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CHAPTER 2 SURFACE CHARACTERISTICS

This chapter identifies the important surface characteristics for pavements such as smoothness, texture, friction, and noise and discusses ways of achieving high levels of these important characteristics in pavements. Other desirable characteristics of durability (or longevity) and aesthetics are also addressed. In the broadest sense, roads exist to serve the traveling public. Nationwide surveys of customer satisfaction (FHWA, 1996) as well as many state-sponsored surveys show that the traveling public is interested in pavement condition and seeing those conditions improved. Other concerns include maintaining safety, addressing congestion by constructing permanent rather than temporary repairs, and doing repairs in a timely fashion.

Customer satisfaction is at the heart and soul of successful pavement preservation programs. From project selection to treatment selection, a good maintenance program will benefit the road users. Smoother and safer roads, faster maintenance and repairs, and the need for fewer repairs over a network of roads are logical outcomes of a pavement preservation program.

2.1 IMPORTANT SURFACE CHARACTERISTICS

Owners of pavements are interested in having pavements possess the following surface characteristics:

- **Ride Quality** – The public demands safe, quiet pavements with a smooth feeling ride. A recent FHWA survey (1996) indicates ride quality to be the most important feature to users of our pavements.
- **Safety** – Users expect the pavements they operated on to be safe. They should offer good texture and surface friction, be free of surface defects, provide contrast for lane markings, minimize splash and spray, and minimize glare.
- **Noise** – Agencies are becoming increasingly aware of the importance of quieter pavements, particularly in urban areas. Reduced pavement noise results in a decreased need for noise barriers and reduced impacts to adjacent neighborhoods.
- **Durability** – Agencies and private owners of pavements want surface layers to withstand the detrimental effects of traffic and environment for their expected surface course lives.
- **Aesthetics** – Users of pavements are also concerned with the appearance of the pavement surface. Patches and other surface irregularities in the surface indicate the pavement are not durable and often result in roughness or safety problems.

2.2 RIDE QUALITY

Distresses commonly found in California's concrete pavements can generally be grouped into three categories: joint deficiencies and cracking, surface defects, and miscellaneous other distresses. All of

these impact the ride quality of the pavement. The distresses commonly found in concrete pavements were discussed in detail in Chapter 1.

2.2.1 Definitions

Smoothness is defined as “deviations of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic load and drainage” (FHWA, 2004). Pavement smoothness is probably the single most important surface characteristic from the standpoint of the traveling public. Rough and uneven pavements adversely affect driver safety, fuel efficiency, ride quality, and vehicle wear and tear. Rough surfaces also negatively impact pavement durability. Because of the public’s focus on smoothness, any improvements in both initial and long-term smoothness of a roadway should lead directly to greater customer satisfaction.

2.2.2 Measuring Smoothness

Several techniques have been used to measure ride or smoothness. Much of the information in this section is a summary of the FHWA documents (Budras, 2001; FHWA, 2004; ACPA, 2006a).

The profilograph has commonly been used to measure the longitudinal profile of a concrete pavement. Its principal use has been for construction control of pavements. Profilographs have successfully been used for construction quality control and assurance on thousands of miles of pavements over the last several decades. In the mid-1980's, computerized data collection was introduced to record and analyze the pavement’s surface profile. With most states using profilographs for measuring smoothness, the profile index became a standard index for smoothness measurement in construction specifications.

Two basic types of profilographs evolved: the California and the Rainhart type profilographs. Profilographs are relatively inexpensive, simple to operate and maintain, and provide a trace of the pavement surface that users can easily understand. Both types can be manually operated by one person at walking speed; however, because of its wheel linkage, it can not be used for high speed network pavement smoothness data collection. Support wheels on the California type profilograph have varied in number from four to twelve, with systems in many States using twelve wheels. These wheels are attached to the ends of a 25-foot (7.6 m) long truss and mounted on a multiple axle carriage that includes four wheels spaced 17 inches (432 mm) from the truss centerline and two wheels spaced 17 inches (432 mm) on the opposite side of the truss centerline. The support wheels are commonly spaced at 2.7-foot (0.82 m) intervals and positioned near the ends of the truss, resulting in an overall profilograph span of approximately 33 feet (10 m). The Rainhart profilograph, however, is no longer in widespread use.

With the advent of non-contact, lightweight profilers, the profilograph has become most suited to retest short, defective pavement sections for verifying the correction of these defects. Bridge profilographs are also highly suited to bridge deck testing, as those projects require only a short profile distance. Figure 2-1 illustrates the two different types of profilographs.

For many years, network pavement smoothness data were obtained with vehicles instrumented with road meters, called by several generic names including: "response-type road roughness measuring systems" (RTRRMS's). RTRRMS's operate at highway speeds, so lane closures are unnecessary. These devices can be mounted on a passenger vehicle, light truck, or special trailer. The RTRRMS measure the response (bounce) of the vehicle to the road smoothness; it is therefore not a true measurement of smoothness. Included in this category of equipment are devices that measure the relative axle-body motion and devices that measure the acceleration of the axle or the vehicle body.

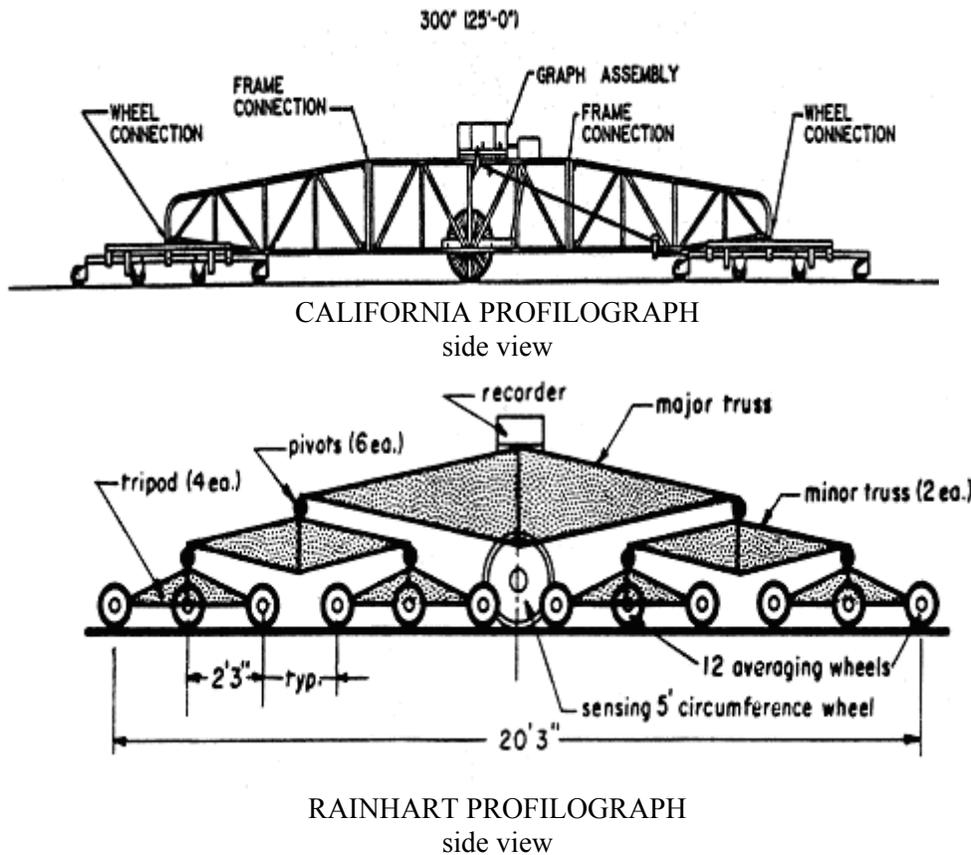
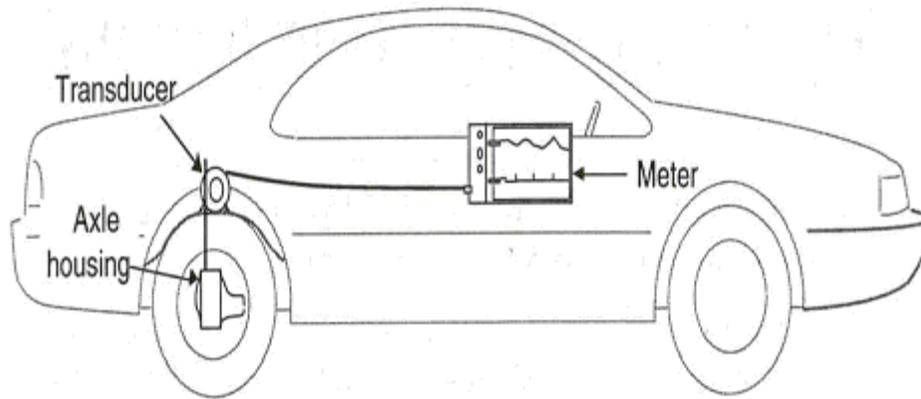


