NCHRP

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

SYNTHESIS 291

Evaluation of Pavement Friction Characteristics

A Synthesis of Highway Practice

TRANSPORTATION RESEARCH BOARD

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Evaluation of Pavement Friction Characteristics

A Synthesis of Highway Practice

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SUBJECT AREAS
Pavement Design, Management, Performance

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Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis report will be of interest to pavement design, construction, management, and research engineers, highway safety officials, and others concerned with pavement friction characteristics. It describes the current state of the practice for evaluating pavement friction characteristics. Information for the synthesis was collected by surveying U.S., Canadian, and international transportation agencies, and by conducting a literature search to gather additional information.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

This report of the Transportation Research Board provides information on wet pavement friction characteristics of new and restored pavements. It includes information on the methods for measuring and reporting friction and texture, causes for friction changes over time, and on the related aspects of aggregate and mix design to provide adequate friction. A limited amount of information on the impact of economic and legal considerations is also included. In addition, considerations of noise and ride quality are discussed when

compromise may be required. The International Friction Index (IFI) is included with information on the measuring and reporting of friction and texture.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the available information was assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the author's research in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

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This study was managed by Stephen F. Maher, P.E., Manager, Synthesis Studies, who worked with the consultant, the Topic Panel, and the Project 20-5 Committee in the development and review of the report. Assistance in project scope development was provided by Donna L. Vlasak, Senior Program Officer. Don Tippman was responsible for editing and production. Cheryl Keith assisted in meeting logistics and distribution of the questionnaire and draft reports.

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Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance are appreciated.

EVALUATION OF PAVEMENT FRICTION CHARACTERISTICS

SUMMARY

Wet pavement friction (skid resistance) is an important consideration in pavement performance. The characteristics of pavement texture that affect wet pavement friction are microtexture, consisting of wavelengths (characteristic dimensions) of 1 μm to 0.5 mm (0.0004 in. to 0.02 in.), and macrotexture, consisting of wavelengths of 0.5 mm to 50 mm (0.02 in. to 2 in.). Pavements typically are designed and constructed to provide sufficient texture, both microtexture and macrotexture, to allow for adequate friction when the surface is wet. This synthesis reviews the models used for evaluating the results of wet pavement friction testing methods and discusses the methods used to measure friction and texture. The International Friction Index (IFI), which consists of two numbers based on friction and texture measurements, is included in the discussion. Finally, methods for constructing and restoring the surfaces of pavements to achieve desired levels of skid resistance are presented.

A questionnaire was prepared to determine current practices in the United States and other countries. Responses were obtained in June and July 1999, from 41 states, the National Aeronautics and Space Administration, Puerto Rico, 9 Canadian Provinces, and 19 countries outside North America. The questionnaire consisted of six parts:

- Friction Measurement
- Texture Measurement
- Requirements for Friction and Texture
- Design Practices for Skid Resistance
- Surface Restoration for Skid Resistance
- Litigation and Economic Considerations.

The design of skid resistant pavements depends on the criteria for evaluating the frictional characteristics of pavements. This synthesis first discusses models for interpreting the results of friction and texture measurements. From the literature it was found that a single number index for evaluating the frictional characteristics of pavements can be misleading. The same value of a friction measurement can be obtained on two pavements having very different frictional properties. It is important to provide both microtexture and macrotexture parameters to assure appropriate frictional characteristics on wet pavements. IFI addresses this problem by requiring simultaneous measurements of friction and macrotexture for its implementation. The IFI consists of two parameters: a speed constant derived from the macrotexture measurement that indicates the speed dependence of the friction and a friction number that is a harmonized level of friction for a slip speed of 60 km/h (36 mph).

This report discusses the methods used to measure pavement friction. For measuring skid resistance, the majority of the responding states use the ASTM locked wheel test method with the standard ribbed tire. Outside the United States, side force and fixed slip

methods are commonly used, and the test tires are, in most cases, smooth tread tires. Friction measurements using a ribbed test tire do not adequately assess macrotexture and it is suggested that a macrotexture measurement be made in addition to friction measurements, particularly when the ribbed test tire is used.

Although recent developments in laser technology have made it possible to measure macrotexture at highway speeds, such measurements have not been used extensively in the United States. Survey results indicated that five state agencies measure macrotexture and only three of these states measure it routinely. Macrotexture evaluation is used much more extensively for pavement management, construction, and surface restoration outside the United States.

Pavement friction measurements are used for many different purposes, including network surveys for pavement management, evaluation of surface restoration, specifications for new construction, accident investigations, winter maintenance on highways, runway conditions for pilot advisories, and runway friction for maintenance. Recent developments include the instrumentation of salt trucks with friction measuring devices to determine the quantity of salt needed. In addition, the Joint Winter Runway Friction Measurement Program is developing the International Runway Friction Index (IRFI) to provide reports of runway friction for pilot advisories during operations in winter conditions.

The relative importance of various pavement performance measures is reported in the context of pavement design considerations. These include durability, skid resistance, noise, splash and spray, rolling resistance, and tire wear. The results of the survey showed that pavement durability was considered the most important consideration, but skid resistance was ranked a close second. It could be argued that skid resistance is included in the durability requirements because a pavement may be considered to have failed when its friction is inadequate.

Construction and surface restoration practices for providing good pavement friction characteristics are also included, as well as practices for both asphalt and portland cement concrete. Porous asphalt and stone mastic asphalt are considered for asphalt concrete pavement new construction, whereas various methods for providing macrotexture for newly placed portland cement concrete are also discussed. Grooving, diamond grinding, and shot peening are used for restoring the surface of portland cement concrete, whereas microsurfacing and seal coats are used for restoration of asphalt concrete pavements.

Responses to questions in the survey relating to economic considerations and litigation were very limited, and few conclusions could be drawn from the responses, perhaps because of the sensitivity of the subject.

CHAPTER ONE

INTRODUCTION

BACKGROUND

Wet pavement accidents continue to be a major concern of most highway agencies around the world. A 1980 report by the National Transportation Safety Board (*1*) concluded that in the United States fatal accidents occur on wet pavements at a rate of from 3.9 to 4.5 times the rate of occurrence on wet pavements. The Nationwide Personal Transportation Survey of 1990 (*2*) reports that of almost 25 million reported accidents, 18.8 percent occurred on wet pavements. Recognizing the importance of providing safe pavements for travel during wet weather, most highway agencies have established programs to provide adequate pavement friction or skid resistance.

The criteria used in the design and maintenance of pavements to provide adequate wet skid resistance depends on the method used to evaluate skid resistance. In the United States, American Society for Testing and Materials (ASTM) Standard Test Method E-274 for "Skid Resistance of Pavements Using a Full-Scale Tire" (*3*) is used by 39 states and Puerto Rico. Thirty-one states and Puerto Rico use only the ASTM E-501 "Standard Rib Tire for Pavement Skid-Resistance Tests" (*4*), whereas 7 states use only the ASTM E-524 "Standard Smooth Tire for Pavement Skid-Resistance Tests" (*5*), and 4 states use both tires. The use of the same test method, but with different standard test tires, could lead to very different strategies for providing skid resistant pavements, as is discussed further in chapter 2.

The ASTM E-274 Test Method is a locked wheel friction measurement, where the relative velocity of the tire surface over the pavement surface (the "slip speed") is equal to the speed of the test vehicle. Outside the United States, the majority of highway agencies use either a fixed slip or a side force measurement method. In these cases, the relative velocity between the tire surface and the pavement surface is expressed as a percentage of the vehicle speed, typically between 12 and 34 percent. It has been demonstrated that at low slip speeds the effect of microtexture dominates the measurement, whereas at high slip speeds the effect of macrotexture becomes important (*6*). For this reason, fixed slip and side force measurements are usually accompanied by a macrotexture measurement.

In 1976, AASHTO published guidelines for the design of skid-resistant pavements (*7*). At that time there were no practical devices capable of measuring macrotexture at highway speeds. It was recognized that the decrease of friction with increasing speed was related to the macrotexture and it was recommended that volumetric techniques (e.g., the "Sandpatch Method") be used for measuring macrotexture depth (*8*). With the development of high-speed laser devices capable of measuring macrotexture at speeds of 60 km/h or more, it is now possible to include macrotexture measurements in routine surveys of the road network. Since the AASHTO guidelines were issued in 1976, there has been no effort to update the guidelines to include data currently obtainable. This synthesis evolved from a recognition of the need for summarizing current practices in use, not only in North America, but also in Europe, Asia, and Australasia.

In 1992, the World Road Association, formerly the Permanent International Association of Road Congresses (PIARC), conducted extensive tests with pavement friction and texture measurement devices. As a result of these tests (*9*), an International Friction Index (IFI) was proposed. The IFI is a harmonized index comprised of a friction number (*F*60) and a speed constant (S_p). The speed constant was found to be linearly related to macrotexture measurements, whereas the friction number is computed from both a friction measurement and the speed constant. ASTM has developed a standard practice for the IFI (*10*), and the Council for European Normalization currently has a draft standard under consideration. The preferred macrotexture measure for the computation of the speed constant is the Mean Profile Depth (MPD), for which both ASTM and the International Standards Organization (ISO) have developed standards (*11,12*).

SCOPE

This synthesis evaluates wet pavement friction characteristics of new and restored pavements. It includes information on the methods for measuring and reporting friction and texture, causes for friction changes over time, and aggregate and mix design to provide adequate friction. A limited amount of information on the impact of legal and economic considerations is also included. In addition, considerations of noise and ride quality are discussed when compromise may be required. The IFI is included, with information on measuring and reporting friction and texture.

SURVEY QUESTIONNAIRES

Two versions of a questionnaire were prepared: one for North American respondents and one for respondents from

Europe, Asia, Australia, and Africa. A questionnaire was sent to each state highway transportation agency in the United States, the National Aeronautics and Space Administration (NASA), Puerto Rico, the District of Columbia, each province of Canada, and to 55 highway agencies and experts outside North America. Forty-one states, Puerto Rico, NASA, and nine Canadian Provinces responded to the North American version. In addition, 19 responses to the non-North American version were received from countries in Europe, Asia, Africa, and Australia. The questionnaire sent to North American agencies is contained in Appendix A. The non-North American version asked the same questions, but included slightly different terminology; for example, using motorway for interstate. Responses are summarized, by category, in Tables B1–B16 in Appendix B.

APPROACH

A study of the literature on wet pavement friction characteristics, together with the responses to the questionnaire provides the basis for this synthesis of practice.

This synthesis first addresses friction and texture measurements and their significance. This is followed by the methods used to produce skid resistant surfaces in construction and surface restoration. A section on related characteristics such as noise, ride quality, splash-and-spray, tire wear, and rolling resistance is included. This is not an in-depth study of these factors, but mention must be made of the necessity to consider trade-offs in favor of friction to provide, for example, better durability and lower permeability to moisture.

For each section of the synthesis, the results of the literature survey and the questionnaire have been integrated to provide both a historical background and a description of current practices.

Following the References, a listing of the nomenclature used in the report is provided.

CHAPTER TWO

PAVEMENT FRICTION

MODELS FOR WET PAVEMENT FRICTION

Wet pavement friction is a measure of the force generated when a tire slides on a wet pavement surface. Wet pavement friction is often referred to as "skid resistance" in the literature and practice, and the two terms are used interchangeably in this synthesis. Wet pavement friction decreases with increasing speed. This was first recognized by Moyer in 1934 (*13*). More specifically, skid resistance decreases as the velocity of the tire surface relative to the pavement surface increases. This relative velocity is called the slip speed. There are several models for determining pavement friction. A few of the most commonly used models are described in this section.

The Penn State Model

The Penn State Model (*6*) describes the relationship of friction (μ) to slip speed (S) by an exponential function:

$$\mu = \mu_0 e^{-\frac{PNG}{100}S} \tag{1}$$

Where μ_0 is the intercept of friction at zero speed, and PNG is the percent normalized gradient (the speed gradient times 100 divided by the friction) defined by:

$$PNG = -\frac{100}{\mu}\frac{d\mu}{ds} \tag{2}$$

It was demonstrated that PNG is constant with speed and therefore Eq. (1) follows by rearranging Eq. (2) and integrating from $S = 0$ to S. Furthermore, it was discovered that PNG is highly correlated with macrotexture and that μ_0 can be predicted from microtexture.

Later versions of the Penn State Model replaced the term [PNG/100] by a speed constant S_p:

$$\mu = \mu_0 e^{-\frac{S}{S_p}} \tag{3}$$

The PIARC Model (9) adopted the Penn State Model, but shifted the intercept to 60 km/h:

$$F(S) = F60\, e^{\frac{60-S}{S_p}} \tag{4}$$

Where $F(S)$ is the riction at slip speed S, and $F60$ is the friction at 60 km/h (36 mph).

Figure 1 shows the Penn State Model for two cases that have the same level of friction at 60 km/h, but behave very differently at other speeds, because of differences in texture, resulting in different values for PNG and S_p. This example demonstrates the need for specifying more than a single value, such as the friction at 60 km/h (36 mph), to describe the skid resistance of a pavement.

The Rado Model

As a tire proceeds from the free rolling condition to the locked wheel condition under braking, the friction increases from zero to a peak value and then decreases to the locked wheel friction. Anti-lock brake systems release the brakes to attempt to operate around the peak level of friction. The rising portion of the friction slip speed curve is dependent on tire properties, whereas the portion after the peak is dependent on the pavement properties. Rado (*14*) modeled this behavior as follows:

$$\mu(S) = \mu_{peak}\, e^{-\left[\frac{\ln(S/S_{peak})}{C}\right]^2} \tag{5}$$

where μ_{peak} is the peak friction level, S_{peak} is the slip speed at the peak (typically about 15 percent of the vehicle speed), and C is a shape factor that Rado found to be related to the harshness of the texture. Figure 2 is a plot of Eq. (5) with some typical values: $\mu_{peak} = 0.6$, $S_{peak} = 15$ km/h (9 mph), $C = 0.5$, with the forward speed of the test vehicle of 120 km/h (66 mph).

The Rado and Penn State Models can be related to actual vehicle braking in emergency situations. When the brake is first applied the friction follows the Rado Model until the wheels are fully locked. If braking continues after the locked wheel condition is reached, the vehicle speed (which then is equal to the slip speed) decreases and the friction follows the Penn State Model until the vehicle stops. Conversely, when the anti-lock break system is used, the friction follows the Rado Model until a predetermined slip percentage is reached, during which time the vehicle speed is incrementally reduced. The brake then releases and the friction drops to zero. The brake

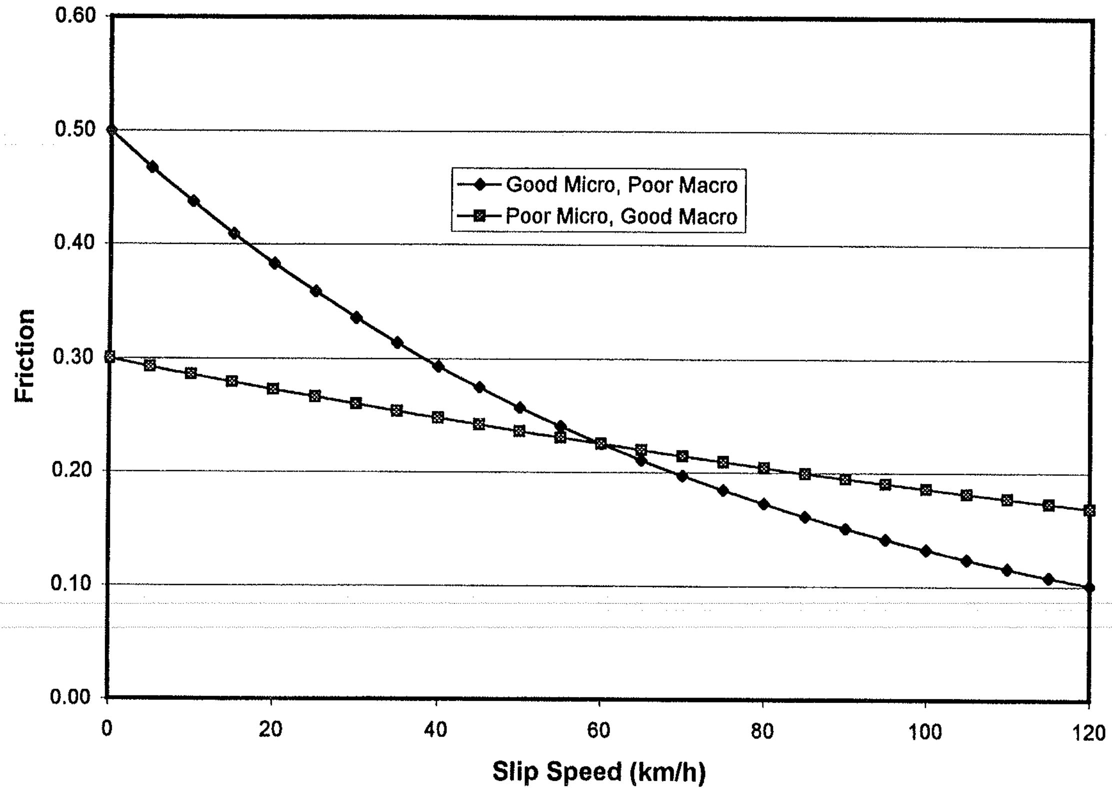

FIGURE 1 Penn State Model.

