety from the standpoint of the road surface. A successful friction management framework is expected to include (1) a system for evaluating in-service pavement friction, (2) a system for correlating available friction with wet-weather crash information, and (3) guidance on the selection, design, and application of friction restoration surfaces that will provide adequate levels of safety for the desired life of the treatment.

In the traditional pavement management system (PMS), pavement sections within a network are grouped together for evaluation based on the consistency of structural features, construction history, and traffic (NCHRP 2009). The pavement friction management program defines pavement sections for evaluation based on similar principles but with consideration to the consistency in friction demand levels. Ideally, friction management programs should consider factors that influence friction demand levels, such as highway alignment, highway features/environment, traffic characteristics, and vehicle/driver characteristics. However, vehicle/driver characteristics are generally not included in such programs because of the difficulty in assessing their effects. Several highway agencies in the U.S. and other countries have established friction demand categories with consideration to the other factors (highway alignment, highway features/environment, and traffic characteristics).

To develop pavement friction management policies, an agency must identify an overall approach for managing pavement friction and a process for implementing it. According to AASHTO, a comprehensive friction management program requires the consideration of pavement friction, pavement texture, and crash rates, and should encompass the following key components (AASHTO 2008):

- Network definition – Subdividing the highway network into pavement-section groups according to levels of friction needed to perform braking, steering, and acceleration maneuvers. Friction demand categories are established according to various roadway factors, such as horizontal and vertical highway alignment, roadway features (presence and types of intersections/interchanges, special turn lanes, and median barriers), roadway environment (urban vs. rural), and highway traffic characteristics (traffic volume, composition, and speed).
- Network-level data collection – Collecting the necessary information (friction and texture testing protocols, friction and texture data, crash data, etc.).
- Network-level data analysis – Analyzing collected data to establish investigatory and intervention friction levels and identify sections requiring detailed investigation or intervention.
- Detailed site evaluation – Evaluating and testing deficient sections to identify remedial actions.
- Selection and prioritization for restoration – Identifying candidate sections for short term and long term corrective actions together with potential restoration treatments and schedule.

A flowchart depicting the AASHTO-recommended friction management program is provided in figure 7. It is based in part on an approach presented in the FHWA's 1980 Technical Advisory on Skid Accident Reduction Programs.

FHWA Research on Pavement Friction Management

As mentioned previously, the FHWA has an on-going study (*Development and Demonstration of Pavement Friction Management Programs*) examining network-level friction and texture testing equipment that would best support the friction management concepts presented in the 2008 AASHTO *Guide for Pavement Friction*. The study is also examining the concepts themselves, such as the establishment of pavement sections and the assignment of friction demand categories, the development of relationships between friction/texture and crashes, and the identification of investigatory and intervention friction/texture levels based on friction/texture–crash trends.