Figure 2-1 Profilographs for measuring roughness (Budras, 2001)

A decade or more ago, the most widely used RTRRMS device in the United States was the Mays Ride Meter. This device determines the smoothness of the roadway by measuring the displacement between the axle housing and the body of the host vehicle or trailer. This device actually measures the relative motion of the sprung mass system in response to traveled surface smoothness where the mass is supported by the automobile-type suspension and tires.

Road meters such as the Mays Ride Meter were devised to be cheap, rugged, and easy to use. However the fact that a response-type system depends on the dynamics of the host vehicle has several negative aspects. Smoothness measuring methods have been shown to be unstable with time. Measurements made today with road meters cannot be compared with confidence to those made several years ago. Also, smoothness measurements have not been transportable. Road meter measurements made by one system are seldom reproducible by another.

In spite of these and other problems associated with response-type meters, they have been in use for the past 50 years, and even with the advent of non-contact profilers a few agencies still use the Mays Road Meter. One reason this device has been in use for so long is that it has convinced engineers that this profiling method has produced meaningful pavement smoothness measurements. Figure 2-2 illustrates the Mays Ride Meter.



A passenger vehicle with a Mays Ride Meter

Figure 2-2 Response-Type Road Roughness Measuring System – Mays Ride Meter (Budras, 2001)

Profiling devices are quite common for network pavement data collection; however, they are not designed for project level quality control. They measure and record the longitudinal profile in one or both wheel tracks. In the USA, inertial type profiling devices are commonly used. Devices in this category of equipment include the original K. J. Law Profilometer (now marketed by Dynatest) and the South Dakota profiling device.

Inertial profilers are capable of measuring and recording road surface profiles for network use at speeds between 10 and 70 mph (15 and 110 kph). Profilers measure and compute the longitudinal profile of the pavement through the creation of an inertial reference system by using accelerometers placed on the body of the measuring vehicle. Relative displacement between the accelerometers and the pavement surface is measured with a non-contact light or acoustic measuring system mounted with the accelerometer on the vehicle body.

Operation typically requires a two-person crew (Caltrans only uses one person to operate), one as a vehicle driver and the other as a system operator. The entire system is mounted in a full size van. The profile computer, data recording, and other system components are all contained in the vehicle. A profiler contains sensors for measuring road surface profile.. With several sensors mounted on the vehicle or using rotating sensors, rut depth can be measured. Accelerometers establish the reference plane for the profiler system's measurement by measuring the vertical accelerations of the vehicle body. The distance traveled by the system is measured with a distance encoder. This is usually a pulse type distance measuring device which is mounted to the front or rear wheel of the vehicle.

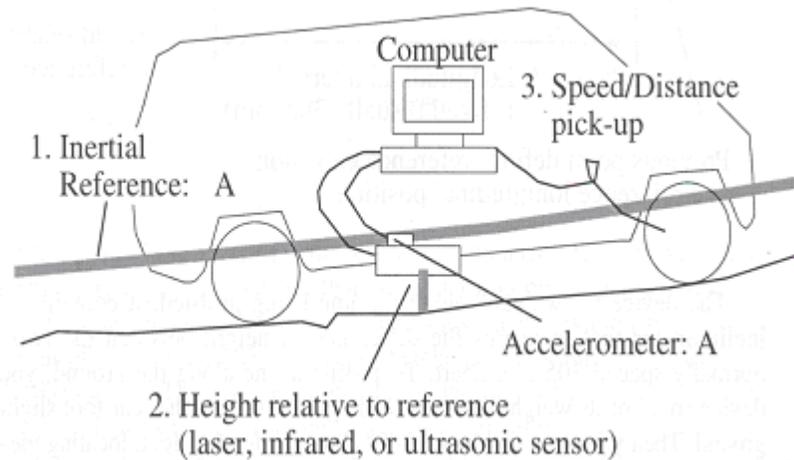
Profile signal processing is performed by a digital computer mounted in the vehicle. Profile computations are performed in real time as the vehicle is driven down the road. Interface between the user and the profiler test system is provided through a system terminal and printer. Pavement profile data points are taken every inch of travel. The program for rut depth computes and stores average rut depth taken every 100 feet (30.5 m) from data taken every 3 feet (1.6 m), or at other selected points.

Vehicle response simulation programs for smoothness index calculations are available with the profiler test system. The selected roughness index is normalized to read inches per mile or meters per kilometer and is printed out on the system printer. The cost of a non-contact inertial profiler varies with the level of precision. The laser is the most precise device. . The South Dakota type device contains ultrasonic sensors.. It measures the profile in one wheel path.. The laser device is available from several manufacturers, including Dynatest (www.dynatest.com), SSI

(www.smoothroad.com), Ames (www.amesengineering.com) and International Cybernetics (www.internationalcybernetics.com), and others. Figure 2-3 illustrates this type of device.



Photo of road roughness profiler van



Schematic of road roughness profiler van

Figure 2-3 Road Roughness Profiling Device (Budras, 2001)

A new generation of lightweight, non-contact profilers has emerged for construction quality control and acceptance purposes. They are much smaller and lighter than the network level profilers, providing the benefit of use immediately after hot-mix asphalt (HMA) construction and much sooner than would be possible with the network level devices on new portland cement concrete (PCC) pavements. However, they have operating speeds ranging from 8 to 25 miles per hour (13 to 40 km/hr), which makes it impractical for high speed, large roadway network data collection. These non-contact profilers require a one or two person operation and are battery powered. The basic system consists of an accelerometer, a non-contact sensor distance measuring instrument, a graphic display, and an IBM-compatible PC with a graphics printer.

Inputs from the accelerometer and non-contact sensor are fed into the system's on-board computer, which calculates and stores a user selected smoothness index. The on-board computer is capable of storing up to 13,000 miles (21,000 km) of data. Pavement profile data points, taken every inch, are stored as profile points.. The results can be viewed on-screen or output to the printer. The

longitudinal measurements are independent of variations in vehicle weight, speed, extremes in temperature, sunlight, wind, and pavement color or texture. The program can also calculate different smoothness indices using the same data.

Some of the emerging profilers include a Lightweight Profiler, manufactured by Dynatest (www.dynatest.com); Lightweight Inertial Surface Analyzer (LISA), manufactured by Ames Engineering (www.amesengineering.com); and the Lightweight Profiler, manufactured by International Cybernetics Corporation (www.internationalcybernetics.com). Surface Systems & Instruments Inc. (www.ssi-profile.com), and Pathway Services, Inc. (www.pathwayservices.com) also manufacture lightweight profilers. Figure 2-4 illustrates these types of devices.



non-contact lightweight profiler



non-contact sensor

Figure 2-4 Non-Contact Lightweight Profiling Devices (Budras, 2001)

The Multi-Laser Profiler (MLP) as shown in Figure 2-5, provides a vehicle mounted system that automatically collects integrated road condition data by recording laser profiles of the road surface at highway speeds. It is very useful for monitoring large road networks. The speed of operation ranges from 18 miles (30 km) to 75 miles (120 km) per hour. The MLP requires one or two person operation and comes with an onboard computer system and a range of software for data acquisition and analysis tasks. It measures IRI and, rut depth in both longitudinal and transverse profiles. The inertial sensors compensate for suspension and tire characteristics. It surveys up to approximately 370 miles (600 km) of road per day at intervals as close as 2 inches (50 mm) for smoothness and , rutting..