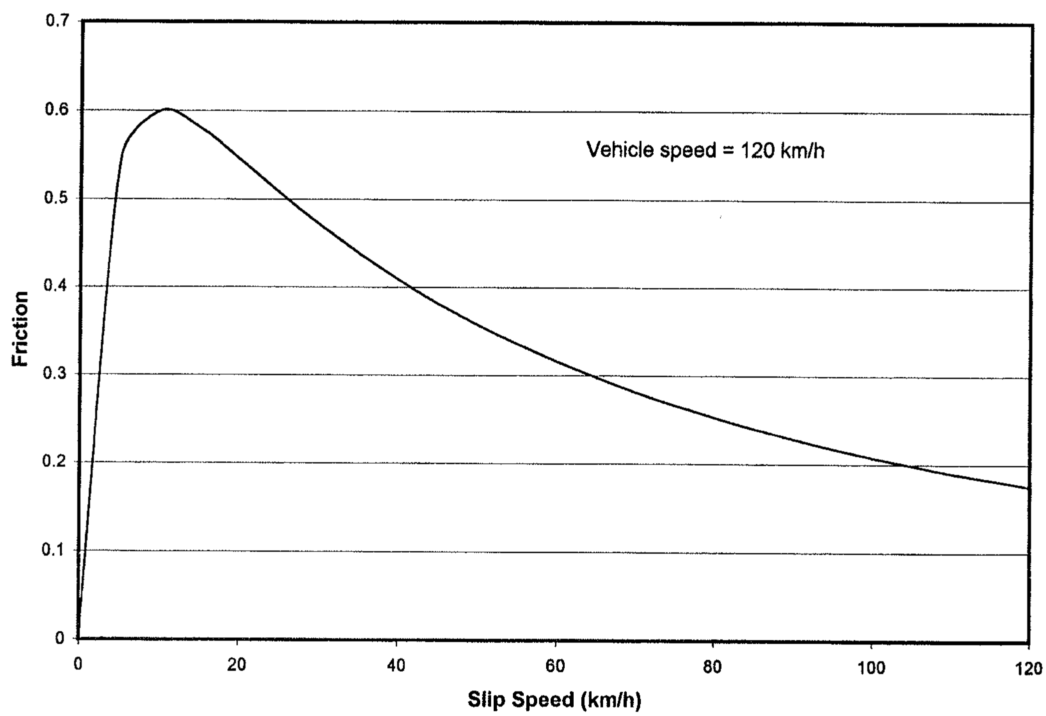

FIGURE 2 Rado Model.

engages after the wheels spin up and the cycle is repeated. Each successive cycle follows a Rado curve for a lower vehicle speed. This behavior was verified experimentally by Bachmann (*15*) on wet and dry portland cement and asphalt concrete pavements. The shapes of Bachmann's curves closely resemble those of the Rado Model.

The PIARC Model and the International Friction Index

The International PIARC Experiment to Compare and Harmonize Texture and Skid Resistance Measurements (*9*) was conducted in Belgium and Spain in the fall of 1992. Each friction tester was operated at three speeds: 30, 60, and 90 km/h (18, 36, and 54 mph), and each tester made two repeated runs at each speed. All texture measurements were made on dry surfaces before any water was applied to the roadway. As a control, a microtexture measurement was made before and after the skid testers made their tests. These data were used to show that there were no statistically significant changes occurring during the testing.

There were 51 different friction and texture measurements made by participants from 14 countries. The measurements were conducted on a total of 54 sites as follows: 28 sites in Belgium (22 on public roads, 2 at airports, and 4 at racetracks) and 26 sites in Spain (18 on public roads and 8 at airports). These data were entered into a database and included equipment description, site characteristics, weather, texture measurements, and friction measurements.

The Rado Model at slip speeds above the peak and the Penn State Model are similar and are dependent on the pavement characteristics. Because the Penn State Model is less complex, it was chosen as the basis for the analysis of the data from the experiment and the development of the IFI. The harmonization process allows skid resistance to be measured by any of the measurement methodologies and the result reported on a common scale.

The IFI consists of two numbers that describe the skid resistance of a pavement: the speed constant (S_p) and the friction number ($F60$). The speed constant is linearly related to the result of a macrotexture measurement (TX):

$$S_p = a + b\,TX \qquad (6)$$

The constants a and b have been determined for each type of macrotexture measurement (TX) used in the experiment.

The friction number ($F60$) is determined from a measurement of friction by:

$$F60 = A + B\,FRS\,e^{\frac{S-60}{S_p}} + C\,TX \qquad (7)$$

where FRS is the measurement of friction by a device operating at a slip speed (S); A, B, and C were determined for that device in the experiment and are tabulated in the ASTM Standard Practice E-1960 (*10*). The value of C is always zero when the friction is measured with a smooth tread tire. However, the term $C\,TX$ was found to be necessary for ribbed or patterned test tires because they are relatively insensitive to macrotexture.

The two parameters that make up the IFI ($F60$ and S_p) are sufficient to describe the friction as a function of slip speed using Eq. (4). Note that a texture measurement is required to apply the IFI. The two parameters, $F60$ and S_p, distinguish the difference between the two pavements shown in Figure 1.

Another advantage of the IFI is that the value of $F60$ for a pavement will be the same regardless of the slip speed. That permits the test vehicle to operate at any safe speed; for example, at higher speeds on high-speed highways and lower speeds in urban situations.

ASTM Standard E-1960 (*10*) includes the values of a, b, A, and B for the devices that participated in the experiment. In addition, the standard describes a procedure to calibrate devices that did not participate in the experiment.

FIELD MEASUREMENT METHODOLOGIES

There are four basic types of full-scale friction measuring devices: locked wheel, side force, fixed slip, and variable slip. In addition, some of the systems detect the peak friction and some vary the slip in an attempt to operate around the peak friction level. Each method of measuring friction has advantages. Direct use of the values produced by any one type of measurement relates to a different scenario. The locked wheel method simulates emergency braking without anti-lock brakes, the side force method measures the ability to maintain control in curves, and the fixed slip and variable slip methods relate to braking with anti-lock brakes. Table 1 summarizes the characteristics of many of the devices currently in use. Table B1 lists the devices used by the agencies that responded to the questionnaire. A majority of the U.S. respondents use the ASTM E-274 trailer as their measuring device.

Locked Wheel Testers

Locked wheel systems produce a 100 percent slip condition. The relative velocity between the surface of the tire and the pavement surface (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. Because the force measurement is continuous during the braking process, these systems usually can detect the peak friction. A variation of this method is a transient slip operation whereby the friction and slip are recorded as the wheel locks up, from free rolling (0 slip) to fully locked (100 percent slip). The locked wheel testers are usually fitted with a self-watering system for wet testing, and a nominal water film of 0.5 mm is commonly used. One type of locked wheel tester is shown in Figure 3.

TABLE 1
REPRESENTATIVE FRICTION MEASURING DEVICES

Device	Operational Mode	% Slip (yaw angle)	Speed[1] (km/h)	Country[2]
ASTM E-274 Trailer	Locked wheel	100	30–90	United States
British Portable Tester	Slider	100	10	United Kingdom
Diagonal Braked Vehicle (DBV)	Locked wheel	100	65	U.S. (NASA)
DFTester	Slider	100	0–90	Japan
DWW Trailer	Fixed slip	86	30–90	The Netherlands
Griptester	Fixed slip	14.5	30–90	Scotland
IMAG	Variable fixed slip	0–100	30–90	France
Japanese Skid Tester	Locked wheel	100	30–90	Japan
Komatsu Skid Tester	Variable fixed slip	10–30	30–60	Japan
LCPC Adhera	Locked wheel	100	40–90	France
MuMeter	Side force	13 (7.5°)	20–80	United Kingdom
Norsemeter Oscar	Variable slip, fixed slip	0–90	30–90	Norway
Norsemeter ROAR	Variable slip, fixed slip	0–90	30–90	Norway
Norsemeter SALTAR	Variable slip	0–90	30–60	Norway
Odoliograph	Side force	34 (20°)	30–90	Belgium
Polish SRT-3	Locked wheel	100	30–90	Japan
Runway Friction Tester	Fixed slip	15	30–90	United States
Saab Friction Tester (SFT)	Fixed slip	15	30–90	Sweden
SCRIM	Side force	34 (20°)	30–90	United Kingdom
Skiddometer BV-8	Locked wheel	100	30–90	Sweden
Skiddometer BV-11	Fixed slip	20	30–90	Sweden
Stradograph	Side force	21 (12°)	30–90	Denmark
Stuttgarter Reibungsmesser (SRM)	Locked wheel, fixed slip	100, 20	30–90	Germany

Note: DWW = Dienst Weg- en Waterbouwkunde friction tester; IMAG = Instrument de Mesure Automatique de Glissance; SCRIM = Sideway-Force Coefficient Routine Investigation Machine; LCPC = Laboratoire Central des Ponts et Chaussées; ROAR = Road Analyzer and Recorder; SALTAR = Salt Analyzer and Recorder.

[1]Typical speed range—many devices can operate outside the listed range (1 km/h = 0.6 mph); [2]The country of manufacture—many devices are also used in other countries.

When the measurement is made in accordance with ASTM Standard Test Method E-274 (*3*), the result is reported as the skid number that is the measured value of friction times 100. The method provides for reporting results using the ribbed test tire (*4*) or the smooth test tire (*5*) as follows: SN{Test Speed} followed by *R* for the ribbed tire or *S* for the smooth tread tire. If the test speed is expressed in kilometers/hour, it is enclosed in parentheses. For example, the value of SN40R is equivalent to SN(64)R. In this synthesis, the term "skid number" is used for results reported for ASTM Test Method E-274. AASHTO terminology for the locked wheel method uses the term "friction number" (FN) in place of skid number (SN). This should not be confused with the friction number of the IFI (*F*60).

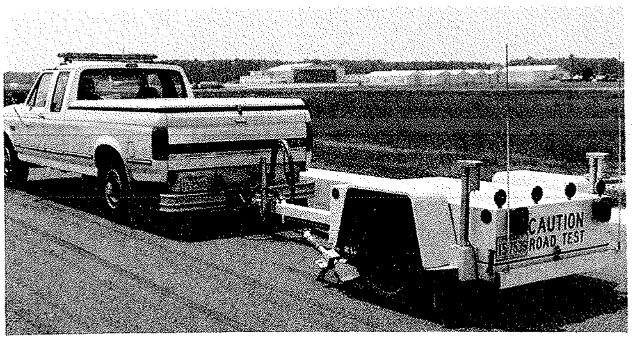

FIGURE 3 Locked wheel tester (ASTM E-274).

Side Force Devices

Side force systems maintain the test wheel in a plane at an angle (the yaw angle) to the direction of motion, otherwise the wheel is allowed to roll freely. The side force (cornering force) is measured perpendicular to the plane of rotation. An advantage of this method is that these devices can measure continuously through the test section, whereas locked wheel devices usually sample the friction over the distance corresponding to 1 second of the vehicle travel, after which the brake is released.

The relative velocity between the rubber and the pavement surface for these devices is approximately $V \sin \alpha$ (where α = yaw angle, and V = vehicle speed) and, therefore, these systems produce a low-speed measurement even though the vehicle velocity is high. Because these devices are low slip speed systems they are sensitive to microtexture. For this reason, they are usually used in conjunction with a macrotexture measure. The most frequently used side force devices are the MuMeter and the Sideway-Force Coefficient Routine Investigation Machine (SCRIM), both of which originated in the United Kingdom. The MuMeter was designed for use at airports, but has also been used by some agencies on highways (Figure 4). Because they are relatively insensitive to variations in macrotexture most SCRIMs are now fitted with a laser macrotexture measurement system mounted on the front of the vehicle and are called SCRIMTEX. Other side force devices are the Belgian Odoliograph and the now Danish Stradograph, which was retired in 1998. The MuMeter is the only side force device that has been used in the United States, primarily at airports, with limited use on highways.

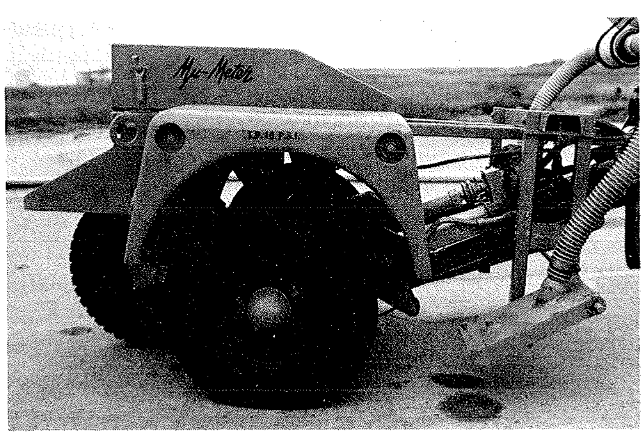

FIGURE 4 Side force tester: The MuMeter.

Fixed Slip Devices

Fixed slip devices operate at a constant slip, usually between 10 and 20 percent. The test wheel is driven at a lower angular velocity than its free rolling velocity. This is usually accomplished by incorporating a gear reduction or chain drive of the test wheel drive shaft from the drive shaft of the host vehicle. In some cases, it is accomplished by hydraulic retardation of the test wheel. These devices also measure low-speed friction as the slip speed is V (% slip/100). Like the side force method, the fixed slip method can also be operated continuously over the test section without excessive wear of the test tire. An example of a fixed slip tester is the Griptester shown in Figure 5. Most fixed slip devices are designed to operate at only one slip ratio; however, the slip ratio can be varied on some fixed slip devices, referred to as variable fixed slip devices in Table 1. An ASTM standard for fixed slip devices is not currently available.

FIGURE 5 Fixed slip tester: The Griptester.

Variable Slip Devices

Variable slip devices sweep through a predetermined set of slip ratios. This is usually accomplished by driving the test wheel through a programmed slip ratio using a hydraulic motor. ASTM Standard E-1859 (*16*) has been developed for devices that perform a controlled sweep through a range of slip ratios. Some locked wheel testers can be operated in a mode that captures the friction as the test tire proceeds from free rolling to the fully locked wheel condition (0 to 100 percent slip). Locked wheel testers can also be programmed to operate in accordance with ASTM E-1337 (*17*), in which the brake is released just after the peak is reached. A variable slip Norsemeter ROAR is shown in Figure 6.

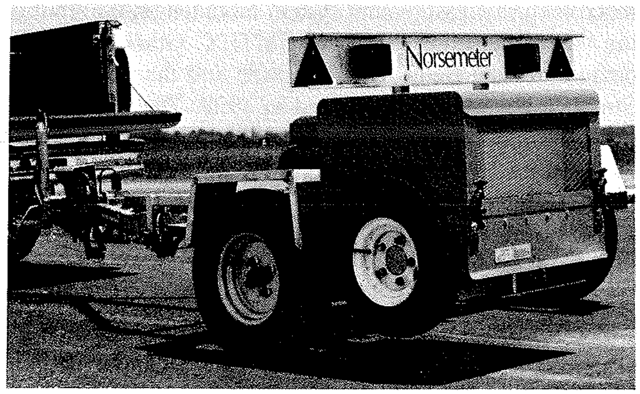

FIGURE 6 Variable slip tester: The Norsemeter ROAR.

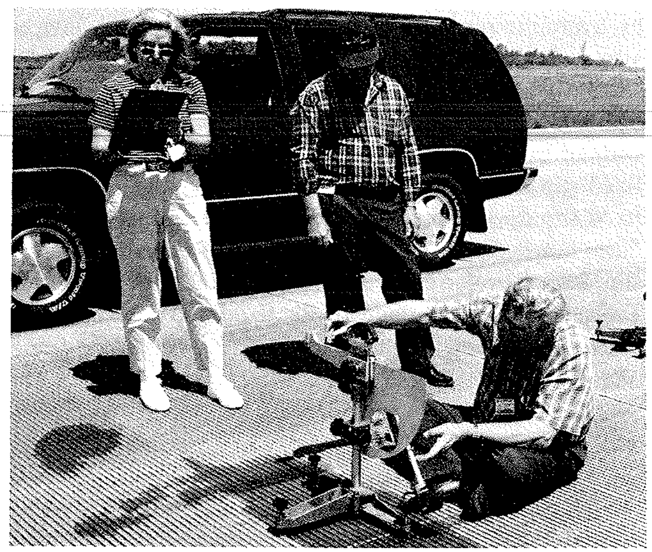

FIGURE 7 British portable tester.