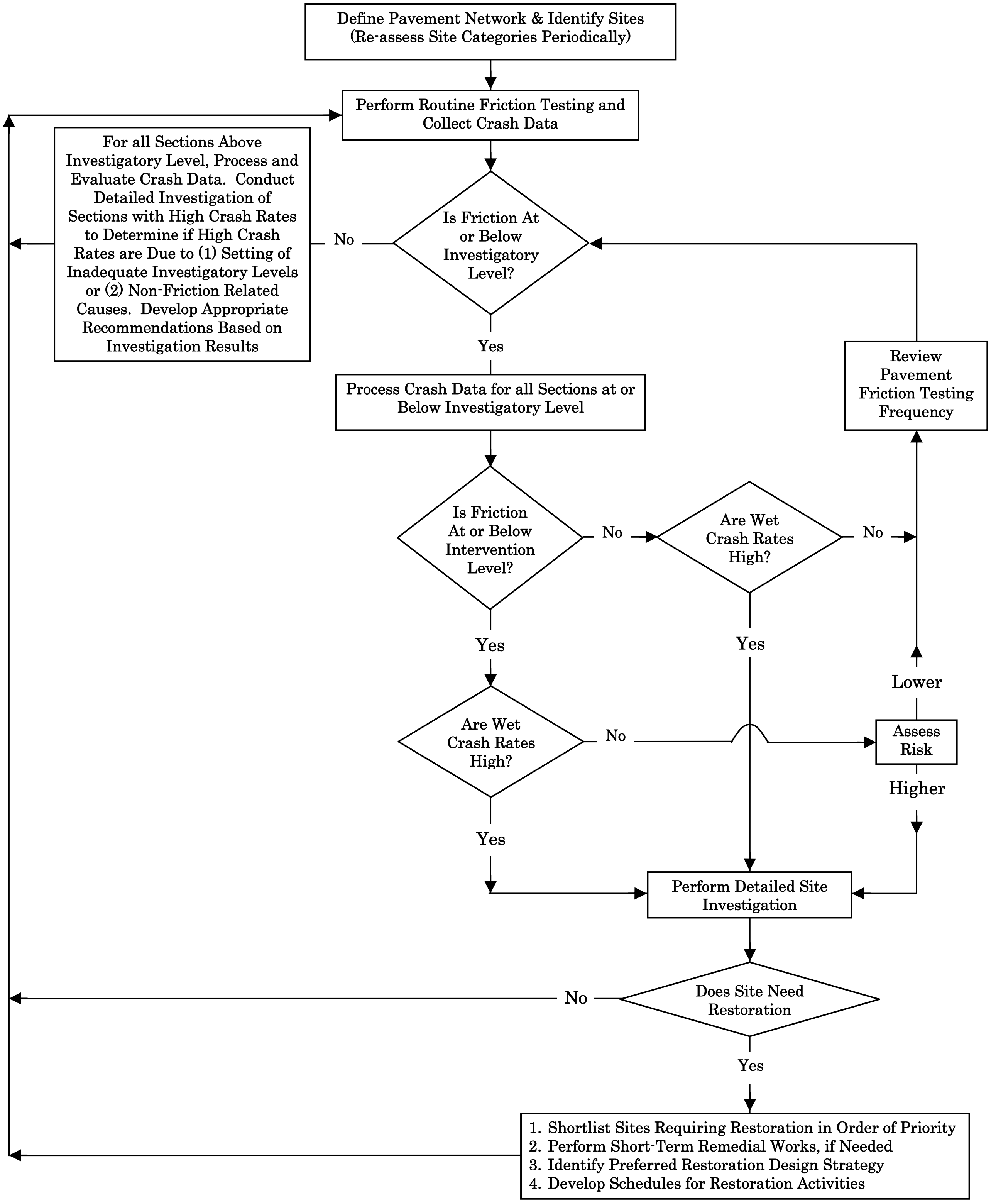


Figure 7. Flowchart for a comprehensive pavement friction management program (AASHTO 2008).

At the core of the FHWA study is the identification and use of continuous friction measurement (CFM) equipment that can better and more fully characterize available pavement friction and texture and can serve as a better predictor of potentially unsafe pavement surface locations, as compared to the ASTM E 274 locked-wheel friction tester that is commonly used in the U.S. The selected CFM device will be deployed in four states, where it will be used to collect friction and macrotexture data on 700 mi of roads (per state). The collected data and corresponding crash information from the state will then provide the basis for developing and demonstrating a state-customized friction management program. The study was begun in November 2010 and is expected to last 4.5 years.

SUMMARY AND CONCLUSIONS

This paper presented a detailed and updated look at how safety is being addressed in the U.S. from the realm of the pavement surface. Descriptions of the various pavement surface characteristics were provided and those having some degree of impact on highway safety (i.e., friction, texture, profile, hydroplaning potential, and splash/spray) were noted. A historical overview of the studies and events at the national level was provided, which showed that after a long period of relative idleness, a significant move is underway to engineer safer road surfaces for the traveling public. One study in particular, the FHWA's *Development and Demonstration of Pavement Friction Management Programs*, is expected to transform the way friction and texture are measured and characterized, and to provide highway agencies with improved methods of monitoring the safety of highway surfaces.

The paper reported on the current-state-of-the practice regarding pavement friction and texture measurement practices, including the types of equipment available and being used and the associated reporting parameters. It also described the highly important aspects of pavement friction design and pavement friction management; the former being focused on the policies and project-level design techniques for ensuring long-lasting friction/texture on new surfaces, the latter being focused on monitoring friction/texture at the network level and ensuring that safe levels are continuously maintained.

The information presented in this paper indicates that the basic principles and a sound framework for managing and designing for friction on highway pavements have been established. Also, many of the needed tools for measuring and characterizing pavement friction and texture exist and have been successfully used over the years to improve the safety of road surfaces. On-going studies and technology developments are expected to help fill gaps in testing equipment, a universal friction/texture measuring index, aggregate and mix type/texturing method selection, friction/texture–crash relationships, and methods of identifying and remediating friction-deficient pavements. The results will greatly enhance the ability of SHAs to engineer safer roads and help the FHWA and AASHTO achieve its current highway safety goal of reducing fatalities by half in 20 years.

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