Portable laser profiler systems contain many other sensors and modules not required for pavement smoothness measurements. These optional features of the system include a global positioning system, a road alignment data and digital mapping system, and voice defect logging which allows an operator to log road defects while driving. These optional features provide framework data for asset management. Trigg Industries, Inc. (www.triggindustries.com), and Pathway Services (www.pathwayservices.com) are among the manufacturers of the MLP. Smaller, less expensive portable devices, such as lightweight profilers, are better suited for quality control in road construction.

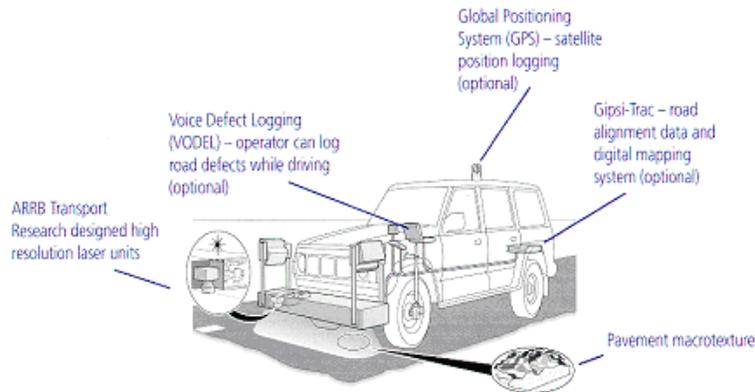


Figure 2-5 Multi-laser Profiler Vehicle (Budras, 2001)

An emerging automated portable laser profiler measurement system is the ROSAN. ROSAN stands for Road Surface Analyzer. Originally designed by FHWA, the ROSAN device serves as a vehicle mounted portable system for measuring longitudinal pavement profile depth at highway speeds, preferably over 30 miles (50 km) per hour. This system is suited for measurement of texture and smoothness. The ROSAN system relies on software to register these measurements. The ROSAN test system requires a vehicle with a step bumper. The entire package, excluding the notebook computer, fits in a wheeled protective case (see Figure 2-6). The ROSAN can be purchased as a complete system from Surfan Engineering and Software.

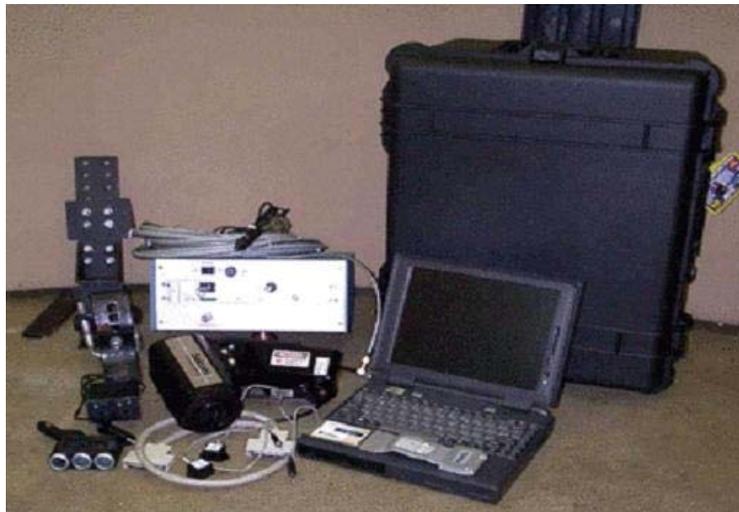


Figure 2-6 ROSAN System (Budras, 2001)

Caltrans is currently moving from profile index (PI) to IRI. All data submitted to Caltrans using profilograph or profilers must be electronic format according to CTM 526.

2.3 TEXTURE

The information in this section comes mainly from ACPA (2000, 2002, 2006a). The work by Neal et al (1978) and Henry (2000) was also used to develop these sections.

2.3.1 Definitions of Surface Texture

It is well known that pavement surface texture influences many different tire-pavement interactions, including wet-weather friction, tire-pavement noise, splash and spray, rolling resistance, and tire wear (Henry, 2000). Overall pavement surface texture includes the contributions of many surface features with different combinations of texture depth (amplitude) and feature length. These features include the contributions of aggregate texture and gradation, pavement finishing techniques, and pavement wear, to name just a few. Different texture characteristics (i.e., combinations of texture depth and wavelength) have different effects on tire-pavement interactions. Therefore, it is important to be able to classify pavement texture in a way that is useful in interpreting the effect of pavement surface texture on pavement performance characteristics.

The following *categories of pavement surface characteristics* have been established based on their amplitude (depth) and wavelength: *microtexture*, *macrotexture*, *megatexture*, and *unevenness (roughness)*. Each of these categories is described below, and the specific influence of each category on tire-pavement interaction is illustrated in Figure 2-7. It should be noted that practicing pavement engineers and contractors generally do not consider unevenness (roughness) to be a traditional component of surface texture, but it is clearly a pavement surface characteristic that does influence pavement ride quality and may contribute to user annoyance and perceptions of noise.

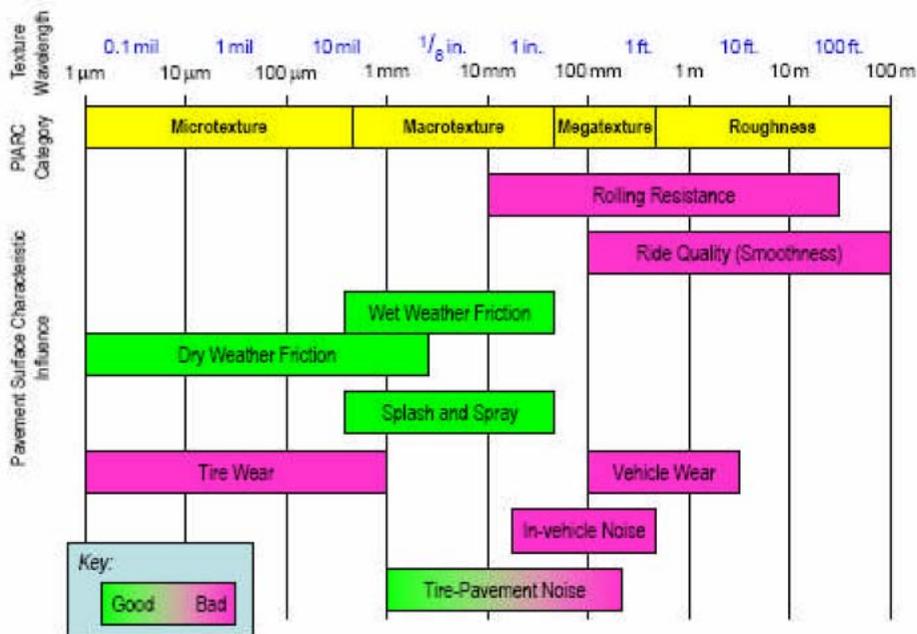


Figure 2-7 Illustration of PIARC pavement surface characteristic classifications and their impact on pavement performance measures (ACPA, 2006a)

Microtexture is defined as texture having 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). In concrete pavements, this very fine texture is typically contributed by the fine aggregate (sand) in the mortar. Good microtexture is usually all that is needed to provide adequate breaking friction on dry JPCP pavements at typical vehicle operational speeds and on wet JPCP pavements when vehicle speeds are less than 50 mph (80 kph). When higher vehicle speeds are expected, both good microtexture and macrotexture are generally required to provide adequate wet pavement friction. Microtexture is not generally considered to be a factor in the development of splash and spray or pavement noise.