LABORATORY METHODS

Laboratory methods are used for evaluating the friction characteristics of core samples or laboratory-prepared samples. The two devices currently in use are the British Portable Tester (BPT), shown in Figure 7, and the Japanese Dynamic Friction Tester (DFTester), shown in Figure 8. Both devices can be used for measurements on actual pavements, as well as in the laboratory.

The BPT has been in use since the early 1960s, and the first version of ASTM Standard E-303 (*18*), specifying its operation, was published in 1961. The BPT is operated by releasing a pendulum from a height that is adjusted so that a rubber slider contacts the surface over a fixed length. When the pendulum reaches the surface its potential energy has become its maximum kinetic energy. As the rubber slider moves over the surface the friction reduces the kinetic energy of the pendulum in proportion to the level of friction. When the slider breaks contact with the surface the reduced kinetic energy is converted to potential energy

FIGURE 8 Dynamic friction tester (DFTester).

as the pendulum reaches its maximum height. The difference between the height before the release and the height recovered is equal to the loss of kinetic energy due to the friction between the slider and the pavement or sample. Because the average velocity of the slider relative to the pavement is also a function of the friction, the average slip speed decreases with increasing friction. However, the typical slip speed for the BPT is usually assumed to be about 10 km/h (6 mph). The BPT is fitted with a scale that measures the recovered height of the pendulum in terms of a British Pendulum Number (BPN) over a range of zero to 140. Because the slip speed of the BPT is very low, the BPN is mainly dependent on microtexture and, therefore, the BPN is used as a surrogate for microtexture. This is very useful, because direct measurement of microtexture is difficult.

According to ASTM Standard E-303, laboratory samples for the BPT must be at least 90 × 150 mm (3.5 × 6 in.), and the slider is 25 × 76 mm (1.0 × 3.0 in.). The BPT is also used for evaluating samples that are subjected to accelerated polishing on a British Wheel as specified by ASTM Standard Test Method D-3319 (*19*). Test samples for determining the polish value of aggregates are 45 × 90 mm (1.75 × 3.5 in.), with a radius of curvature of 203 mm (8 in.) on the 90-mm (3.5-in.) dimension. The slider for polish value tests is 25 × 32 mm (1.0 × 1.25 in.). In Europe, the rubber sliders for the BPT are made of natural rubber, whereas in the United States it has been the practice to

use the rubber compound specified for the ASTM standard test tires (*4,5*). Because natural rubber friction is temperature dependent, a correction for temperature is usually applied. The ASTM-specified synthetic rubber was formulated to be independent of temperature and therefore no temperature correction due to the rubber properties is made.

The operation of the DFTester is specified in ASTM Standard Test Method E-1890 (*20*). The DFTester has three rubber sliders that are spring mounted on a disk at a diameter of 350 mm (13.75 in.). The disk is initially suspended above the pavement surface and is driven by a motor until the tangential speed of the sliders is 90 km/h (55 mph). Water is then applied to the test surface, the motor is disengaged, and the disk is lowered to the test surface. The three rubber sliders contact the surface and the friction force is measured by a transducer as the disk spins down. The friction force and the speed during the spin down are saved to a file. The DFTester has the advantage of being able to measure the friction as a function of speed over the range of zero to 90 km/h (55 mph). The entire operation is controlled by software in a notebook computer. For use in the laboratory the DFTester requires samples that are at least 450 × 450 mm (17.75 × 17.75 in.). The DFTester value at 20 km/h (12 mph) together with a texture measurement provides a good estimate of the friction number of the IFI.

CALIBRATION OF FRICTION MEASURING DEVICES

Periodic calibration of friction measuring equipment is necessary to ensure the quality of the data. Most agencies that operate friction testers perform some type of periodic calibration. In many cases the calibration consists of simply performing in-house calibration of components such as the force or torque transducers, the speed measuring instruments, and the water delivery rate. Some degree of component calibration is usually performed before each test session. This often consists of setting up the electronics of the force measurement. Also, periodic checks of the force transducer using a calibrated force plate are often performed in-house.

A system calibration consists of operating the friction tester over a set of test surfaces that are also measured by a reference device. An approach for system calibration used in Europe is to hold group trials of similar devices wherein the average of the reported values of all systems participating is taken as the true value. Each system is provided with a calibration equation that adjusts its reported values to the average of the group. This philosophy was also used in the development of the IFI (*9*). Manufacturers will sometimes maintain a master system and use it to calibrate new production or devices returned for calibration. Table B2 summarizes the responses to the questionnaire regarding calibration. In this table, the entries listed as "in-house" generally refer to component calibration, as described previously, however, in some cases, a system calibration is performed by operating over a set of surfaces in the vicinity of the garage where it is housed. This practice can identify gross changes, but because pavement friction of in-service surfaces experiences short-term, seasonal, and long-term variations, it cannot be used as a calibration procedure.

In 1971, recognizing the need for calibration, the FHWA established calibration centers in East Liberty, Ohio; College Station, Texas; and Phoenix, Arizona. The FHWA also contracted for three state-of-the-art locked wheel friction testers, which became the Area Reference Friction Measurement System (ARFMS) for each center. The center in Phoenix was closed in 1975. The Eastern Field Test Center in East Liberty, Ohio, and the Central/Western Field Test and Evaluation Center in College Station, Texas, are currently providing calibration services to those states whose programs provide for the calibration of ASTM E-274 locked wheel trailers. Realizing that the aging ARFMS units would have to be replaced, an ASTM standard guide for validating the replacement systems was developed in 1997 (*21*). The units were replaced in 1999 and extensive tests were made to assure that the two new units were in agreement (*22*).

When a system arrives at the calibration center it is first operated in its present condition over the test surfaces with the ARFMS. Following that, a component calibration of the force transducers and watering system is performed and any necessary repairs or adjustments are made. Finally, it is again operated over the test surfaces at the center with the ARFMS, and a correlation (linear regression) of the resulting data is provided to the client. This equation is then used to adjust the calibrated tester until its next visit. In practice, the frequency of calibration varies considerably, as shown in Table B2. States that have more than one friction tester often send one tester at a time to the center and use the tester most recently calibrated to perform a secondary calibration of the other testers for that period.

The calibration centers have been successful in the United States, where the ASTM E-274 standard is followed by nearly all the states that have friction measuring programs. In other parts of the world the variety of types of friction testers in use complicates the calibration procedure and that was the incentive for the development of the IFI. However, periodic system calibration is still necessary to assure that the systems are maintained in their as-calibrated state.

THE USE OF FRICTION DATA

Friction data are used for the following purposes:

- Network surveys for pavement management,
- Specifications for surface restoration,
- Specifications for new construction,
- Accident investigations,
- Measurements for winter maintenance on highways,
- Measurements of runway conditions for pilot advisories, and
- Measurements of runway friction for maintenance.

Table B3 summarizes the use of friction measurements according to the responses to the questionnaire. In addition, the respondents were asked whether they experienced low friction on newly placed pavements. Seven states and 11 non-U.S. agencies reported occasional deficient friction in newly placed surfaces, but most of the responses were "rarely" or "never."

Network Surveys for Pavement Management

Surveys of the road network are conducted regularly by most of the agencies that responded to the questionnaire. A summary of the responses is given in Table B4. Of the U.S. agencies responding, 24 states and Puerto Rico reported conducting regular surveys. Three states, Kansas, South Carolina, and Utah reported not using the survey results in their pavement management systems. Alaska and Vermont contract their surveys. In addition, four states (Alaska, Connecticut, Kentucky, and Pennsylvania) do not conduct regular network surveys, but do consider skid resistance in their pavement management systems. Of the non-U.S. agencies responding, 13 reported conducting regular surveys. Three agencies, Hungary, Japan, and Ontario do not incorporate the survey data into their pavement management systems.

The frequency of friction measurements varies considerably, as can be seen in Table B4. Local roads are not included in routine surveys, but may be measured by some state agencies on request. Florida and Oklahoma reported testing a limited number of airport runways.

The ASTM E-501 ribbed test tire is predominately used in the United States, but recently there has been an increased interest in using the ASTM E-524 smooth tire (see Table B1). Of the 39 states and Puerto Rico that use the ASTM E-274 locked wheel trailer, 27 reported using the ribbed tire exclusively. Seven states use both ribbed and smooth tires, whereas four states use the smooth tire exclusively. Texas used the ribbed tire prior to 1999, but began using the smooth tire exclusively beginning in 1999. Illinois and Louisiana mount both tires on their trailer, the ribbed on the left and the smooth tire on the right. North Carolina only uses the smooth tire for special tests and Georgia uses it to evaluate texture. Arizona currently uses a MuMeter, but has plans to acquire a fixed slip friction tester, a runway friction tester, in 2000.

The most common test speed for the E-274 locked wheel test is 64 km/h; however, in some situations there is a safety concern about operating at such a low speed. Texas has increased the test speed to 80 km/h. South Dakota also tests at higher speeds, but adjusts the results to 64 km/h. Arizona plans to test at higher speeds when they begin using the RFT. North Carolina is currently developing a protocol for testing at different speeds. The Netherlands plans to increase the test speed from the current 50 km/h to 70 km/h.

Although 24 states conduct regular surveys and use the results in their pavement management systems, and three others incorporate skid resistance in their systems, only 10 states and Puerto Rico have established minimum acceptable levels (intervention levels) for skid resistance. The reported intervention levels are given in Table B5. With the exception of Arizona, which currently uses a MuMeter, and Idaho, which uses the smooth ASTM E-524 tire, the intervention levels are based on locked wheel skid numbers at 64 km/h measured with the ribbed ASTM E-501 tire, SN40R = SN(64)R. Texas began using the E-524 smooth tire in 1999, but their response reported only the levels for the ribbed tire.

Outside the United States, 11 agencies reported minimum friction levels for intervention and/or investigation. The most detailed program is that of the United Kingdom (*23*), as summarized in Table B5. Most non-U.S. agencies use data from measurement with a smooth tread tire in their pavement management programs.

Specifications for Construction or Surface Restoration

Only 11 agencies responded that they include friction requirements in their specifications for new construction or surface restoration. Their responses are summarized in Table B6. However, 20 agencies in the United States and 14 non-U.S. agencies reported that they measure friction on both new and restored pavements. Puerto Rico and one Japanese agency measure friction on new, but not restored pavements.

Accident Investigations

Thirty-six responses, 26 of which came from the United States, reported that skid testing is performed at accident sites. It is important to realize that the friction measured in skid testing cannot be used to calculate vehicle-stopping distance. The following is an extract from the scope of the ASTM standard method for the locked wheel method (*3*):

> The values measured represent the frictional properties obtained with the equipment and procedures stated herein and do not necessarily agree or correlate directly with those obtained

by other pavement friction measuring methods. The values are intended for use in evaluating the skid resistance of a pavement relative to that of other pavements or for evaluating changes in the skid resistance of a pavement with the passage of time. The values are insufficient to determine the distance required to stop a vehicle on either a wet or a dry pavement. They are also insufficient for determining the speed at which control of a vehicle would be lost, because peak and side force friction are also required for these determinations.

The reasons for this caveat are many:

- The test tires used in skid testing are not the same as those on the accident vehicle.
- The amount of water that is placed on the surface by the skid tester is not the same as that experienced by the accident vehicle.
- A four-wheel vehicle has front tires that displace the water so that the rear wheels encounter less water than the front.
- The skid resistance varies with speed and therefore the relationship between skid resistance and speed for the entire speed range of the accident vehicle (i.e., from the initial speed at which the wheels are locked to zero speed).
- The accident vehicle often will not maintain a locked wheel condition in order to maintain directional control.
- Seasonal and short-term variations of skid resistance are difficult to predict and therefore the measurement would be different than that at the time of the accident.
- The load on the test tire of a skid tester is not the same as that on the tires of the accident vehicle.
- The suspension characteristics of the accident vehicle and the skid tester are not the same and the load distribution on the tires of the accident vehicle during braking depends on the condition of its suspension.

Pavement friction measurements are useful in evaluating the safety of a pavement relative to other pavements in the system, but they should not be used for quantitative determinations of stopping distance.

Measurements for Winter Maintenance on Highways

Twelve agencies in the United States and abroad reported that friction measurements are performed occasionally on snow and ice for research. Michigan and Minnesota are participating in a research project in which a salt truck is fitted with a friction-measuring device. The Norsemeter SALTAR (Figure 9) is being used in the project with the objective of optimizing the amount of salt used by continuously monitoring the friction during salt application. NCHRP Project 6-14 was initiated in 2000 to investigate the use of friction measurements in winter maintenance. This project will categorize equipment, practices, and methods for measuring friction on winter contaminated surfaces. Climatic conditions, traffic levels, road characteristics, and other factors will be incorporated with the friction information for winter maintenance operations and motorist information.

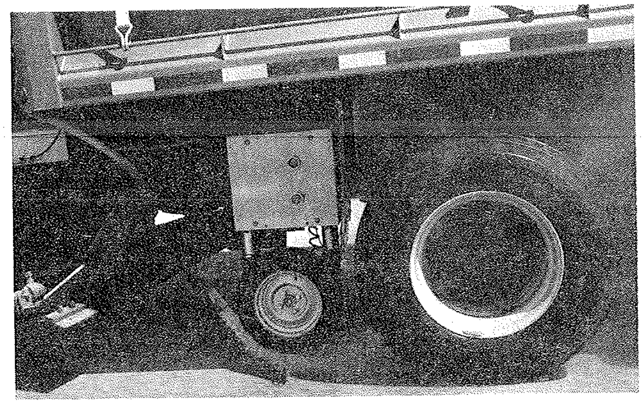

FIGURE 9 Norsemeter SALTAR mounted on salt truck.

In winter conditions, where the road is covered with snow or ice, the tire is in contact with the contaminant and pavement surface characteristics do not affect the friction. However, pavement characteristics do have an effect on the ease of contaminant removal and on the rate of melting under natural conditions. For example, when exposed to sun, clear ice on very black pavements debonds and melts at the ice-pavement interface.

Measurements on Open Grate Bridge Decks

Poor friction is often claimed to be the cause of accidents occurring on open grate bridge decks. A study in Florida (*24*) investigated several methods for measuring the friction on open grate bridge decks. Locked wheel measurements were made with both two-wheel and single-wheel testers. The two-wheel tester produced slightly lower values (7 percent lower) due to the side force induced on the test tire by the free rolling tire. In all cases, the values of SN40S were above 25 and the average for the 10 bridge decks tested was 34.5. In addition, 12 bridge decks were tested with a passenger car under full braking in wet conditions. The car was equipped with a G-Analyst to measure both longitudinal and lateral accelerations. Immediately before the test, the bridge was closed to traffic and water was applied to the deck by a tank truck. The car entered the bridge at 64 km/h (40 mph) and the driver locked the brakes until the car came to a full stop. On 11 of the decks the range of decelerations was 0.51 to 0.79 g. One deck

where the main grid bars ran parallel to the direction of traffic the deceleration was only 0.33 *g*. This deck was old and scheduled for replacement.

It appears that the friction was adequate on these open grate bridge decks. A likely cause of accidents is the overreaction to lateral accelerations by drivers who are inattentive, tired, or inexperienced. When driving over the bridge deck at the speed limit with no braking there is a normal slight side-to-side sensation that is common with all open grate bridge decks. This is normal, because the two front tires are always seeking the same magnitude (but opposite direction) side force. Thus, unless both tires are on the same number of longitudinal rails and in the same position on the deck, the vehicle will move left or right to obtain such a condition. Lateral accelerations measured during braking were between 0.02 and 0.06 *g* and without braking the typical lateral accelerations are in the range of 0.01 to 0.03 *g*. If the driver overreacts by introducing severe steer angle, the result may be due to a loss of control.

Measurements of Runway Conditions for Pilot Advisories

The Joint Winter Runway Friction Measurement Program is a joint government/industry program with the objective of developing a harmonized International Runway Friction Index (IRFI). The program is led by NASA and Transport Canada, with support from the Federal Aviation Administration and the Norwegian Civil Aviation Administration. In addition, there is the participation of organizations and equipment manufacturers from France, Germany, Scotland, Norway, and Sweden.

Conditions at airports during winter storms change rapidly and the operational window for aircraft movements can change so frequently that a measuring service operated by airport ground staff is warranted. Many airports subject to adverse winter conditions provide a measure of friction when snow and ice are present on the runways, but there is a lack of uniformity around the world. In Canada, airports report a Canadian Runway Friction Index, which is a measurement by an electronic recording decelerometer. Norwegian airports use the Griptester and the Skiddometer BV-11. French airports use the Instrument de Mesure Automatique de Glissance (IMAG) and several variations of the Saab Friction Tester. Two examples of fixed slip testers designed for use by airports are shown in Figures 10 and 11. As a result of the use of such a variety of devices that report different numbers, a pilot unfamiliar with the local reporting procedure finds it difficult to judge the aircraft stopping distance either for landing or in the event of a rejected take off. A reference tester is being prepared for calibrating ground vehicle testers to the IRFI. The international reference vehicle (IRV) is a variable fixed slip trailer based on the design of the IMAG (Figure 12).