Macrotexture refers to texture having wavelengths of 0.02 in to 2 in (0.5 mm to 50 mm) and vertical amplitudes ranging from 0.004 in to 0.8 in (0.1 mm to 20 mm). Macrotexture plays a major role in the wet weather friction characteristics of pavement surfaces, especially at higher vehicle speeds. Therefore, pavements that are constructed to accommodate vehicles traveling at speeds of 50 mph (80 kph) or faster require good macrotexture to help minimize hydroplaning. For concrete pavements, macrotexture is most commonly produced through small surface channels, grooves, or indentations that are intentionally formed in the plastic (wet) concrete or cut into hardened concrete to allow water to escape from beneath a vehicle's tires. In addition to providing wet weather friction, macrotexture is the pavement surface characteristic that has the strongest impact on tire-pavement noise and splash and spray. The impact of macrotexture on pavement friction and noise (both interior and exterior) is strongly influenced by the type of surface texture selected (e.g., transverse tining, longitudinal tining, turf drag, exposed aggregate, etc.) and its design details (e.g., width, depth and spacing of surface grooves, regularity of spacing, direction of texture, etc.). Figure 2-8 illustrates the difference between microtexture and macrotexture through a series of drawings of different combinations of these two pavement surface characteristics.

SURFACE		Scale of Texture	
		Macro (Large)	Micro (Fine)
A		Rough	Harsh
B		Rough	Polished
C		Smooth	Harsh
D		Smooth	Polished

Figure 2-8 Differences between Macrotexture and Microtexture (Shahin, 1994)

Megatexture comprises texture with longitudinal wavelengths of 2 in to 20 in (50 mm to 500 mm) and vertical amplitudes ranging between 0.004 in to 2 in (0.1 mm to 50 mm). This level of texture is typically the result of poor construction practices, local settlements, or surface deterioration. Megatexture can cause vibration in tire walls, resulting in in-vehicle noise and some external noise as well. Megatexture also adversely affects pavement ride quality and can produce premature wear of the vehicle suspension (i.e., tires, shock absorbers and struts). It is rarely measured or considered directly; it is defined primarily to provide a continuum between macrotexture and unevenness (roughness).

Unevenness or Roughness (Smoothness) is defined as surface irregularities with wavelengths longer than the upper limit of megatexture (>20 in [500 mm]). Wavelengths in this range have an impact on vehicle dynamics, ride quality, and surface drainage. Unevenness is generally attributed to the environment (i.e., temperature and moisture effects) and/or poor construction practices and

deformations in any pavement layer that have been induced by vehicle loads. Unevenness does not significantly affect tire-pavement noise.

2.3.2 Techniques to Create Texture

Surface textures in concrete pavements are usually made during construction by dragging various materials or tools across the fresh concrete (ACPA, 2000). This imparts a continuous series of undulations or grooves in the surface before the concrete hardens. The spacing, width and depth of the grooves affect surface friction, skid resistance, and tire/road noise. The purpose of surface texture is to reduce wet-weather accidents caused by skidding and hydroplaning.

Over the past several decades, there have been several shifts in the types of textures used. For city streets and local roads where speeds are low, burlap drag or broom surfaces are typical. The most common texture on high speed roads remains transverse tining; however a shift is underway to longitudinal tining which results in lower tire-pavement interface noise, both in the vehicle and along the roadway.

Drag Textures

Until the mid-1960s, new concrete pavement texturing was achieved primarily through shallow texturing techniques, such as a burlap drag, belting, or brooming. A 1969 report stated that 60 percent of the highway departments used burlap drag, and 12 percent specified either a burlap drag or a broom finish. More recently developed drag-type textures include longitudinal brushing and artificial turf drag. Each is described below.

Burlap Dragging. Burlap drag texturing is created by dragging moistened, coarse burlap across the surface of the pavement, typically creating a very shallow longitudinal texture (typically 0.008 inches [0.2 mm] deep) with actual texture depth varying with burlap coarseness, concrete mix design, and finishing conditions.

Broomed Surfaces – Transverse and Longitudinal. Broomed surface textures are created by dragging a hand broom or mechanical broom along the surface of the pavement, creating shallow surface ridges with texture depths ranging from 0.008 to 0.012 in (0.2 to 0.3 mm). Broomed textures may be constructed either longitudinally or transversely.

Like burlap drag textures, broomed surface textures are constructed easily and inexpensively and are relatively quiet, but may not provide adequate wet weather friction at high speeds unless combined with other features. However, if measures can be taken to ensure adequate friction and improved wear resistance, it should be possible to continue using these techniques on many lower speed facilities.

Longitudinal Plastic Brushing. This process consists of a longitudinal burlap drag followed by longitudinal dragging of a plastic bristled brush. The resulting texture is deeper than those described previously (having a mean texture depth of 0.03 to 0.04 in [0.7 to 1.0 mm]). A minimum of 30 percent siliceous sand is typically specified for the concrete mixture to provide a satisfactory microtexture. It has been reported that surfaces constructed with this texture have friction characteristics similar to those of porous asphalt friction courses, and successful installations in Spain have shown this technique to be effective at providing good friction characteristics while minimizing tire-pavement interface noise. However, data are not available to compare wet weather accident rates between this type of texture and others.

Artificial Turf Dragging. Artificial turf drag surfaces are created by dragging an inverted section of artificial turf along the plastic surface of the concrete pavement. Early versions of this process produced textures that were similar to those produced by burlap dragging and longitudinal brooming, with typical texture depths of 0.03 to 0.04 in [0.7 to 1.0 mm]. Like the other shallow texturing techniques, early turf drag textures commonly resulted in quiet pavements, but there were still concerns regarding wet weather skid resistance, particularly for high-speed facilities. The Minnesota DOT has used this method since 1999. Because the resulting surface texture offers good wet weather friction and is quiet (compared to other concrete surfaces), artificial drag is now the sole method used in Minnesota (ACPA, 2000). A wet weather study is currently underway by MnDOT which should provide more information on the benefits of this texture type.

Tined Textures

The recognition of the need for improved pavement friction in the early 1970s led to rapid changes in pavement texturing. By the mid-1970s, the most common texturing practices often featured a shallow texturing technique (such as burlap dragging) in combination with deeper transverse grooves produced by drawing a “tining head” (typically a rake-like structure with long, thin metal teeth) across or along a plastic concrete surface to produce a pattern of relatively shallow grooves.

Tined textures can be produced using hand tools or automated equipment within a paving train. The resulting surface grooves or tining marks provide channels (similar to tread grooves on a tire) through which water can escape the tire-pavement contact patch, thereby allowing better contact between the tire and pavement surfaces and reducing hydroplaning potential.

Transverse tining (often preceded by a longitudinal drag texturing) is produced by drawing the tining head across the pavement surface, perpendicular to the flow of traffic. It has proven to be an economical approach for consistently providing durable, high-friction surfaces on new PCC pavements. Caltrans uses longitudinal tining to produce grooves parallel with the centerline. The tining device (section 40-1.10 of the standard specs) shall be operated within 5 inches, but not closer than 3 inches of the pavement edge. The longitudinal tining produces a quieter pavement.

The durability of transversely tined surfaces is related mainly to the quality of the concrete (including the quality of the coarse and fine aggregates) and the spacing and depth of the tine marks. Tine marks that are spaced too closely have a higher potential for spalling under traffic and snow removal operations, which can lead to reduced surface friction. For example, it has been noted that concrete pavements with tine marks spaced uniformly at 0.5 in (13 mm) center-to-center are less durable than pavements with wider tine mark spacing. Experience suggests that transverse tining can provide adequate surface friction characteristics for 30 years or longer when good construction practices and high-quality materials are used (and when there is minimal exposure to studded tires and tire chains). While these deeper transverse texture patterns have greatly improved the wet weather friction characteristics of concrete pavements, they have also been associated with tire-pavement interface noise with objectionable tonal qualities, i.e., a “whine.”

Researchers have learned much about the characteristics of tining and their effects on both surface friction and noise. The sounds produced by the interaction of tires and transversely tined pavements are strongly correlated with the width, depth, and spacing of the tine marks. Typical pavement texturing heads have tines that are about 0.12 in (3 mm) wide, and they are set up to produce texture depths of 0.12 to 0.24 in (3 to 6 mm).

Recent research has led to the development of non-uniform (often called “random”) transverse tine spacing patterns that eliminate this “whine” while longitudinally tined pavements do not produce strong tonal sounds.

Diamond Grinding

Diamond grinding can also be used to create surface texture. This technique is gaining wider acceptance nationwide and is to-date the quietest surface available for concrete pavements. The reader is referred to Chapter 5 of this document for further details on diamond grinding.

2.3.3 Measurement of Surface Texture

Research has shown that pavement surface texture characteristics can strongly affect both vehicle operations and the surrounding environment by impacting both surface friction and ambient sound levels (noise). As a result, much attention has recently been focused on the direct measurement of surface texture characteristics, especially macrotexture, which is the characteristic most strongly associated with many aspects of pavement-tire friction and sound emissions.

There are several different methods for measuring surface texture, but their results cannot generally be compared directly (although correlations and conversion equations have been developed). Some of the most commonly used measures and measurement methods are described in the following. A brief summary of current surface texture measurement practices in the United States is included below.

Mean Texture Depth (MTD). The mean texture depth (MTD) is a measure that is determined using the traditional *volumetric* method (commonly referred to as the “sand patch” test or ASTM E 965). The volumetric method originally required the use of a special tool to spread a specified volume of specially graded Ottawa silica sand (passing the No. 50 sieve, but retained on the No. 100 sieve) on the pavement in a circular motion (see Figure 2-9). In recent years, the use of Ottawa silica sand (Figure 2-10) has been replaced with manufactured glass spheres because the glass spheres spread more uniformly than the Ottawa sand.



Figure 2-9 Photo of original “sand patch” test using Ottawa sand and spreading tool (Hoerner and Smith, 2002)



Figure 2-10 Photo of volumetric texture depth (“sand patch”) test equipment with glass beads and a hockey puck (Wambold and Henry, 2002)

The MTD is calculated by dividing the known volume of sand by the average of four equally spaced diameters of the roughly circular sand patch. Acceptable levels of MTD vary widely among highway agencies and often depend upon expected vehicle speed and other factors. For example, it is recommended that PCC surfaces have an average MTD of at least 0.03 in (0.8 mm), with a minimum of 0.02 in (0.5 mm) for any individual test, to achieve adequate surface friction.

Mean Profile Depth (MPD). Advances in laser technology and computational power have led to the development of systems that measure pavement longitudinal profile at highway travel speeds. The data from these systems can be used to compute the mean profile depth (MPD). The MPD is computed by analyzing 4-in (100-mm) segments of the collected profile data. Each segment is divided in two and the average of the highest profile peaks in each half is computed. The MPD is then computed as the average of all individual segment peak averages. It is believed that the MPD is the best parameter for estimating macrotexture for the prediction of wet pavement friction.

MPD can also be measured using the Circular Texture Meter (CTMeter), a portable device (shown in Figure 2-11) introduced in 1998 that uses a laser to measure the profile of a circle with a circumference of 35 in (890 mm). The circular profile is then divided into 8 arc segments of 4.4 in (111 mm) and the mean depth of each arc segment is computed according to standard ASTM practices (ASTM E 2157). The MPD is most accurately estimated when all eight segment mean depths are averaged to produce a single value at each test location. Excellent results have been observed using this method, even on grooved pavements.



Figure 2-11 Photo of Circular Texture Meter (CTMeter) (Abe et. al, 2001)

The MPD produced using the CTMeter is highly correlated with MTD. Procedures are available in the literature for estimating MTD with MPD (ACPA, 2006b).

Outflow Time (OFT). The outflow time (OFT) is measured using the Outflow Meter and is used to provide an indication of pavement surface macrotexture characteristics. The Outflow Meter consists of a transparent vertical cylinder that rests on a rubber annulus placed on the pavement, as shown in Figure 2-12. A valve at the bottom of the cylinder is closed and the cylinder is filled with water. The valve is then opened and the time required for a specified volume of water to flow through the system (as indicated by a specified fall in water level within the cylinder) is measured and called the outflow time (OFT). ASTM Standard E 2380-05 provides standard procedures for determining outflow time.



Figure 2-12 Photo of Outflow Meter in use (Wambold and Henry, 2002)

2.3.4 Summary

Pavement surface texture influences many different tire-pavement interactions, including wet weather friction, tire-pavement noise, splash and spray, rolling resistance, and tire wear. *Microtexture, macrottexture, megattexture and unevenness (roughness)* are the four categories most commonly used to characterize pavement surface texture.

Microtexture has wavelengths of 0.0004 in to 0.02 in (1 μm to 0.5 mm). In concrete pavements, microtexture is typically contributed by the fine aggregate (sand) in the mortar. Good microtexture is usually all that is needed to provide adequate stopping (braking) on dry PCC pavements. Microtexture is not generally considered to be a factor in the development of pavement noise or splash and spray.

Macrottexture has wavelengths of 0.02 in to 2 in (0.5 mm to 50 mm). Macrottexture plays a major role in wet weather friction characteristics of pavement surfaces. In concrete pavements, macrottexture is most commonly produced through small surface channels, grooves, or indentations that are intentionally formed in the plastic concrete or cut into hardened concrete surfaces to allow water to escape from beneath a vehicle's tires. Macrottexture is also the pavement surface characteristic that has the strongest impact on tire-pavement noise and splash and spray.

Megattexture and unevenness have longer wavelengths and greater depth and are usually the result of poor construction practices, local settlement, surface deterioration, or environmental effects. They may result in both noise and loss of ride quality.

Several methods have been used for measuring surface texture, including:

- Mean texture depth (MTD), a measure that is determined using the “sand patch test” (ASTM E 965).
- Mean profile depth (MPD), the computed average of the highest profile peaks measured in 4-in (100-mm) segments of laser-based profile measurement data.
- Outflow time (OFT), the time required for a specified volume of water to flow through a transparent vertical cylinder that rests on a rubber annulus placed on the pavement.

The results of these methods cannot generally be compared directly, although correlations and conversion equations have been developed. Acceptable levels of these measures vary widely and often depend upon expected vehicle speed and other factors. As a result there is no universal standard. It is widely believed that the MPD is the best parameter for estimating macrottexture for the prediction of wet pavement friction.

While the importance of the role of pavement macrottexture in providing adequate surface friction has been increasing in the United States, few states actually measure it and even fewer appear to have minimum macrottexture requirements.

2.4 SURFACE FRICTION

2.4.1 Background

Pavement texture affects both roadway friction and noise characteristics. While highway users and adjacent abutters are clearly concerned with roadway noise issues, they also deserve roadways that have good surface friction and are capable of providing safe travel.

Pavement surface friction (often referred to in the literature as “skid resistance”) is the force developed

at the tire-pavement interface that resists tire slippage and sliding when acceleration, braking, or when lateral forces are applied. While adequate surface friction often exists on dry pavements, water acts as a lubricant that reduces the direct contact between the pavement surface and the tire. If this film of water becomes sufficiently thick or if vehicle speeds are sufficiently high, tires can lose contact with the pavement surface completely, resulting in a dangerous phenomenon known as hydroplaning (Dahir and Grambling, 1990).

Water on the pavement also contributes to splash and spray. This occurs when standing water on the surface is picked up by vehicle tires and splashed or sprayed into the air. Such airborne water can cause a reduction in visibility of the drivers of vehicles traveling next to or closely behind the vehicle creating the splash and spray. Clearly, the reduction of wet weather accident potential must be a high priority in the pavement design process. However, it must also be recognized that most fatal crashes occur on dry roadways. While frictional characteristics of dry pavements are generally considered adequate under normal driving conditions, improved texture and friction can significantly reduce dry pavement accident rates and their severity by reducing stopping distances.

Thus it is essential that the pavement design process include the selection and design of surface textures that reduce hydroplaning potential and provide improved surface friction, both for wet and dry pavements and, especially, for higher speed roadways in urban areas.