FIGURE 10 Surface (Saab) friction tester (SFT).

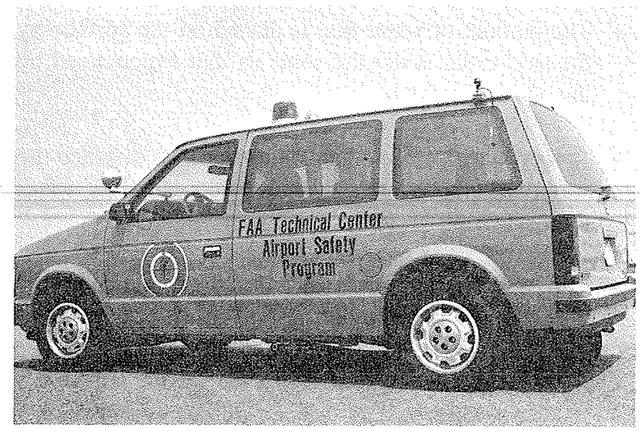

FIGURE 11 Runway friction tester (RFT).

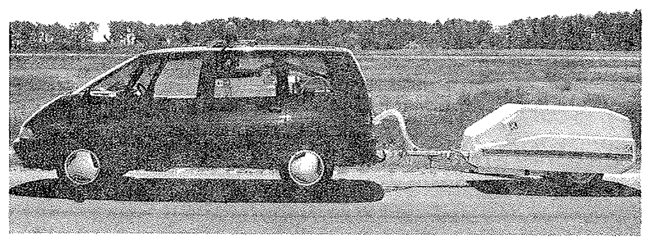

FIGURE 12 Instrument de Mesure Automatique de Glissance (IMAG)/international reference vehicle (IRV).

The Joint Winter Runway Friction Measurement Program has been collecting data with ground vehicles and aircraft since 1995. Airports that have participated in the program are Jack Garland, North Bay, Ontario; K.I. Sawyer, Gwinn, Michigan; Gardermoen, Oslo, Norway; and Franz Strauss, Munich, Germany. Aircraft that have participated in the program are Falcon 20, Boeing 727, 737, and 757, Dash-8, and Airbuses A219, 220, and 221.

OTHER CONSIDERATIONS IN FRICTION TESTING

The survey questionnaire included questions relating to other considerations, such as sample frequency, methods for dealing with seasonal variations, the type of test tire used, the use of accident data, and methods for dealing with hydroplaning. These topics are discussed here.

Sample Frequency

One disadvantage of the locked wheel test method is that the tire cannot be locked continuously without excessive tire wear. Fixed slip and side force methods can measure continuously without excessive wear or creating a flat spot on the tire. The ASTM standard for the locked wheel method (*3*) requires that at least five lockups be made in a uniform test section. The standard defines test sections and their uniformity as follows:

> Test Sections—Test sections shall be defined as sections of pavement of uniform age and uniform composition that have been subjected to essentially uniform wear. For instance, sharp curves and steep grades shall not be included in the same test section with level tangent sections, nor shall passing lanes be included with traffic lanes. Take skid resistance measurements only on pavements that are free of obvious contamination.
>
> Skid Resistance of a Test Section—Make at least five determinations of the skid resistance, at intervals not greater than 1 km (0.6 mph), in each test section with the test vehicle at the same lateral position in any one lane and at each specified test speed. Consider the arithmetic average of all determinations to be the skid resistance of the test section. If statistical or other criteria applied to the skid number for a long test section indicate that it cannot be considered to be uniform, treat the section as two or more sections.

The sample frequencies (number of measurements per mile), reported by the states using the locked wheel testers in the United States, are given in Table B7.

Wheel Path Measured

Most states test in the left wheel path of the driving lane. Under normal conditions, where driving is on the right, that is the location where the skid resistance is minimum. Three states and Puerto Rico test only in the right wheel path. Seven states and Puerto Rico test in both driving and passing lanes. Six states test in both wheel paths, two of which, Illinois and Louisiana, test with the ribbed test tire in the left wheel path and the smooth tire in the right wheel path.

Seasonal and Short-Term Variations

Pavement friction usually decreases as the pavement ages. This is due to two mechanisms: under traffic the aggregate polishes, which decreases the microtexture, and the aggregate wears, which decreases the macrotexture. This general trend is observed as pavements age and is the reason for conducting regular surveys. However, particularly in the northern climates, there are seasonal changes that are not monotonic (*25*). Winter conditions, together with winter maintenance operations, tend to increase the microtexture of the aggregate. Therefore, measurements taken in the spring or early summer may be higher than they would be on the same pavement if the measurements were made during the late summer or fall. Because network surveys generally require testing from spring to fall, this seasonal effect could distort the distribution of the skid resistance of the network. Another effect, not limited to northern climates, is a short-term variation caused by rainfall. During dry periods dust and oil accumulate on the pavement. When a skid test is made during the dry period the water that is applied mixes with the dust and oil, which reduces the measured friction. When the measurements are made shortly after periods of rain, the pavements are less contaminated and this effect is reduced. There have been attempts to model these seasonal and short-term effects; however, the models are complex and require detailed local weather data. No agency, domestic or foreign, reported correcting for short-term variations. Only Virginia reported applying corrections for seasonal variation using the reductions to the measured value shown in Table B8. The Slovak Road administration also reported using multipliers to adjust for seasonal variation. These are also shown in Table B8. As an example, the January multiplier is 0.86, so that a measurement in January of 50 would be adjusted to 43, which would be the expected result of a measurement in July and August.

Smooth Versus Ribbed Tread Tire

The original ASTM E-274 standard for the locked wheel method specified a tire with five ribs. This tire (ASTM E-249) was developed for use on a two-wheel trailer on which both wheels were locked and the force on the hitch was measured. The lateral stability problem resulting from locking both wheels on the trailer was alleviated somewhat when a ribbed test tire was used. In the early 1960s force and torque measuring locked wheel trailers were introduced, which made it possible for only one of the wheels to be locked. These systems were the forerunners of the system described in the current E-274 standard, the first version of which was adopted in 1966.

The sensitivity to the water flow rate also influenced the choice of the standard test tire. It was noted that the ribbed tire was less sensitive to water flow rate than a smooth tire and hence the data would be more reproducible with the early water delivery systems. *NCHRP Report 151* (*26*), on the correlation and calibration of skid testers, concluded: "The ribbed tire, because of its lesser sensitivity to water-film thickness, is therefore the preferred choice for skid-resistance measurement, which ideally is insensitive to all operational factors." Figure 13 shows the data cited in this report. Because the ribbed tires, both new and when worn to the limit, showed no effect of water film thickness between 0.5 and 0.75 mm (0.02 and 0.03 in.), a nominal film thickness of 0.64 mm (0.025 in.) was recommended.

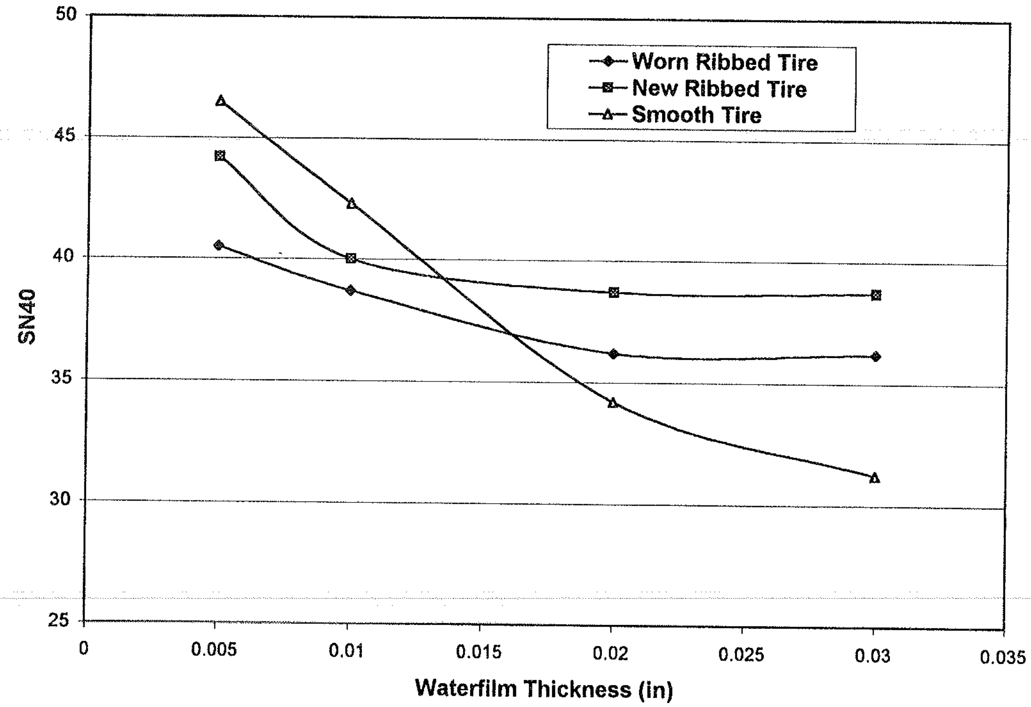

FIGURE 13 Effect of waterfilm on skid number.

In 1973, the E-249 tire was replaced by the E-501 seven-ribbed bias-belted tire (*4*). The E-524 smooth tread companion to the E-501 tire was developed in 1975 (*5*). The original title of this standard was "Standard Specification for Standard Smooth-Tread Tire for Special Purpose Pavement Skid-Resistance Tests." In 1988, the title was changed to "Standard Specification for Standard Smooth Tire for Pavement Skid-Resistance Tests." In 1990, the E-274 standard was amended and the E-501 and E-524 were given equal status, whereas previous versions of the standard had referred to the smooth tire as used in "alternative testing for special purposes."

This history demonstrates the increased interest in the use of the smooth tire for skid testing. In summary, the ribbed tire was chosen as the test tire for the E-274 locked wheel method for two reasons: (1) a five-ribbed tire was already available as a standard for use in an earlier method, and (2) ribbed tires are not sensitive to the water flow rate. The grooves in the ribbed tire provide channels for the water to flow out of the tire pavement interface. These channels are much larger than the flow area provided by the macrotexture. Therefore, measurements with the ribbed tires are also insensitive to macrotexture, but are predominantly influenced by microtexture (*27*).

One reason that agencies may be reluctant to use the smooth tire is that their friction numbers would be lower. Another reason for the resistance to change is that changing to a smooth tire would produce data that could not be compared with historical data. Both tires have their merits in the evaluation of skid resistance, but the information they provide must be interpreted correctly. When both tires are used, as in Illinois and Louisiana, both microtexture and macrotexture can be evaluated.

Either tire can be used to report the IFI because macrotexture is also measured in the IFI approach. A ribbed tire locked wheel measurement, together with a macrotexture measurement, can be used to determine the IFI (*9*). This could allow an agency to continue the use of a ribbed tire if the IFI is adopted. However, the adjustment of the ribbed tread data to determine the friction number (*F60*) is slightly less reliable than the smooth tread tire.

Skid Resistance and Accident Data

Early attempts to relate accident data to skid resistance measured with a ribbed tire were unsuccessful. Rizenbergs et al. (*28*), using accident data from Kentucky, plotted the ratio of wet-to-dry accident frequency against skid number (Figure 14). It is evident from this plot that there is no direct correlation between this measure of wet pavement safety and the skid number measured with the ribbed tire.

During the late 1970s after the smooth tread tire standard was introduced, there was increased interest in its use, particularly with respect to accident frequency. A 1979 Connecticut study (*29*) concluded that "A good correspondence between low smooth-tire skid numbers and accident

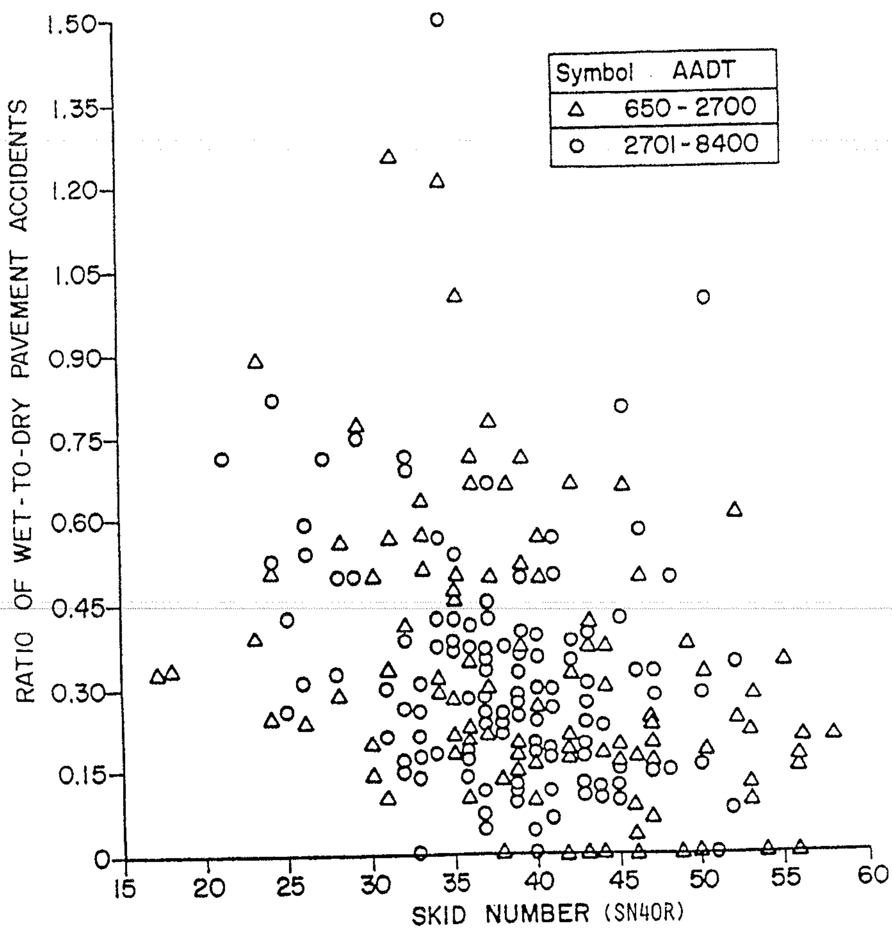

FIGURE 14 Ratio of wet-to-dry pavement accidents versus skid number (*28*).

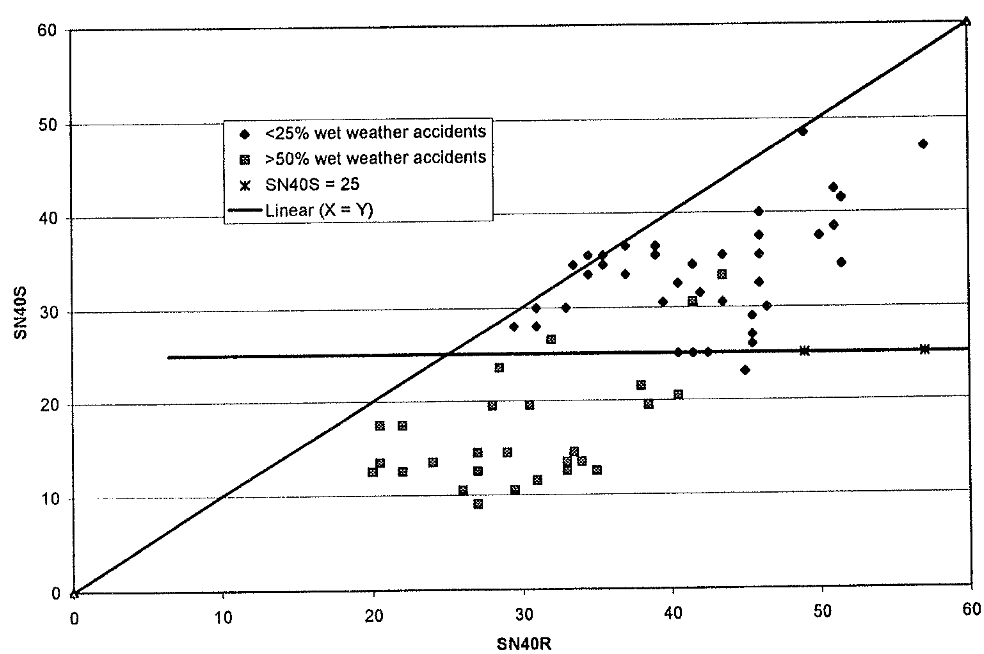

FIGURE 15 SN40S versus SN40R on accident sites in Florida (*30*).

experience can be seen" and "Ribbed-tire correspondence was quite poor." The study further concluded that on pavements that had smooth tire skid numbers (SN40S) greater than 25 there were fewer wet skidding accidents.