2.4.2 Factors that Affect Pavement Friction

Tire Design and Condition

The frictional force between the tire and the road surface consists of four primary components: adhesive, deformation, and viscous and tearing forces (ACPA, 2006a). Each of these components is influenced in a different way by factors such as contact stress, sliding speed, temperatures of the tire and roadway surface, properties of the rubber compound used in the tire, texture of the road surface, contamination of the surface, tire tread pattern and wear, and presence of a water film.

It has been suggested that tires that are designed to provide good frictional performance under various conditions (e.g., wet weather or hard cornering) must, by necessity, produce higher amounts of tire-pavement noise. For example, it has been claimed by some that the “open” tread patterns necessary to prevent hydroplaning at high speeds will also cause higher noise levels.

It is clear from this discussion that tire design parameters strongly influence the safety of the traveling vehicle, especially in wet weather. It is also clear that good tire friction characteristics do not necessarily have to result in significantly higher noise levels.

Microtexture and Macrotecture

The characteristics of pavement texture that affect friction are microtexture (0.0004 to 0.02 in [1 μ m to 0.5 mm]) and macrotecture (0.02 to 2 in [0.5 to 50 mm]). If both can be maintained at good levels, they can provide improved resistance to skidding on wet pavements. Increasing macrotecture generally reduces the potential for splash and spray and increases skid resistance at higher speeds. Microtexture has a strong influence on friction at lower speeds.

Time and Seasonal Effects

Pavement friction usually decreases with pavement age due to two mechanisms: 1) aggregate polishing under traffic reduces microtexture, and 2) aggregate wear under traffic reduces macrotexture. However there are other seasonal changes (especially in colder climates) that may produce either decreases or increases in pavement friction. For example, winter conditions and winter maintenance operations tend to increase aggregate microtexture, sometimes leading to higher friction measurements in the spring and early summer than in the late summer or fall.

Periodic rainfall can also influence friction test results in almost any climate. Dust and oil that accumulate on pavements during dry periods sometimes mix with test water to reduce measured friction values. This effect is less pronounced when testing is performed shortly after periods of rainfall have flushed the dust and oil from the pavement surface.

Hydroplaning

Hydroplaning is different from skidding on wet pavement. When hydroplaning occurs, the entire tire footprint is separated from the pavement by a layer of water and the pavement surface texture no longer plays a role in the friction process.

When a rolling tire encounters a film of water on the roadway, the water is channeled through the tire tread pattern and also through the surface roughness of the pavement. Hydroplaning occurs when the drainage capacity of the tire tread pattern and the pavement surface is exceeded and the water begins to build up in front of the tire. This build-up creates a water wedge, which produces a hydrodynamic force that can lift the tire off the pavement surface—a condition referred to as “full dynamic hydroplaning.” Since water offers little shear resistance, the tire loses its traction and the driver may lose control of the vehicle.

The potential for hydroplaning increases with increasing water depth and vehicle speed and decreases with increasing tire pressure and tread depth. It has been shown that hydroplaning can occur at speeds of 55 mph (90 km/hr) with a water depth of only 0.08 in (2 mm). Hydroplaning potential is also influenced by roadway geometric factors and pavement surface condition.

Pavement surface texture does not directly influence the potential for hydroplaning. Tests have shown that the hydroplaning speed was the same on grooved and un-grooved surfaces that were flooded to the same depth (ACPA 2006a). Pavement texture and transverse profile influence the amount of water available to cause hydroplaning (i.e., rutted pavements can collect and hold significant depths of water while the very smooth surfaces can have greater effective water film thicknesses than surfaces with significant macrotexture).

Hydroplaning potential can be reduced in many ways. For example, the highway geometry can be designed to reduce the length of the drainage paths to remove water more quickly from the pavement surface. Another technique is to increase the depth of pavement surface texture to increase the water channeling/drainage capacity at the tire-pavement interface. The use of open-graded and porous pavement surfaces has also been shown to greatly reduce the hydroplaning potential of the roadway surface. They allow water to be forced through the pavement under the tire, releasing hydrodynamic pressures.

2.4.3 Measurement of Pavement Friction

The assessment of surface friction should be an integral component in the process of monitoring pavement performance. The following is an introduction to the most commonly used measures of pavement surface friction (or skid resistance) and friction measurement devices. A brief summary of current practices for measuring surface friction is also included.

Measures of Surface Friction

Friction Number (FN): Most agencies in the United States currently measure pavement friction using an ASTM locked-wheel trailer (similar to the one shown in Figure 2-13) using either a standard ribbed or smooth (blank) tire (in accordance with ASTM E 274 or ASTM E 524, respectively). Locked wheel testing devices simulate emergency braking conditions for vehicles without anti-lock brakes. In this procedure, water is applied to the dry pavement in front of the locked-wheel trailer. The friction between the locked tire and pavement surface is generally measured at a speed of 40 mi/hr (65 km/hr). The friction number (formerly referred to as skid number) is computed as 100 times the force required to slide the locked test tire over the pavement surface at the specified test speed divided by the effective wheel load.



Figure 2-13 Pennsylvania DOT E-274 locked-wheel friction tester (Wambold and Henry, 2002)

Friction numbers are reported by the designation “FN” followed by the test speed in mph and the letter “R” if a ribbed tire is used or the letter “S” if a smooth (blank) tire is used. If the test speed is expressed in km/h, the test speed is enclosed in parentheses. For example, if a ribbed tire was used in a locked-wheel trailer test at a test speed of 40 mph (65 km/h), the friction number would be reported as FN40R or FN(65)R (for U.S. Customary and SI units, respectively).

International Friction Index (IFI). The International Friction Index (IFI) was proposed in 1992 by PIARC as a method of incorporating simultaneous measurements of friction and macrotexture into a

single index that represents overall pavement frictional characteristics. It is now an approved ASTM standard test (ASTM E1960).

The IFI is dependent on the two most important parameters that describe the skid resistance of a pavement: a speed constant (S_p) derived from the macrotexture measurement that indicates the speed dependence of the friction, and a friction number (F60) that is a harmonized level of friction for a speed of 36 mph (60 km/h). One advantage of the IFI is that valid tests can be conducted at any speed, since the F60 value for a pavement is the same regardless of the slip speed used. This allows the test vehicle to operate at any safe speed (e.g., higher speeds on high-speed highways and lower speeds in urban situations). It is believed that the adoption of the IFI will eliminate concerns related to the use of different equipment/procedures and test speeds (Hoerner and Smith, 2002). By using IFI, skid resistance can be related to speed.

Common Surface Friction Measuring Devices

Four basic types of full-scale devices are most commonly used to obtain direct measurements of pavement surface friction: locked wheel, side force, fixed slip, and variable slip testers.

All of the devices listed above can be equipped with tires featuring either a “ribbed” tread (one with longitudinal grooves on the tread surface) or with a “blank” or smooth tread. Ribbed treads have been used widely in the U.S. because they are relatively insensitive to water film thickness, which makes them a good choice for performing a test that would ideally be insensitive to all operational factors (such as water film thickness). The grooves in the standard ribbed tires are much larger than the flow areas provided by typical pavement surface macrotexture. Therefore measurements obtained with ribbed tires are somewhat insensitive to macrotexture and are mainly influenced by microtexture (Henry, 2000). This helps to explain why the use of ribbed tires in friction testing is partially responsible for the sometimes poor correlation between friction test values and highway accident rates. Many studies indicate that standard smooth tires produce friction test results that correlate much better with wet weather accident rates (Henry 2000).

Using smooth test tires generally produces lower friction numbers, which may be one reason why many agencies are reluctant to use them. Either tire can be used to report the IFI, which requires the measurement of macrotexture to adjust the ribbed tire data in determining the friction number, F60.