In 1984, the Florida Department of Transportation began collecting smooth and ribbed tread tire data at wet accident sites (*30*). They reported data for pavements where more than 50 percent of the total accidents occurred during wet weather and for pavements where less than 25 percent of the total accidents occurred during wet weather. Pavements where between 25 percent and 50 percent of the accidents occurred during wet weather were not reported. These data are plotted in Figure 15. Note that a horizontal line drawn at SN40S = 25 separated the two categories quite well. Only three accident rate sites have a value of SN40S greater than 25 and only one low accident rate site has a value of less than 25. Further investigation showed that the three points above the line were on four-lane highways and it was not certain which lane was reported. There was no corresponding vertical line at a value of SN40R, which separates the two categories as well. This indicates that the smooth tire skid resistance data are a better indicator of safety than data from ribbed tire measurements. However, because many other factors contribute to accidents, including pavement condition, prevailing speed, and traffic conditions, one should not expect to be able to predict accident frequency from skid resistance data alone.

Hydroplaning

The term hydroplaning should not be confused with wet skidding; the two are very different. When hydroplaning occurs the entire tire footprint separates from the pavement and the pavement no longer plays a role in the friction process. Conversely, the pavement texture and transverse profile does influence the amount of water available to cause hydroplaning. Tests at the NASA Wallops Flight Facility on Virginia's Eastern Shore showed that the hydroplaning speed was the same on flooded grooved and nongrooved surfaces (*31*). An NCHRP study (*32*) concluded that grooving should be in the direction of the gradient to allow for better drainage and, therefore, to reduce the potential for hydroplaning.

CHAPTER THREE

PAVEMENT TEXTURE

The levels of pavement texture that affect friction are microtexture, consisting of wavelengths of 1 μm to 0.5 mm (0.0004 in. to 0.02 in.), and macrotexture, with wavelengths of 0.5 mm to 50 mm (0.02 in. to 2 in.). If both microtexture and macrotexture are maintained at high levels, they can provide resistance to skidding on wet pavements. A recent European study (*33*) reports that increased macrotexture reduces total accidents, under both wet and dry conditions. Furthermore, this study shows that increased macrotexture reduces accidents at lower speeds than previously believed.

TEXTURE EFFECTS

Pavement texture is the feature of the road surface that ultimately determines most tire/road interactions, including wet friction, noise, splash and spray, rolling resistance, and tire wear. Pavement texture has been categorized into three ranges based on the wavelength of its components: microtexture, macrotexture, and megatexture. Wavelengths longer than the upper limit of megatexture are defined by the terms roughness or evenness. At the 18th World Road Congress, the Committee on Surface Characteristics of the World Road Association (PIARC) proposed the definitions of the wavelength range for each of the categories shown in Figure 16 (*34*). The committee further proposed the range of the texture wavelengths that are important for various tire/road interactions, which are also shown in Figure 16. Wet pavement friction is primarily affected by the range described by microtexture and macrotexture. Because the range of microtexture and macrotexture affects noise, splash and spray, and tire wear, pavements designed with high friction values may have adverse affects on these characteristics.

Theoretically, it should be possible to predict tire/road interactions, including wet pavement friction, from texture alone. Kummer (*35*) proposed a model for rubber friction that considered two components of the friction: an adhesion component that depends on microtexture and a hysteresis component that is determined by the macrotexture. This model has not been implemented, primarily because of the difficulty of direct measurement of microtexture profiles. However, macrotexture profiles, which now can be obtained at highway speeds to supplement friction measurements, are used by some agencies. The Penn State Model (*6*), the International Friction Index (*9*), and the Rado Model (*14*) all require a macrotexture measurement.

MICROTEXTURE MEASUREMENT

Currently there is no system capable of measuring microtexture profiles at highway speeds. A profile of the microtexture of an in-service pavement surface also could be misleading. The portions of the pavement surface that contact the tires are polished by traffic, and it is the microtexture of the surface of the exposed aggregate that comes into contact with the tire that influences the friction. The valleys are not subjected to polishing and their contribution to the overall microtexture should not be included in prediction of friction.

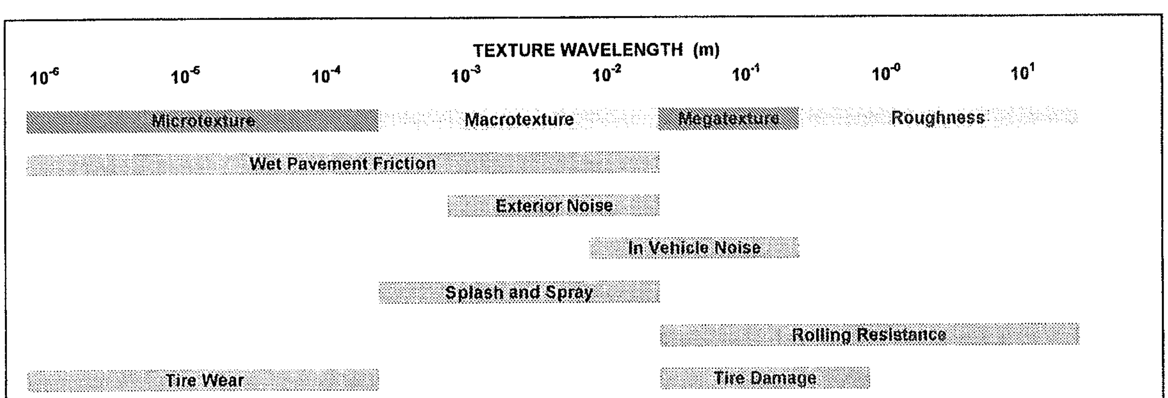

FIGURE 16 Texture wavelength influence on surface characterisitcs (*34*).

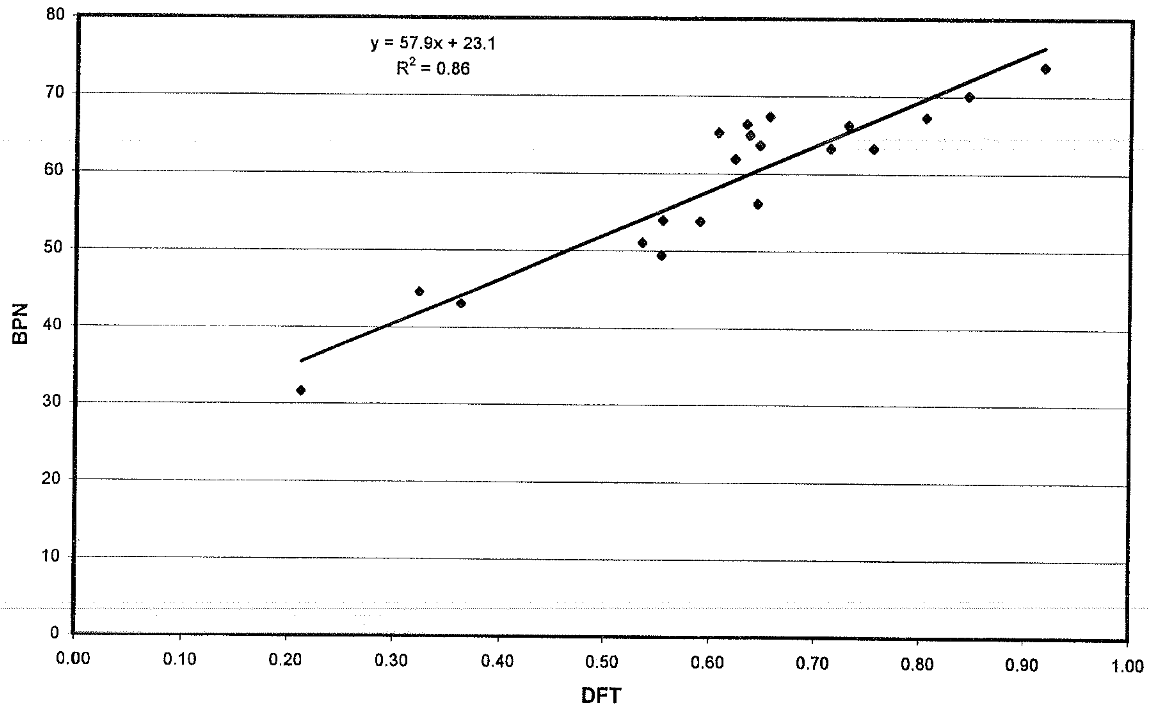

FIGURE 17 British pendulum number versus dynamic friction tester for sites at the NASA Wallops Flight Facility (1998).

Because of the difficulty in measuring microtexture profiles, a surrogate for microtexture is generally preferred. As noted in chapter 2, wet pavement friction at low speeds is primarily influenced by microtexture. In research at the Pennsylvania State University (*36*), a high correlation was found between the parameter μ_0 of the Penn State Model in Eq. (1) and the root mean square (RMS) of the microtexture profile height. The parameter, μ_0, is the zero speed intercept of the friction-speed curve and characterizes the friction at low slip speeds. It was also found that the British Pendulum Numbers (BPNs) were highly correlated with the parameter μ_0. The slider of the British Portable Tester (BPT) engages only the portion of the asperities that are subject to polishing by traffic and therefore the BPN values could be considered as the surrogate for microtexture.

The DFTester measures the friction between three sliders mounted on a spinning disc. The values of the friction when the slip speed is 20 km/h are highly correlated with BPN values, as shown in Figure 17. Measurements at the annual NASA Friction Workshops (1993–1999) have included several DFTesters and BPTs. There is a significantly higher variability among the BPTs than among the DFTesters (*37*).

In the United Kingdom, the SCRIM values are synonymous with microtexture. The SCRIM is a side force coefficient measuring device and therefore the sliding speed of the test tire is relatively low. The SCRIM operates at traffic speeds; however, because the slip speed is low, it serves as a surrogate for a microtexture measurement.

The PIARC Model for the IFI avoids the need for measuring microtexture, if macrotexture measures are available. A measurement at any slip speed, together with the macrotexture parameter, determines the friction as a function of slip speed.

There is currently no practical procedure for the direct measurement of the microtexture profile in traffic. Such a procedure would possibly enable testers to avoid the measurement friction altogether by measuring microtexture and macrotexture in order to predict the wet pavement friction as a function of speed. This would eliminate the need to carry water and use a high-powered host vehicle.

MACROTEXTURE MEASUREMENT

The classic measure of pavement macrotexture is a volumetric method (*8*), typically referred to as the "sandpatch" method. Originally the method required spreading a specified volume of Ottawa sand, which passed a No. 50 sieve and was retained on a No. 100 sieve. The sand is spread on the pavement in a circular motion with a spreading tool. The area of the roughly circular patch of sand is calculated by using the average of four equally spaced diameters. The volume divided by the area is reported as the Mean Texture Depth (MTD). The tools required to perform the volumetric method are shown in Figure 18. The current ASTM standard requires the use of glass spheres instead of sand. The material was changed for two reasons: (1) glass spheres spread more uniformly than sand with its irregular

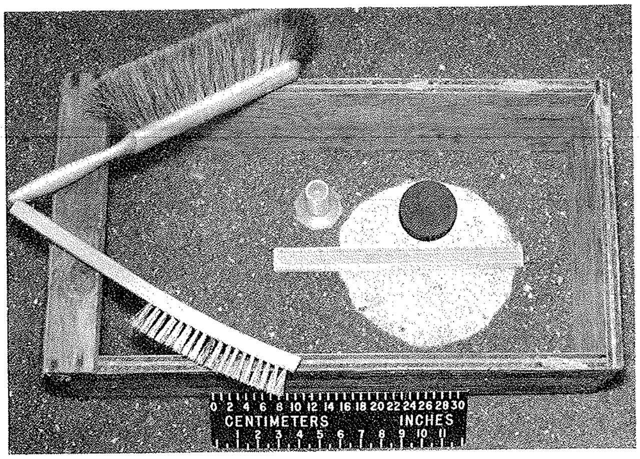

FIGURE 18 Equipment for volumetric method for mean texture depth.

shape and (2) very low yields are usually obtained when bags of sand are sieved, whereas glass spheres that meet the size specification are commercially available, and the necessity to sieve the material is avoided. A variation of the volumetric method used by NASA is the "Grease Patch Method" (*38*) in which the material is grease.

In Japan, another variation of the method uses glass spheres, but spreads them in a linear track using a spreader that is maintained at a small fixed distance above the surface in a fixture of constant width. The length of the track on a surface and the length of a track on a glass plate allow the texture depth (*TD*) to be calculated from:

$$TD = \frac{V(L_g - L_s)}{a\, L_g\, L_s} \qquad (8)$$

where V is the volume of the glass spheres used, L_g is the length of the track on the glass plate, L_s is the length of the track on the surface, and a is the width of the fixture. It would appear that this method would have less operator variability than with the traditional method; however, at this time there are no sufficient data to support this hypothesis. One problem with this method is that on surfaces having very deep texture the glass spheres tend to flow under the sides of the fixture, resulting in the overestimation of the texture depth. In practice, this is usually not a significant problem, because macrotexture is not critical in such cases.

In the past decade significant advances have been made in laser technology and in the computational power and speed of small computers. As a result, systems are now available that can measure macrotexture at traffic speeds. The profiles produced by these devices can be used to compute various profile statistics such as the Mean Profile Depth (MPD) (*11,12*), the overall RMS of the profile height, and other parameters that reduce the profile to a single parameter. Octave band and third octave band spectral analysis is also used in applications for tire/road noise. The center texture wavelengths for profile spectral analysis have been standardized by the International Standards Organization (ISO) (*39*). Narrow band spectral analysis was not previously considered to be very useful in tire/road interactions by some researchers; however, a recent study in Wisconsin (*40*) has found narrow band fast Fourier transform analysis to be useful in tire noise analysis for portland cement concrete (PCC) pavements.

It was found in the PIARC international experiment (*9*) that the best parameter to describe the macrotexture for the prediction of wet pavement friction is the MPD, as defined by ASTM and ISO (*11,12*). The MPD is calculated as follows:

> The measured profile is divided into segments having a length of 100 mm (4 in.). The slope of each segment is suppressed by subtracting a linear regression of the segment. This also provides a zero mean profile, i.e., the area above the reference height is equal to the area below it. The segment is then divided in half and the height of the highest peak in each half segment is determined. The average of these two peak heights is the mean segment depth. The average value of the mean segment depths for all segments making up the measured profile is reported as the MPD.

When the MPD was used to determine the speed constant (S_p) of the IFI, the best results were obtained. The volumetric method also produced good results in predicting S_p in the experiment. The results for both predictions are given in the ASTM standard practice for calculating the IFI (*10*):

$$S_p = 89.7MPD + 14.2 \qquad (9)$$

where MPD and MTD are expressed in millimeters, and S_p is in kilometers/hour.

$$S_p = 113.6MTD - 11.6 \qquad (10)$$

Combining Eqs. (9) and (10), an expression relating the MTD to the MPD yields:

$$MTD = 0.79MPD + 0.23 \qquad (11)$$

When MPD is used to predict MTD the result is called the Estimated Texture Depth (ETD). The expression given for the ETD in the ISO and ASTM standard practices for calculating MPD (*11,12*) uses Eq. (11), but with the coefficients rounded to single precision: 0.8 and 0.2, respectively. The mean size of the glass spheres is approximately 0.2 mm (0.0075 in.), and when MTD was measured on a smooth aluminum panel at the NASA Wallops Flight Facility the result was 0.16 mm (0.006 in.) (*37*).

A new device for measuring MPD, called the Circular Track Meter (CTMeter) (*41*), was introduced in 1998. The CTMeter (Figure 19) can be used in the laboratory as well as in the field and is a companion to the DFTester. It

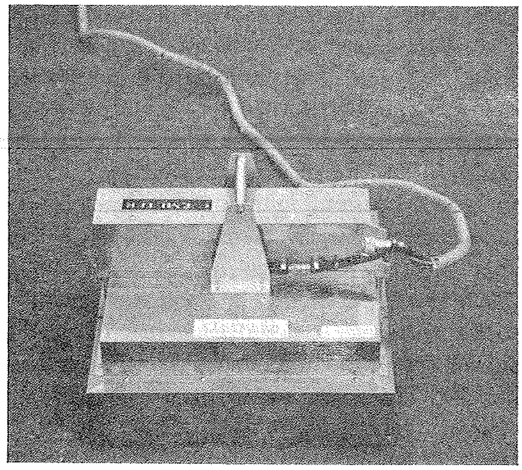

FIGURE 19 Circular track meter (CTMeter).

uses a laser to measure a profile in a circle 800 mm (31.5 in.) in circumference. The mean depth of each 100-mm (4-in.) segment or arc of the circle is computed according to the standard practices of ASTM and ISO. The CTMeter is controlled by a notebook computer, which also performs the calculations and stores the mean depth of each segment. The averages of the depths of the two arcs that are perpendicular to the travel direction and the two arcs that are in the direction of travel are also computed. For estimating the MTD it has been found that the best results are obtained when all eight segment depths are averaged. Excellent results are obtained even on grooved pavements. Figure 20 shows the results of tests at the NASA Wallops Flight Facility during 1998 and 1999. The coefficients in the relationship between MTD and MPD are different from those in Eq. (11), as might be expected because of the different manner in which the profile is obtained.

Another useful device for characterizing pavement macrotexture is the outflow meter (*42*). The outflow meter, shown in Figure 21, is a transparent vertical cylinder that rests on a rubber annulus placed on the pavement. 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 for the water level to fall by a fixed amount is measured. In the original outflow meter, the time, in seconds, was measured with a stopwatch as the level passed two marks inscribed on the cylinder and was reported as the outflow time (OFT). A major improvement has been the incorporation of an electronic timer, which measures the time for the level to fall from an upper electrode to a lower electrode in the water. The OFT is highly correlated with the MPD and the MTD for nonporous pavements. Figure 22 shows the correlation between MTD and OFT, as measured by the FHWA outflow meter for nonporous surfaces at the NASA Wallops Flight Facility. It should be emphasized that this

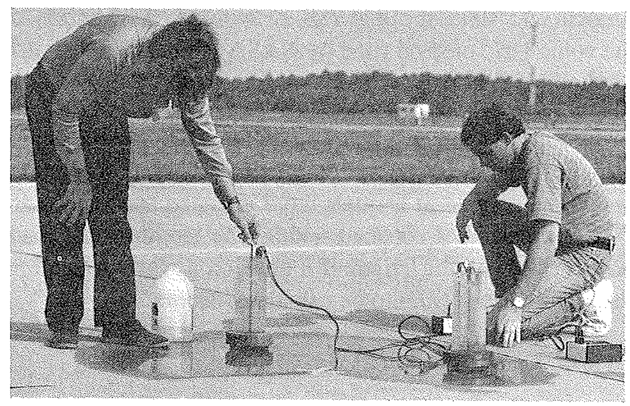

FIGURE 21 Outflow meter.

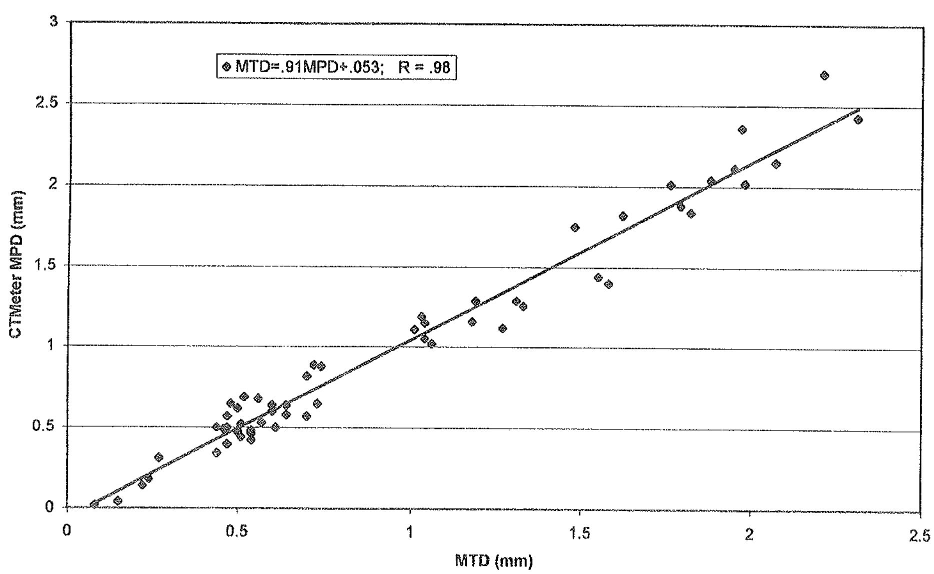

FIGURE 20 CTMeter mean profile depth versus mean texture depth for sites at the NASA Wallops Flight Facility.

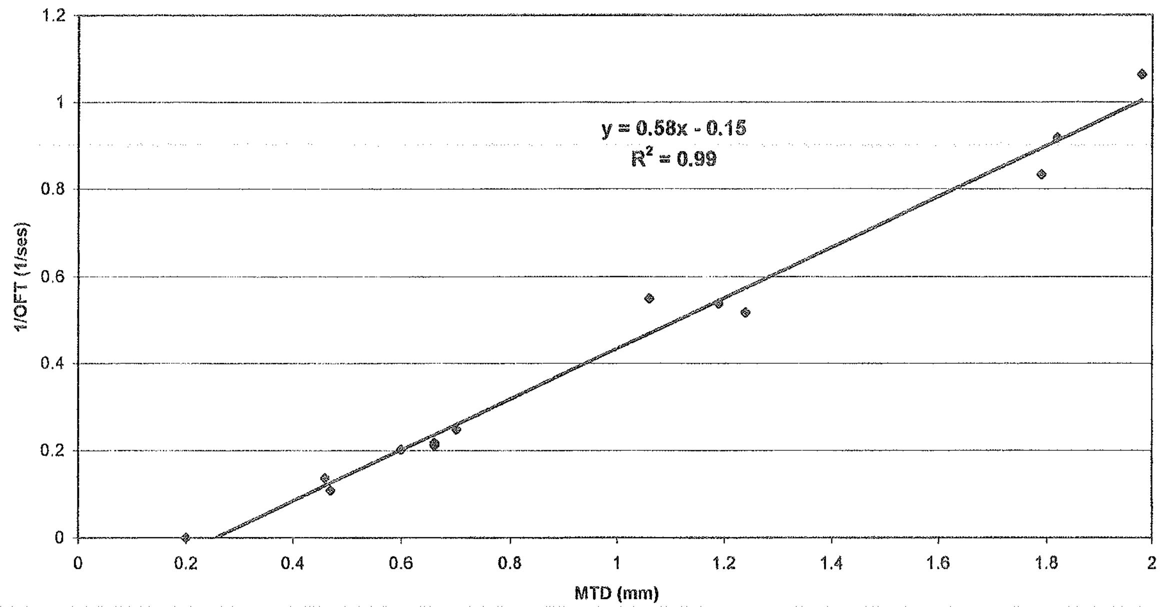

FIGURE 22 Outflow time versus mean texture depth at the NASA Wallops Flight Facility.

relationship is for data obtained with the FHWA outflow meter, which may have different dimensions than other outflow meters in use. Comparison of the OFT and the MTD is a potential method to assess the effectiveness of the porous surface.

THE USE OF TEXTURE DATA

Of the 42 U.S. agencies that responded to the questionnaire, five states and NASA reported that they measure macrotexture. In addition, Texas began using macrotexture measurements in 2000 for condition surveys, accident analysis, and noise. Comparatively, 15 of the 28 non-U.S. agencies responding measure macrotexture. Table B9 summarizes the use of macrotexture measurements by those agencies that measure macrotexture.

No states specify minimum requirements for macrotexture. Great Britain attempts to provide an MTD of 1.5 mm (0.06 in.) for new pavements. Denmark has begun to measure macrotexture simultaneously with their friction measurements and is developing intervention levels. Target levels for maintenance, surface restoration, and construction are given in Table B10 for the eight agencies that reported levels in the questionnaire.

CHAPTER FOUR

CONSTRUCTION AND SURFACE RESTORATION CONSIDERATIONS

The development of strategies for construction and surface restoration includes criteria not only for friction, but also other performance considerations such as noise, durability, splash and spray, tire wear, and rolling resistance. Various strategies for achieving pavement performance requirements are available both for new construction, including tining and dragging, and mix design for porous surfaces. For surface restoration, grinding, grooving, microsurfacing, shot peening, and seal coating are widely used.

DESIGN CRITERIA

Table B11 summarizes the ratings of relative importance of pavement performance considerations given by agencies that responded to the questionnaire. The averages of each factor are given in Table 2 for ratings derived from both U.S. and non-U.S. responses. Each respondent was asked to rate performance on a scale of 1 to 3, where a rating of 1 is very important and a rating of 3 is relatively unimportant. Where no rating was given, a value of 4 was assigned for the purposes of computing an average rating.

TABLE 2
SUMMARY OF DESIGN CRITERIA RATINGS

	Ranking	
Design Criteria	United States	Other Countries
Durability	1.1	1.3
Skid resistance	1.2	1.4
Splash and spray	2.0	1.8
Exterior noise	2.4	2.2
In-vehicle noise	2.4	2.4
Rolling resistance	2.7	2.7
Tire wear	2.7	2.9

The ratings are remarkably consistent; showing no great differences between the United States and other countries. Skid resistance is a close second to durability in importance.

Durability

Respondents ranked durability as the most important design consideration. This high ranking was only slightly above the reported importance given to skid resistance. Durability is closely related to economic considerations; therefore, it is logical that it would rank as the highest design criteria.

Limestone aggregates, although generally very durable, often polish, resulting in poor microtexture. Polish resistant aggregates maintain their surface macrotexture by sacrificial wear (*43*). Ideally, an aggregate should wear at a rate just sufficient to renew its microtexture, thereby providing resistance to polishing with a minimum of wear.

When porous surfaces are used to provide good skid resistance and splash and spray qualities there is often a sacrifice in durability. Raveling occurs because of the aging of the binder, and the layer may be worn away in a very short period of time (*44*). However, improvements in the technology of mixture design, including the use of modified binders to reduce the tendency to ravel, have improved the performance of porous friction courses.

Grooving or tining of PCC pavements is often necessary to provide adequate skid resistance, but introducing grooves causes the resulting surface to be more susceptible to wear, particularly where chains and studded tires are in use.

Skid Resistance

As discussed in chapter 2, skid resistance can be evaluated by several different methods. When skid resistance is used as one of the criteria for pavement design the method of measurement will influence the result. Twenty states reported measuring skid resistance on both newly constructed and restored pavements (see Table B3). Puerto Rico reported skid testing on new construction only, and Kansas tests both new and restored surfaces after 1 year. Although these states report that they measure skid resistance on these projects, only four states (Maine, Minnesota, Washington, and Wisconsin) reported minimum friction requirements for construction and surface restoration (see Table B6). Maine, Washington, and Wisconsin specify levels for locked wheel numbers (SN40R) with a ribbed tire greater than 35, 30, and 38, respectively. Minnesota requires an SN40R greater than 45 and an SN40S greater than 37. Minnesota also requires an MTD greater than 0.8 mm (0.03 in.) on new PCC surfaces. Although not contractually required, those states that did not report minimum requirements for new surfaces would probably expect levels above their intervention levels reported in Table B5.

Aggregate specifications are used by agencies to design skid resistant pavements. For evaluating aggregate

polishability the most commonly used test is the Los Angeles Abrasion Test (*45*). The British Wheel (*19*) is also used by many agencies, particularly in Europe. Arkansas uses the Penn State Reciprocating Polisher (*46*). In addition, laboratory samples of mixes are tested by some agencies using the British Portable Tester (*18*), which provides an evaluation of the microtexture. In Japan, the DFTester (*20*) is used for evaluating laboratory samples. Table B12 summarizes the survey responses for tests used for evaluating aggregates.

A survey of the guidelines for evaluating skid resistance in hot mix asphalt pavement design was conducted in 1997 (*47*). The responses from the 48 contiguous states are summarized in Table 3.

TABLE 3
USE OF SKID RESISTANCE IN ASPHALT CONCRETE PAVEMENT EVALUATION (*46*)

Guidelines	No. of States
No specific guidelines to address skid resistance	14
Skid resistance accounted for through mix design	9
General aggregate classification procedures are used	7
Laboratory evaluation of aggregate frictional properties	18
Incorporate field performance in aggregate qualification	4

Note: There were 52 responses because 4 states use both items 4 and 5.

Skid resistance, however, is an important element of the long-term pavement performance (LTPP) study (*48*) being conducted in the United States and Canada. Locked wheel tests were conducted in 46 states, the District of Columbia, Puerto Rico, and 9 provinces in Canada. Historical data on the sites with measurements were collected every 2 years, from 1989 to 1995, and are available for the comparison of materials and pavement design. Measurements continue to be performed on some of the sites, although not as a part of the LTTP program.

Splash and Spray

Increasing macrotexture reduces splash and spray and increases skid resistance (see Figure 16). Also, porous wearing courses reduce splash and spray and increase skid resistance. In general, pavements with good splash and spray characteristics have good skid resistance.

Exterior Noise

Tire pavement noise is a prime consideration when addressing skid resistance. Exterior noise levels increase with increasing macrotexture, as shown in Figure 16. This is the range of texture that is important in providing good skid resistance, particularly at high speeds. Transverse grooving or tining of pavements to provide skid resistance can result in high levels of exterior noise. When grooves or tines are uniformly spaced, producing noise with a tonal quality, the resulting noise can be particularly annoying to residents adjacent to the roadway. Randomly varying the spacing or skewing the grooves or tines can reduce this problem (*40*). Transverse grooves and tines were found to generate more noise than longitudinal grooves or tines.

In-Vehicle Noise

According to the PIARC study (*34*), in-vehicle noise is affected primarily by the higher wavelengths of macrotexture and by megatexture. Some design trade-off may be necessary if in-vehicle noise is considered important. This is particularly true for tined and transverse-grooved PCC pavements, which have macrotexture in the high wavelength range.

Rolling Resistance

Rolling resistance is affected by wavelengths above those of the macrotexture and, because wavelengths above macrotexture do not significantly affect skid resistance, it is not necessary to compromise design for rolling resistance. The overall ranking of rolling resistance was found to be relatively unimportant.

Tire Wear

Tire wear increases with increasing microtexture. Good microtexture is required to provide good skid resistance. As with rolling resistance, the overall ranking of tire wear was found to be relatively unimportant. A model based on laboratory data at low speed (8 km/h) shows that wear is a directly proportional area under the microtexture portion of the power spectral density curve (*49*). There are no data in the literature to quantify the relationship between tire wear and microtexture at high speeds.

DESIGN FOR NEW CONSTRUCTION

Porous Wearing Courses

Porous asphalt wearing courses provide excellent wet weather friction and reduce splash and spray and exterior noise levels. There are, however, disadvantages to porous surfacing. This type of surface has potential for early failure. A "rule of thumb" in The Netherlands is that porous asphalt surfaces must be reconstructed after 9 years (*50*), although the response to the questionnaire from this country claims

a life expectancy of up to 12 years (see Table B13). Construction costs are higher due to the requirements of quality aggregates and the necessity to use modified asphalt or additives. The life expectancy of porous wearing courses reported by the states that routinely use them, such as Arizona, Florida, Georgia, Oregon, and Wyoming, varies from 8 to 20 years.

Porous asphalt requires more salt during winter maintenance, which has a negative influence on the environment. Maintenance of the surface course is more expensive than traditional asphalt, particularly if the porous properties deteriorate because of accumulation of dirt in the voids (*44*). Cleaning methods have been experimented with, but have not been very successful in providing a lasting improvement.

Table B13 summarizes the responses to the survey questions about porous friction courses. Note the wide range of expected life: from 4 to 20 years. Wearing course thicknesses range from 13 to 50 mm, but 25 mm is typical.

Tining

Tining is commonly used in new PCC pavements, often in conjunction with burlap drag or Astro Turf finishes, to provide adequate friction characteristics. Transverse tining is most common, but longitudinal tining is sometimes used in areas sensitive to noise. The tentative recommendation of the FHWA PCC Surface Texture Technical Working Group (*51*) for transverse tining is a spacing between 10 and 76 mm (0.4 and 3 in.), a width of 3 ± 0.5 mm (0.12 ± 0.02 in.), and a depth of between 3 and 6 mm (0.12 and 0.24 in.). Narrow, deep grooves are better from the standpoint of noise generation than shallow, wide grooves. The New South Wales Concrete Pavement Design Manual (*52*) recommends groove depths of between 1.5 and 3 mm (0.06 and 0.12 in.), with variable spacing ("to reduce humming") for rural roads. These surfaces are reported to be equivalent to dense-graded asphalt for noise generation, but have friction characteristics equivalent to open-graded asphalt at both 80 and 110 km/h (50 and 65 mph).

When longitudinal tining is used, the FHWA Technical Working Group (*51*) recommends a spacing of 19 mm (0.75 in.), a width of 3 ± 0.5 mm (0.62 ± 0.02 in.), and a depth of between 3 and 6 mm (0.12 and 0.24 in.). The spacing of 19 mm (0.75 in.) was also the recommendation of a Wisconsin study. To provide adequate microtexture, a high-quality mix with a minimum of 25 percent of the total aggregate should be quartz (siliceous) sand (*40*).

Of the agencies responding to the questionnaire, most reported using transverse tining (Table B14). Only Michigan and Quebec reported the use of longitudinal tining, and although not reported by the respondent, California also uses longitudinal tining. Thirty-one U.S. agencies reported the use of tining, but nine of those did not indicate the tine spacing. The majority use a tine spacing of between 12 and 25 mm (0.5 and 1.0 in.). Japan uses 30-mm (1.2-in.) and New Jersey reported 50-mm (2.0-in.) spacing.