- **Locked Wheel Devices**

As described previously, locked wheel trailers simulate emergency braking conditions for vehicles without anti-lock breaks by dragging a locked wheel (i.e., a 100 percent slip ratio) on a pavement wetted with a specified amount of water. The slip speed is equal to the vehicle speed. The brake is applied and the force is measured and averaged for 1 second after the test wheel is fully locked. Peak friction can be determined because the force measurement is continuous during the braking process. Locked wheel testers are usually equipped with a self-watering system for wet testing. A nominal water film thickness of 0.5 mm is commonly used (Henry, 2000).

- **Side Force Devices**

Side force testers are designed to simulate a vehicle’s ability to maintain control in curves. They function by maintaining a test wheel in a plane at an angle (the yaw angle) to the direction of motion, while the wheel is allowed to roll freely (i.e., a 0 percent slip ratio). The side force is measured perpendicular to the plane of rotation.

The main advantage to the side force method is that these devices can measure friction continuously through the test section (rather than over 1-second intervals, like the locked wheel devices). It should be noted that the relative velocity is proportional to the sine of the yaw angle, which is usually small. Therefore, these systems produce low-speed measurements even though they can be operated at high speeds. Thus, they tend to be most sensitive to pavement microtexture.

Examples of specific side force testing equipment include the MuMeter (Figure 2-14) and the Sideway force Coefficient Routine Investigation Machine (SCRIM – Figure 2-15), both of which originated in the United Kingdom. The SCRIM averages side force measurements from two wheels that are toed out at an angle of 7.5 degrees. Some SCRIM's are now fitted with laser macrotexture measurement systems to provide a more complete indication of a pavement's surface friction characteristics. The MuMeter was developed mainly for airport use and has seen only limited use on highways in the United States.



Figure 2-14 Photo of Mu Meter (Wambold and Henry, 2002)



Figure 2-15 Photo of SCRIM (Wambold and Henry, 2002)

- Fixed and Variable Slip Devices

The fixed and variable slip methods attempt to detect or operate around the peak friction level to simulate a vehicle's ability to brake while using increasingly more common antilock brakes. Fixed slip devices operate at a constant slip, usually between 10 and 20 percent slip (i.e., the test wheel is driven at a lower angular velocity than its free rolling velocity) while the variable slip devices sweep through a predetermined set of slip ratios, in accordance with ASTM Standard E 1859. Examples of fixed slip devices include the Griptester (Figure 2-16) and SAAB Friction Tester (Figure 2-17). A specific example of a variable slip device is the Norsemeter Road Analyzer and Recorder, ROAR (Figure 2-18). The fixed and variable slip testing devices have not been widely used on highway pavements in the United States and there is no current ASTM standard for fixed slip testing



Figure 2-16 Photo of GRIPTESTER-towed mode (Wambold and Henry, 2002)



Figure 2-17 Photo of SAAB Surface Friction Tester (Wambold and Henry, 2002)



Figure 2-18 Photo of Norsemeter ROAR – Variable Friction Tester (Wambold and Henry, 2002)

- British Pendulum Tester

Another method of measuring pavement friction (or microtexture, indirectly) is the British (portable) Pendulum Tester (BPT), which is described in ASTM E 303. Developed for use as a laboratory test for cores or lab-prepared samples, it can also be used on pavements in the field.

The BPT (shown in Figure 2-19) is operated by releasing a pendulum from a height that is adjusted so that a rubber slider on the pendulum head contacts the pavement surface over a fixed length. Friction between the slider and the pavement surface reduces the kinetic energy of the head, and the reduced kinetic energy is converted to potential energy as the pendulum breaks contact with the surface and approaches its maximum recovered height. The difference between the initial and recovered pendulum heights represents the loss in energy due to friction between the slider and the pavement surface. The BPT is equipped with a scale that measures the recovered height of the pendulum in terms of a British Pendulum Number (BPN). The slip speed of the BPN is very slow (typically about 6 mph), so the BPN is generally believed to correlate most strongly with pavement microtexture. This is useful, because direct measurement of microtexture is difficult. However, recent studies suggest that the BPN is also influenced by macrotexture in some situations.

- Dynamic Friction Tester

The Dynamic Friction Tester (DFT), shown in Figure 2-20, consists of a disk that spins with its plane parallel to the test surface. The use of this apparatus is described in ASTM E 1911. Three rubber sliders are mounted on the lower surface of the spinning disk and can reach tangential speeds of up to approximately 55 mph (90 kph). Water is placed on the test surface in front of the sliders and the test is performed by lowering the spinning disk to the surface of the pavement and then monitoring the torque as the speed of the disk is slowed to a stop by the friction between the pavement texture and the rubber sliders.

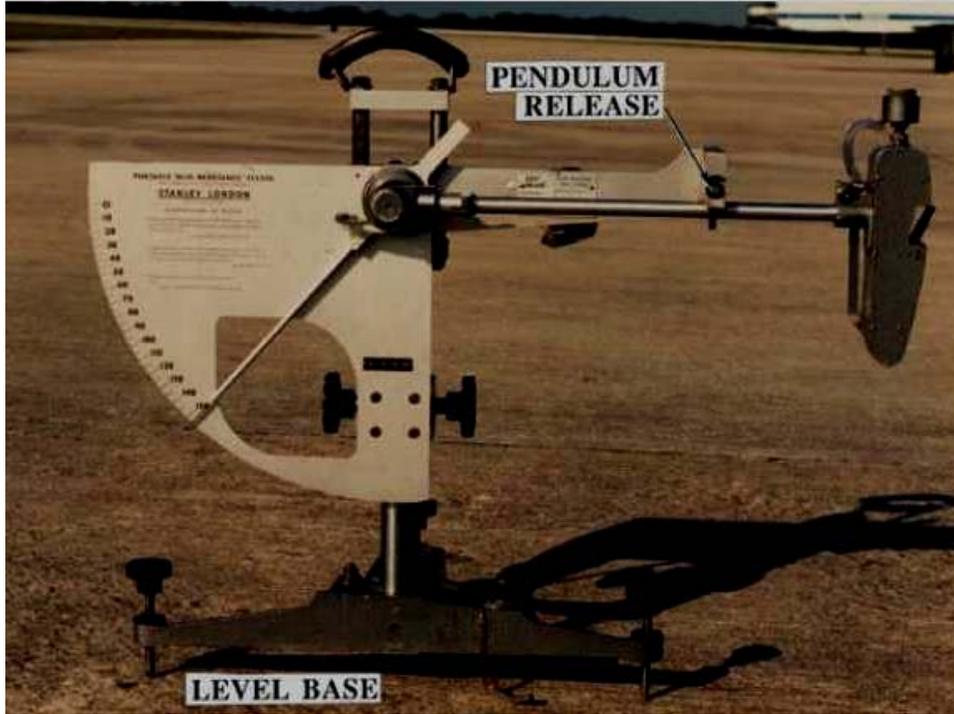


Figure 2-19 Photo of British Pendulum Tester (Wambold and Henry, 2002)



Figure 2-20 Photo of Dynamic Friction Tester (courtesy of Nippou Sango Co, Ltd)
(www.nippou.com)

The torque measurement is converted to a friction measurement by determining the slider force required to produce the measured torque and then dividing that force by the weight of the disk and motor assembly. Friction measurements are typically determined at speeds of 12.5, 25, 37.5 and 50 mph (20, 40, 60 and 80 kph). It should be noted that the rotational nature of the DFT test prevents it from distinguishing directional effects of pavement texture (e.g., it will produce the same values for tining performed in the transverse and longitudinal directions).

2.4.4 Current Surface Friction Criteria and Measurement Practices

This section presents a brief summary of current friction criteria and measurement practices.

FHWA

In 1979, the Federal Highway Administration (FHWA) provided guidance to state and local highway agencies in establishing skid accident reduction programs through Technical Advisory TA 5040.17, “Skid Accident Reduction Program.” This document was superseded in June 2005 by TA 5040.36. Neither document provides specific recommended values for minimum or desirable pavement friction test results. The current applicable technical advisory states that agencies “... should consider many factors including splash and spray, climate, traffic, speed, geometry, conflicting movements, materials and costs, and presence of noise sensitive receptors...” but that “... it is unlikely that one surface type or texturing method will always be the best choice for all projects within a State or jurisdiction ...” because of wide variations in design, materials and maintenance factors.