Astro Turf Drag

In 1994, Colorado initiated a study of Astro Turf drag (*53*). Nine surfaces were prepared with various combinations of Astro Turf drag, tining, and grooving (see Table 4). Friction was measured by the ASTM E-274 locked wheel method with both the smooth and ribbed test tires as placed in 1994 and after a year in 1995. Astro Turf drag without tining or grooving was unsatisfactory after 1 year (sections 1 and 2). The Astro Turf drag did not significantly improve the state standard tining, either as placed or after 1 year (sections 3 and 4 were about the same). Sections 5 through 9 performed well, but the contribution by the Astro Turf drag could not be evaluated, because there were no corresponding control sections without the Astro Turf drag.

TABLE 4
COLORADO ASTRO TURF DRAG STUDY (*53*)

Section	Tine/Groove Spacing (mm)	Astro Turf Drag
1	None	Transverse
2	None	Longitudinal
3	25 transverse tine	None
4	25 transverse tine	Longitudinal
5	Random transverse tine	Longitudinal
6	12 transverse tine	Longitudinal
7	19 longitudinal tine	Longitudinal
8	Random transverse groove	Longitudinal
9	19 transverse groove	Longitudinal

Burlap Drag and Broomed Surfaces

It is a common practice to provide texture to PCC surfaces by dragging or brooming the surface during placement. These practices provide a modest amount of macrotexture, but are inadequate for high-speed highways unless followed by tining. They also provide an initial improvement of the microtexture, but this does not last under heavy traffic (*51*).

Stone Mastic Asphalt (SMA)

The use of SMA originated in Europe in the 1960s, but was not introduced into the United States until the early 1990s (*55,63*). Its primary advantage is resistance to deformation, but it has been shown to have better frictional characteristics than traditional asphalt.

SMA is a gap-graded, dense asphalt cement concrete, with a high percentage of coarse aggregate, typically 10 to 15 mm (0.4 to 0.6 in.). The mix contains a high percentage of mineral filler, and modified asphalt and/or fibers are often used to prevent draindown. As a result of the aggregate gradation SMA has excellent macrotexture. Trials in Ontario in the early 1990s (*54*) reported "better" skid resistance than hot mix asphalt. Trials in the United Kingdom in the late 1990s (*55*) confirmed that SMA has excellent macrotexture levels and that it retains these levels under heavy truck traffic. The initial sandpatch texture depth (MTD) was 1.5 mm (0.06 in.), which fell to 1.2 mm (0.05 in.) after a few months of traffic on a single-lane highway, with 1,000 heavy vehicles per day. After 21 months it maintained an MTD of 1.1 mm (0.04 in.). In addition, the speed gradient is less than that for large-aggregate hot-rolled asphalt. Friction measurements made with a Griptester on a runway resulted in a reading of 0.81 at 60 km/h (36 mph), only falling to 0.73 at 130 km/h (78 mph).

Superpave

Superpave is a design procedure developed under the Strategic Highway Research Program from 1987 to 1993. The name is an acronym for Superior Performing Asphalt Pavements. The Superpave design procedure does not directly address skid resistance, but it does address rutting, which has a direct relationship to hydroplaning.

SURFACE RESTORATION STRATEGIES

The questionnaire responses on practices to improve the frictional characteristics of existing pavements are summarized in Table B15. For asphalt concrete pavements the most common practices are microsurfacing and seal coating. For PCC the most common practice has been grooving, although the use of diamond grinding is increasing. Shot peening is also used for PCC pavements to a lesser extent. In addition, it is used for rubber removal on runways.

Microsurfacing

Microsurface treatments are widely used to restore pavements that are structurally sound, but have surface distress or inadequate friction characteristics. It consists of applying a very thin binder and a monolayer of aggregate. Special equipment is usually required and the binder and aggregate are often proprietary.

Aggressive microsurface treatments have been promoted to improve skid resistance. In the United Kingdom, ShellGrip was introduced in the early 1960s for treating black spots. ShellGrip is an epoxy resin with calcined bauxite chippings. It was introduced into the United States under the trade name SprayGrip in the late 1960s, but was abandoned due to logistics and cost. ShellGrip is also used in continental Europe. The Italian Autostrade has used ShellGrip extensively in the past, but has cooperated with Italian industry to develop the Italgrip System. Italgrip was applied in demonstration projects in Wisconsin and Virginia in the late summer of 1999. The Italgrip binder is a two-component epoxy resin and the aggregate is a synthetic corundum-like material with high porosity. The result is long-lasting macrotexture of approximately 1-mm texture depth (MTD). Italgrip is currently being evaluated for its potential use in North America (*56*). Novachip was developed in France in the 1980s and was introduced to the United States in 1998. Initial applications in Minnesota and Iowa were made in 1998 and 1999. Novachip is a thin, gap-graded hot mix placed over a polymer-modified membrane.

In 1996, the Georgia Department of Transportation used microsurfacing to restore 92 lane-km of Interstate 285, using 9.5-mm (0.37-in.) screenings with a polymer-modified asphalt emulsion. It reportedly has performed quite well to date, providing excellent ride quality, good pavement friction characteristics, and low noise levels.

Seal Coat

Seal coats or chip seals are also used to restore pavement friction characteristics and extend the life of pavements. Asphalt binder is sprayed onto the surface followed by the application of a single layer of single-sized aggregate. As opposed to microsurfacing, seal coats use conventional materials and do not require the same level of care in application. However, particular care must be taken to obtain the proper aggregate and binder application rates. Seal coats generally have a shorter useful life than microsurfacings.

Grooving

Saw cut grooving has been the traditional means to restore adequate frictional characteristics of PCC pavements. Tined PCC pavements lose their macrotexture with wear and grooving restores the macrotexture. Most grooving is longitudinal (parallel to the direction of travel), but transverse grooving is used on bridge decks, airport runways, and at intersections. Where tire-pavement noise is a problem, transverse grooves should be randomly spaced. Transverse grooves provide drainage paths to the shoulder, which alleviates ponding, but produce higher noise levels.

If ASTM E-274 (*3*) locked wheel skid numbers with a ribbed ASTM E-501 (*4*) test tire were the criterion for pavement friction evaluation, pavements would not be grooved. The ribs of the test tire provide sufficient drainage in

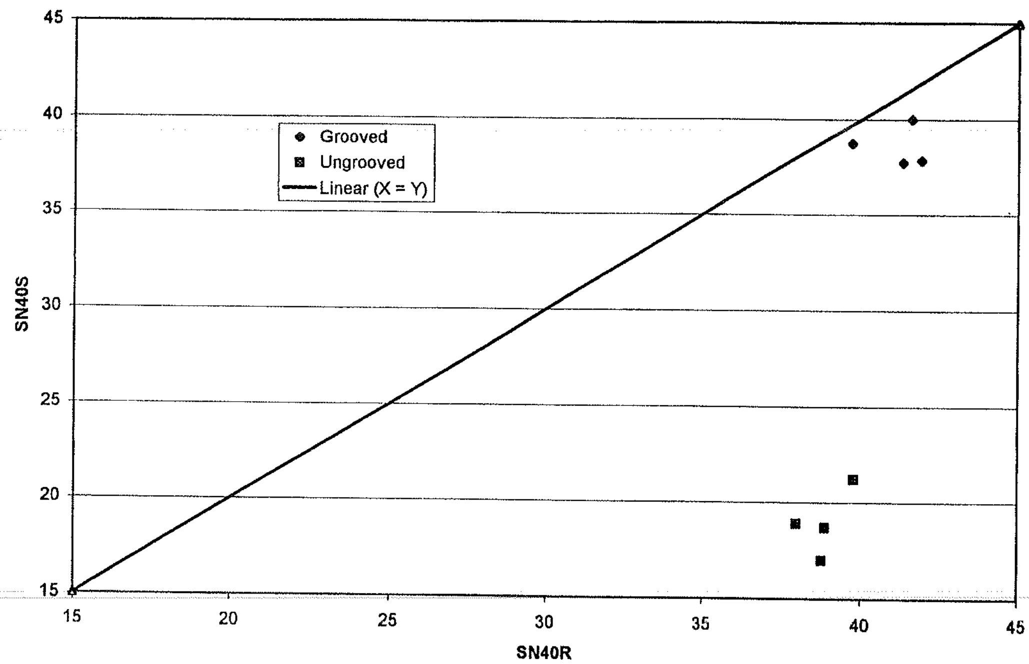

FIGURE 23 SN40S versus SN40R on grooved and ungrooved sections.

the footprint, and the grooves do not increase the skid number. However, if the ASTM E-524 (*5*) smooth test tire is used, the increase of the skid number due to grooving is large. Figure 23 shows the results of tests performed with both tires on four sections of Interstate 80 in Pennsylvania, where a portion of the pavement was grooved, but the original surface remained before and after the grooved portion (*6*). Measurements were made on both the grooved and ungrooved portions with both tires. Note that there is very little increase in the values of SN40R: the average increase is 2.2 skid numbers or 5 percent. Conversely, the values of SN40S increased remarkably in the grooved portions: 19.7 skid numbers or 104 percent. Most states still use the E-274 test with the ribbed E-501 tire to evaluate skid resistance; therefore, "improvement" of skid resistance is not the criterion for choosing grooving. They do, however, recognize that grooving results in a reduction of accidents and suggests that tests with smooth tires would correlate well with accident experience (see Figure 14).

Typical dimensions of sawed transverse grooves are width and depth between 3 and 6 mm, respectively, with a spacing of between 13 and 25 mm (*52*). Random spacing and/or skewed grooves are often used to reduce the high sound pressure level of a narrow band of frequency (tonality, "humming").

Shot Peening

Shot peening with steel balls was first used on airport runways for rubber removal. Very light shot peening is used for this purpose and the equipment speed is relatively high. Slowing down the process can remove binder and increase the macrotexture. The slower the process the greater the increase in macrotexture. For highways, the rejuvenation of macrotexture by shot peening is often evaluated by the outflow time (*42*) or the sandpatch method (*8*). Shot peening is performed on asphalt surfaces to a lesser extent than on PCC surfaces. Shot peening is performed in Europe and Japan, as well as in the United States and Canada. Six sections of a PCC runway at the NASA Wallops Flight Facility have been treated with varying degrees of shot peening (*57*), using the Skidabrader equipment shown in Figure 24. Figure 25 shows the effect of shot peening. A summary of the results is contained in Table 5, where the speed of the treatment is given for each section. The speed to produce a given level of macrotexture depends, however, on the material properties of the binder and aggregate. Shot peening increases the skid resistance and reduces the tire pavement noise (*52*). The long-term effectiveness of shot peening may depend on the aggregate type and quality.

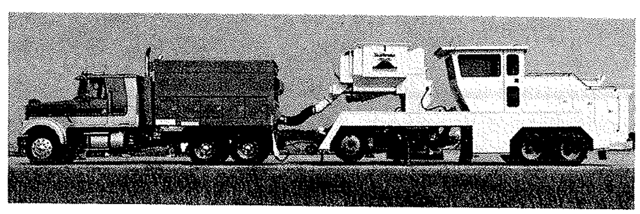

FIGURE 24 Skidabrader equipment.

Diamond Grinding

Diamond grinding is primarily used to remove roughness in order to improve ride quality and rutting, but the skid resistance is also improved. Mosher (*58*) measured five

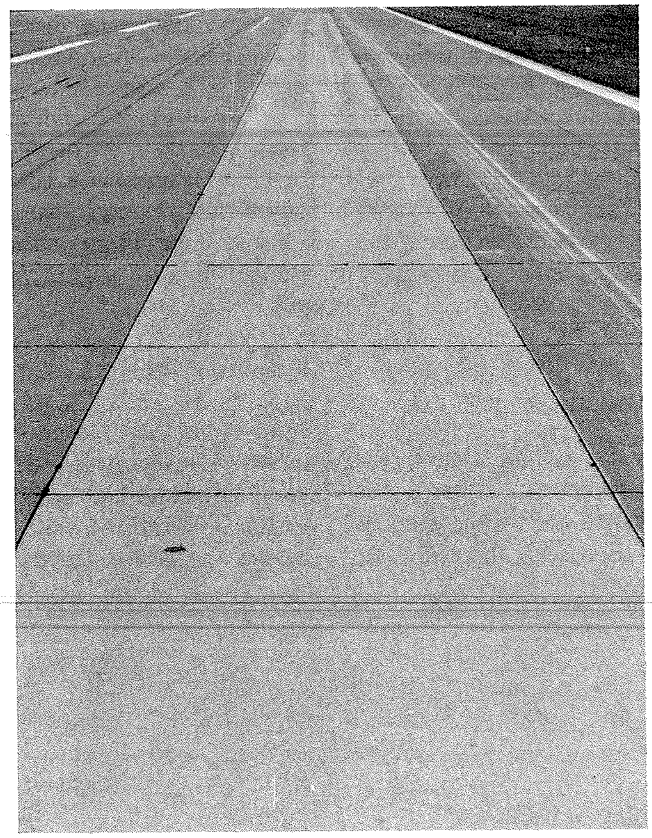

FIGURE 25 Surface after Skidabrader treatment.

TABLE 5
SKIDABRADER RESULTS AT THE NASA WALLOPS FLIGHT FACILITY—1996

Section	Level of Treatment	Operating Speed [m/min (ft/min)]	SN40S	MTD (mm)
S0	Untreated surface	Not applicable	16.2	0.51
S1	Light treatment, 1993	21.3 (70)	31.5	0.65
S2	Moderate treatment, 1993	15.2 (50)	30.6	0.73
S3	Normal treatment, 1993	10.7 (35)	39.9	1.12
S4	Severe treatment, 1993	6.1 (20)	53.1	2.27
S5	Normal treatment, 1995	10.7 (35)	44.0	1.53

projects in five different states using a Saab Friction Tester with a smooth test tire. The average increase of the friction measurements immediately after grinding was 90 percent. An average reduction of 1.2 m/km (75 in./mile) in roughness was also measured with a Mays Ridemeter. Early studies by Farnsworth in California (*59*) and Walters in Louisiana (*60*) reported significant reduction in accidents on both wet and dry surfaces. A 1998 Wisconsin study (*61*) compared the accident rates on ground and tined surfaces. The results are given in Table 6.

TABLE 6
COMPARISON OF ACCIDENT RATES ON TINED AND DIAMOND GROUND PAVEMENTS (*61*)

Pavement Conditions	Accidents per 100 million vehicle-km		Reduction on Ground Pavements (%)
	Ground	Tined	
Dry	65	112	42
Wet	99	170	42
Snow/Ice	173	205	16

Diamond ground grooves are much smaller and more closely spaced than saw cut grooving: 5- to 6-mm (0.2- to 0.24-in.) spacing, 1.6-mm (0.06-in.) typical depth, 2.3- to 3.8-mm (0.09- to 0.15-in.) width, and 1.5- to 3.3-mm (0.06 to 0.13-in.) land area. Diamond grinding can remove as much as 19 mm (0.75 in.) of the surface when used to improve roughness and rutting (*62*). One disadvantage is that if a significant depth of the surface is removed, the coarse aggregate will become exposed. Usually the coarse aggregate

has poor polishing resistance, and unless a good quality coarse aggregate is used the microtexture may, in time, become inadequate for good skid resistance.

ECONOMIC CONSIDERATIONS

Table B16 summarizes the responses to the section of the questionnaire that addressed the economic concerns of material costs and litigation.

Litigation

Of the 11 states that felt that their wet weather friction program was adequate for litigation purposes, 3 reported that they felt it was not necessary to have a wet weather friction program, whereas 8 were satisfied with their present program. Two states that do not have programs also reported that the situation was inadequate.

Material Costs

Seven states reported that they consider the cost of aggregates in their design, whereas five do not. Responses included: "some," "slight," "minor," and "minimal."

Incentive Programs

None of the four states that stipulate minimum friction requirements reported offering incentives for producing pavements with higher than the minimum friction levels. Quebec, France, Slovakia, and Slovenia were the only agencies reporting incentive programs.

CHAPTER FIVE

CONCLUSIONS

To determine current practices, a questionnaire was sent to state agencies in the United States, provinces in Canada, and to countries in Europe and Asia. In the United States, the ASTM locked wheel method is used by all but one of the responding state agencies; whereas in other countries, fixed slip and side force methods are predominantly used.

The side force and fixed slip methods measure friction at low slip speeds and their results depend largely on microtexture, even when a smooth test tire is used. Locked wheel tests with a ribbed or patterned tire measure friction at high slip speeds, but are relatively insensitive to the level of macrotexture due to the water escaping from the footprint through the channels provided by the ribs. For these cases it would be helpful to establish a criterion for macrotexture in addition to the friction values reported. The use of smooth test tires at high slip speeds emphasizes the importance of providing good levels of macrotexture. Ideally, both friction and macrotexture can be measured to assess pavement frictional characteristics. Ten state agencies and Puerto Rico have established intervention levels for friction, and 12 agencies outside the United States reported having intervention levels.