AASHTO

The 1976 AASHTO Guide for the Design of Skid Resistant Surfaces is currently being updated under NCHRP Project 1-43 (<http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+1-43>). The updated guide is expected to be considered by AASHTO for adoption. It is expected that the updated guide will provide more specific guidance on considering texture and friction during the pavement design process.

New Guidelines for PCC Surfacing Texturing are currently being developed under NCHRP Project 10-67 (<http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+10-67>). These guidelines will address the need for adequate friction and for low noise PCC surfaces.

State Highway Agencies

A 1999 survey of both U.S. and foreign agencies documented current friction measurement practices around the world (Henry, 2000). The survey revealed that only 11 of 42 responding U.S. highway agencies had published minimum acceptable levels for skid resistance. It appears that many highway agencies are reluctant to assign minimum acceptable friction levels for highway pavements due to liability concerns.

In practice, FN4OR values of 30 to 40 have generally been considered acceptable for interstate highways and other roads with design speeds greater than 40 mph (65 km/h). Lower friction numbers have generally been accepted for pavements with low traffic volumes (e.g., average daily traffic of less than 3,000 vehicles) and traffic speeds less than 40 mph (65 km/h). It should be noted that these criteria are based on pavement friction measurements obtained using a ribbed tire. As described previously, the current applicable FHWA technical advisory recommends the use of ASTM E 574

smooth tires for pavement friction testing because they correlate better with wet weather accident rates, therefore different threshold values may be required for FN4OS.

2.4.5 Summary

While highway users and abutters are clearly concerned with roadway noise issues, they also deserve roadways that have good surface friction and are capable of providing safe travel. Highway safety must not be sacrificed in favor of reductions in roadway noise. Pavement surface friction or “skid resistance” is the force developed at the tire-pavement interface that resists tire slippage and sliding when acceleration, braking, or lateral forces are applied. While adequate surface friction often exists on dry pavements, in wet weather water acts as a lubricant that reduces the direct contact between the pavement surface and the tire. Excessive surface water can also cause hydroplaning. Water on the pavement also contributes to splash and spray. It is essential that the pavement design process specifically include the selection and design of surface textures that reduce hydroplaning potential and provide improved surface friction for both wet and dry pavements, especially on higher speed roadways in urban areas.

Tire design and condition (e.g., rubber compound, tread design, wetness and wear) strongly influence vehicle safety, especially in wet weather. Good tire friction characteristics do not necessarily have to result in significantly higher noise levels. The pavement texture characteristics that affect friction most strongly are microtexture (0.0004 to 0.02 in [1 μm to 0.5 mm]) and macrotexture (0.02 to 2 in [0.5 to 50 mm]). If both microtexture and macrotexture can be maintained at high levels, they can provide resistance to skidding on wet pavements. Increasing macrotexture also generally reduces the potential for splash and spray and increases skid resistance.

Pavement friction usually decreases with pavement age due to two mechanisms: 1) aggregate polishing under traffic reduces microtexture, and 2) aggregate wear under traffic reduces macrotexture. However there are other seasonal changes, such as winter conditions, winter maintenance operations, periodic rainfalls, etc., that may produce either decreases or increases in pavement friction.

Hydroplaning potential can be reduced in many ways, including the use of increased cross-slope, increased pavement surface texture depth, and the use of open-graded and porous pavement surfaces. Grooving, where used, should be performed in the direction of the predominant pavement surface slope to allow for better drainage.

Several types of devices are commonly used to obtain direct measurements of pavement surface friction. Each has various advantages and applications. Each device can be equipped with tires featuring either a “ribbed” tread (one with longitudinal grooves on the tread surface) or with a “blank” or smooth tread. Ribbed treads are relatively insensitive to water film thickness, which makes them a good choice for tests that are insensitive to operational factors, such as water film thickness. However, ribbed tires are somewhat insensitive to macrotexture and are therefore mainly influenced by microtexture, which partly explains the sometimes poor correlation between friction test values and highway accident rates. Many studies indicate that standard smooth tires produce friction test results that correlate much better with wet weather accident rates.

Most agencies in the United States currently measure pavement friction using a locked-wheel trailer equipped with either a standard ribbed or smooth (blank) tire. Locked wheel testing devices simulate emergency braking conditions for vehicles without anti-lock brakes. Water is applied to the dry pavement in front of the trailer and the friction between the locked tire and pavement surface is

measured. The friction (or skid) number is computed as 100 times the force required to slide the locked test tire over the pavement surface divided by the effective wheel load.

The International Friction Index (IFI) incorporates simultaneous measurements of friction and macrotexture into a single index that represents overall pavement friction characteristics. One advantage of the IFI is that valid tests can be conducted at any speed.

Current and past FHWA documents have provided state and local highway agencies with guidance in establishing skid accident reduction programs, but have not provided specific recommended values for minimum or desirable pavement friction test results. The 1976 AASHTO Guide for the Design of Skid Resistant Surfaces will be updated under NCHRP Project 1-43. It is expected that the updated guide will provide more specific guidance on considering texture and friction during the pavement design process. As of 1999, only 11 of 42 responding U.S. highway agencies had published minimum acceptable levels for skid resistance. Friction numbers of 30 to 40 (40 mph test with ribbed tires) have generally been considered acceptable for interstate highways and other roads with design speeds greater than 40 mph (65 km/h). Lower friction numbers are generally been accepted for pavements with low traffic volumes.

2.5 NOISE

Sound is acoustic energy that results from variations in air pressure and density. “Noise” by definition is simply unwanted sound. Noise emitted from vehicles and their interaction with pavements can be attributed to several source categories. Tire-road noise is a major contributor to overall sound levels.

Pavement type and texture contribute to tire-pavement interface noise levels. Pavement texture does not remain constant over time, thus affecting tire-pavement noise levels. Preventive maintenance techniques can be employed to slow down pavement deterioration, which prolongs the quieter characteristics of the pavement. These techniques are discussed in more detail in later chapters.

The issue of quieter pavements has received increasing attention over the past several years. In response, Caltrans has developed a quieter pavement advisory guide and web page containing the latest information and findings on this topic. For more information, reader should visit the web site at <http://www.dot.ca.gov/hq/oppd/pavement/qpavement.htm>.

2.6 ACHIEVING DESIRED SURFACE CHARACTERISTICS

The desired surface characteristics (smooth, quiet, and safe ride) are addressed during the construction of the new pavement or the rehabilitation projects. As the pavement wears out, it begins to get rough, loses its surface texture and become noisier. The preventive maintenance techniques discussed in this guide are all intended to improve the overall pavement condition. In reality, only few of the preventive maintenance treatments will actually have an effect on the desirable surface characteristics.

2.6.1 Ride Quality

Ride quality or smoothness will be most affected by applying the following treatments:

- Grinding: Diamond grinding can have a significant effect on ride quality;
- Thin Overlays: Thin overlays, either on portland cement or asphalt concrete pavements, can also impact ride quality;

- Spall repair: Spall repair can improve ride quality, but the greatest improvement would probably be obtained when it is done before diamond grinding;
- Isolated Slab Replacement: Slab replacement can improve ride quality, but the greatest improvement would probably be obtained when it is done before diamond grinding.

The use of treatments such as joint resealing or dowel bar retrofit will likely not impact ride quality unless some of the other treatments mentioned above are applied at the same time.

2.6.2 Texture and Friction

Surface texture and friction can be improved by grinding or with an overlay. Spall repair, dowel bar retrofit, or slab replacement will not likely improved the overall surface texture of the pavement, which is why they should be done in conjunction with diamond grinding. In fact, joint resealing and crack sealing can result in a loss of surface texture if applied too generously.

2.6.3 Noise

For latest information on options to reduce noise, please visit the Caltrans Quieter Pavement Advisory Guide at: <http://www.dot.ca.gov/hq/oppd/pavement/qpavement.htm>.

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