Few states measure macrotexture in their routine surveys, whereas outside the United States, approximately 40 percent of the respondents measure macrotexture routinely. One state uses macrotexture in pavement management and a second state employs it in construction specifications. The incorporation of macrotexture measuring equipment onto pavement friction testers is increasing in the United States.

Of the 43 questionnaire responses from state agencies in the United States, 27 reported measuring friction with the ASTM locked wheel method of testing and use the ASTM standard ribbed tire exclusively, whereas five agencies measure with the locked wheel method and use the ASTM standard smooth tire exclusively. Seven states use the locked wheel method and test with both the smooth and ribbed test tires.

Of the 21 non-U.S. agencies that reported measuring wet pavement friction, 17 use a smooth test tire for fixed slip or side force friction measurements.

The International Friction Index (IFI) requires simultaneous measurement of friction and macrotexture. With the technology currently available it is feasible to measure macrotexture at highway speeds and, therefore, a texture measuring system can be fitted to a friction tester. This is done routinely in several European countries and several states, including Virginia, Texas, and Missouri, have mounted texture-measuring systems on their friction testers.

The questionnaire included a request to rank the relative importance given to various considerations in pavement design. The rank order was the same for responses from U.S. agencies and non-U.S. agencies. The overall average combined ratings (where 1 is very important and 3 is relatively unimportant) were: durability 1.2, friction 1.3, splash and spray 1.9, exterior noise 2.3, in-vehicle noise 2.4, rolling resistance 2.7, and tire wear 2.8. Durability is the most important consideration, but friction ranked only slightly below durability. Pavement roughness is often used as the criterion for resurfacing, but fatalities, injuries, and the resulting litigation seldom involve pavement roughness. It had been expected that noise would rank higher in importance than it did.

In asphalt construction, porous asphalt and stone mastic asphalt provide superior frictional characteristics. For portland cement concrete, transverse tining is preferred but longitudinal tining is used, particularly where tire pavement noise is an issue. For surface restoration of asphalt concrete pavements, seal coats and longer lasting microsurfaces are used to improve skid resistance. For portland cement concrete, saw cut grooving, shot peening, and diamond grinding all provide good skid resistance, but when noise is a concern, the choice of shot peening is preferred.

States responding to the question regarding the adequacy of their wet weather friction program were satisfied (11 of 14) that it was adequate for defense in litigation. Two of the state agencies that were dissatisfied reported that they do not have a wet weather safety program. When asked about the added cost of superior aggregates, seven state agencies responded that it was a consideration, but most agencies are satisfied that the added costs are not great or are justifiable. Because friction was ranked only slightly behind durability as the most important design consideration, it is suggested that more emphasis be placed on its use in the design process as well as in pavement management. Routine surveys may want to include macrotexture measurements to fully characterize the friction

characteristics. This could also lead to the implementation of the IFI, which would harmonize measurements made at different speeds and permit the use of a wider range of devices. In particular, it would allow for increased use of friction testers that measure continuously, such as the fixed slip and side force devices.

As more agencies include macrotexture measurements along with friction in their routine surveys, it will be possible to implement the IFI. To assure stability of the IFI, periodic calibration of the systems to the IFI will be necessary. Research is needed to extend the current calibration procedures to include the IFI.

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NOMENCLATURE

ARFMS	Area Reference Friction Measurement System
ASTM	American Society for Testing and Materials
BPN	Value reported for measurement by the BPT (British Pendulum Number)
BPT	British Portable Tester
C	Shape factor in the Rado Model
CEN	Council for European Normalization
CRFI	Canadian Runway Friction Index
DWW	Dienst Weg- en Waterbouwkunde Friction Tester (NL)
ETD	Estimate of MTD from MPD (Estimated Texture Depth)
F	Friction force
$F(S)$	Value at slip speed S of the PIARC Model
$F60$	Friction number of the IFI
IFI	International Friction Index
IMAG	Instrument de Mesure Automatique de Glissance
IRFI	International Runway Friction Index
IRV	International Reference Vehicle (Friction Tester for IRFI)
ISO	International Standards Organization
LTPP	Long-term pavement performance
MPD	Mean Profile Depth as determined by ASTM or ISO standard
MTD	Mean Texture Depth by the volumetric method
mTX	A microtexture measurement
MTX	A macrotexture measurement
N	Normal load on the test tire
NASA	National Aeronautics and Space Administration
OFT	Outflow time (s)
PNG	Percent normalized gradient = slope of the friction-speed curve divided by the local friction multiplied by 100
r	Rolling radius of the test tire
RFT	Runway Friction Tester
RMS	Root mean square of profile height
S	Slip speed = slip ratio times test speed = % slip times test speed divided by 100. Velocity of the test tire surface relative to the pavement surface
SCRIM	Sideway-Force Coefficient Routine Investigation Machine
SCRIMTEX	SCRIM with macrotexture measurement instrumentation
SFT	Surface (Saab) Friction Tester
Slip Ratio	$(V - r\omega)/V$
SN	Skid number = $100(F/N)$
SN(XX)R	Skid number at xx km/h with the ribbed test tire
SN(XX)S	Skid number at xx km/h with the smooth test tire
SNXXR	Skid number at xx mph with the ribbed test tire
SNXXS	Skid number at xx mph with the smooth test tire
S_p	Speed constant of the IFI
S_{peak}	Slip speed at which the peak friction occurs
V	Vehicle speed (test speed)
% Slip	Slip ratio times 100
μ	Tire pavement friction = F/N
μ_0	Zero intercept of the Penn State Friction Model
μ_{peak}	Peak friction
ω	Angular velocity of the test tire

APPENDIX A

Questionnaire

Two versions of the questionnaire were prepared. Both versions asked the same questions, but some differences in terminology were used for North American and non-North American experts. Responses to the survey were received from the following agencies:

Alaska	Arizona	Arkansas
California	Colorado	Connecticut
Florida	Georgia	Hawaii
Idaho	Illinois	Kansas
Kentucky	Louisiana	Maine
Maryland	Massachusetts	Michigan
Minnesota	Mississippi	Missouri
Montana	Nebraska	New Hampshire
New Jersey	New Mexico	New York
North Carolina	Oklahoma	Oregon
Pennsylvania	Rhode Island	South Carolina
South Dakota	Texas	Utah
Vermont	Virginia	Washington
Wisconsin	Wyoming	Puerto Rico
NASA		
Alberta	British Columbia	Manitoba
New Brunswick	Newfoundland	Nova Scotia
Ontario	Quebec	Saskatchewan
Australia–South Australia	Australia–Victoria	Australia–New South Wales
Denmark	France	Hungary
Iran	Japan Highways	Japan–Nippon Hodo
Morocco	Netherlands, The	New Zealand
Poland	Portugal	Slovakia Bratislava University
Slovakia Road Administration	Slovenia	Switzerland
United Kingdom		

Survey Form for North America

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Project 20-5, Topic 30-11

Design and Testing of Pavement Friction Characteristics

QUESTIONNAIRE

PURPOSE OF THIS SURVEY

This is a survey to collect information on issues pertaining to wet pavement friction characteristics, including methods of testing and monitoring, aggregate and mix design properties, and the evaluation of pavement friction properties after construction, rehabilitation or maintenance.

Agency: ________________________________

Name of respondent: ________________________

Title: __________________________________

Phone: ______________ Fax: ______________ e-mail: ______________

PLEASE RETURN THIS QUESTIONNAIRE AND SUPPORTING DOCUMENTS BY JUNE 15, 1999 TO:

John Jewett Henry
P.O. Box 84
Huntingdon, PA 16652-0084

For questions and/or discussion, please contact him by:

e-mail: jjhenry123@aol.com
by FAX: 1-814-643-6428
or by Phone: 1-814-643-4474

I. FIELD TESTING—FRICTION (SKID RESISTANCE)

1. Does your agency conduct regular surveys of the friction of your network?

YES ______ NO _____

If yes, please indicate what percentage of each system is tested on an annual, biennial, or other basis:

	Annual	Biennial	Other
Interstate	_______	________	__________
Primary	_______	________	__________
Secondary	_______	________	__________
Local Roads	_______	________	__________
Airports	_______	________	__________

COMMENTS:

2. What type of friction measuring equipment does your agency use?

Type: __________________ Manufacturer: __________________
ASTM E-274 Trailer ______ __________________
Other: ____

COMMENTS:

3. What type of test tire do you use for the surveys?

ASTM E-524 (smooth) _______
ASTM E-501 (ribbed) _______
Other ____________________________

COMMENTS:

4. What test speeds does your agency use for surveys? _______________

COMMENTS:

5. What is the spatial frequency and sample length of your survey testing?

_____ samples per (km) (mile) __________ m sample length
varies (explain): ________________________________

Where are the measurements taken?

Driving lane _____ Passing lane _____
Right wheel path _____ Left wheel path _____

COMMENTS:

6. Please list any additional measurements such as temperature, texture, etc., that you make when performing friction measurements.

7. Do you calibrate your friction measuring equipment?

In-house _______ Frequency ___________
At a calibration center _______ Frequency ____________ Location ___________

COMMENTS:

8. Do you report the raw data or data as adjusted by the calibration equation?

Raw data _______
Adjusted data _______
Both _______

COMMENTS:

9. Do you adjust for temperature, seasonal, and speed variations?
If so, what algorithms do you use?
Temperature:
Seasonal variations:
Speed:

COMMENTS:

10. Does your agency measure friction at accident locations?

Yes ____ No _____

If yes, what type of test(s) do you use?

COMMENTS:

11. Do you measure friction on newly placed or rehabilitated surfaces?

Newly placed _______
Rehabilitated _______
Maintenance treatments _______

COMMENTS:

12. Have you experienced unacceptable friction on newly placed surfaces?

Never _____
Rarely _____
Occasionally ______
Frequently _______

COMMENTS:

13. What type of tire do you use for evaluating newly placed surfaces?

E-524 (smooth) _________
E-501 (ribbed) _________
Other __________________________

COMMENTS:

14. Do you perform any friction testing on winter contaminated (snow, ice, etc.) pavements?

Yes _____ No ______

If yes: what tire type do you use? ________________

How often are these measurements performed? ___________

Are these measurements for winter maintenance? _______
for research only? _______

COMMENTS:

15. Do you use friction data in your Pavement Management System?

Yes_____ No _____

If yes, how is it used?:

II. FIELD TESTING—TEXTURE

1. Does your agency measure macrotexture of surfaces in your network?

Yes ____ No ______

If yes, under which applications do you measure macrotexture?

Routine surveys for maintenance decisions _______
Accident investigations ________
Newly placed surfaces (construction) _________
Rehabilitated surfaces (maintenance) _________

COMMENTS:

2. What macrotexture parameter do you report?

E-865 (sandpatch) Texture Depth _________
ISO Mean Profile Depth ___________
ASTM E-1845 Mean Profile Depth _________
Other _____________________________________

COMMENTS:

3. Where are texture measurements taken?

4. Do you use texture data in your Pavement Management System?

Yes_____ No _____

If yes, how is it used?:

5. If you are not currently measuring pavement texture, do you plan to do so in the future for:

Purpose	When	Currently Use
Research ____	_____	_____
Accident Analysis ______	_____	_____
Pavement Condition Monitoring _____	_____	_____
Construction Acceptance _____	_____	_____
Noise Evaluations ______	_____	_____
Other (Please specify)_____________	_____	_____

COMMENTS:

III. FRICTION AND MACROTEXTURE LEVEL REQUIREMENTS

1. Do you specify target and/or macrotexture levels (intervention levels) of pavements in your network?

Yes______ No ______

If yes, what are the target levels for:

	Friction	Texture
Interstate	________	________
Primary	________	________
Secondary	________	________
Local Roads	________	________
Airport Runways	________	________

COMMENTS:

2. How were these target levels developed (i.e., crash data, experience, or other)?

3. Do you take into consideration the highway characteristics such as curves, number of intersections, grade, operating speeds?

Yes ______ No _______

COMMENTS:

4. Do you have information that would be useful in relating friction and/or texture characteristics to wet and total pavement accident (crash) rates?

Yes ______ No ______

COMMENTS:

5. Do you specify a required friction and/or texture levels for newly placed or rehabilitated pavements or maintenance treatment?

Yes ______ No ______

COMMENTS:

IV. PAVEMENT DESIGN FOR SKID RESISTANCE

1. Are your agency's pavement mix design specifications based on friction considerations?

Yes _______ No _______

COMMENTS:

2. Do you specify texture requirements in your asphalt concrete pavement design?

Yes _______ No _______

If yes:

Directly _________
Indirectly by specifying coarse aggregate gradation ________
Other _________

COMMENTS:

3. Are the specifications compromised by considerations of noise and/or ride quality?

Yes ______ No _______

COMMENTS:

4. Do you specify aggregate properties to maintain:

Microtexture (non-polishing aggregate) ________________
Macrotexture (aggregate gradation and wear) ___________
Other aggregate characteristics ______________________

COMMENTS:

5. What types of texture does your agency specify for newly placed Portland Cement Concrete pavements?

Transverse Tining	______	Tine spacing _______ mm
Longitudinal Tining	______	Tine spacing _______ mm
Burlap Drag only	______	
Transverse Grooving	______	Groove width _______ mm
Longitudinal Grooving	______	Groove width _______ mm
Diamond Grinding	______	
Other ___________________		

COMMENTS:

6. Does your agency require non-polishing properties for the coarse aggregate in Portland Cement Concrete?

   Yes _____ No _____

   COMMENTS:

7. Does your agency specify properties of the fine aggregate in Portland Cement Concrete? If yes, please comment.

   Yes _____ No _____

   COMMENTS:

8. Do you use porous friction courses?

   Yes _____ No ______

   If yes, what are the void requirements? ________
   What is the thickness of your porous friction courses? _________
   What is the typical service life? _________

   COMMENTS:

9. Please attach copies of specifications that your agency uses for skid resistant pavements. Thank you.

10. How does your agency evaluate the skid resistance properties of a mix design in the laboratory?

    British Portable Tester ______
    DF Tester ________
    Other ____________________

    COMMENTS:

11. How does your agency evaluate the polish resistance of aggregates?

    British Wheel _________
    LA Abrasion __________
    Penn State Reciprocating Polisher ________
    Other _________________________________

    COMMENTS:

12. Please rate the importance of the following considerations of pavement performance on a scale from 1 (very important) to 3 (relatively unimportant).

Noise (Interior)	_____
Noise (Exterior)	_____
Splash-and-Spray	_____
Wet Pavement Friction	_____
Durability (Pavement expected life)	_____
Rolling Resistance	_____
Tire wear	_____
Other	_____

COMMENTS:

V. PAVEMENT REHABILITATION FOR SKID RESISTANCE

1. What types of pavement rehabilitation strategies do you use for improving pavement friction?

	Asphalt	Portland Cement	Porous Friction Courses
Longitudinal Grooving	_____	_____	_____
Transverse Grooving	_____	_____	_____
Microsurface applications	_____	_____	_____
Abrasion (Skidabrader)	_____	_____	_____
Seal Coat	_____	_____	_____
Other	_____	_____	_____

COMMENTS:

VI. LITIGATION AND ECONOMIC CONSIDERATIONS

1. Does your agency have a wet weather friction program?

Yes _____ No _____

If yes, a copy would be appreciated.

2. Do you feel that the wet weather friction program of your agency adequately addresses its litigation needs?

Yes _____ No _____

COMMENTS:

3. What are the economic ramifications of specifying aggregates that provide good friction in your pavement design?

COMMENTS:

4. Do you provide incentives for higher than minimum friction levels?

Yes _____ No _____

APPENDIX B

Responses to Survey Questionnaire

TABLE B1
FRICTION MEASURING DEVICES IN USE BY AGENCIES

Agency	Tester Type	Test Tire	Test Speed (km/h)
	United States		
Alaska	ASTM E-274 Trailer	E-501	65
Arizona	MuMeter	MuMeter	65
Arkansas	ASTM E-274 Trailer	E-501	65
California	ASTM E-274 Trailer	E-501	Posted speed
Colorado	ASTM E-274 Trailer	E-501 & E-524	65
Connecticut	ASTM E-274 Trailer	E-501	65
Florida	ASTM E-274 Trailer	E-501	65
Georgia	ASTM E-274 Trailer	E-501 & E-524	65
Hawaii	ASTM E-274 Trailer	E-501	65
Idaho	ASTM E-274 Trailer	E-524	65
Illinois	ASTM E-274 Trailer	E-501 & E-524	65
Kansas	ASTM E-274 Trailer	E-501	65 & 90
Kentucky	ASTM E-274 Trailer	E-501	65
Louisiana	ASTM E-274 Trailer	E-501 & E-524	65
Maine	ASTM E-274 Trailer	E-501	65
Maryland	ASTM E-274 Trailer	E-501	65
Michigan	ASTM E-274 Trailer	E-501	35 & 65
Minnesota	ASTM E-274 Trailer	E-501 & E-524	65
Mississippi	ASTM E-274 Trailer	E-501	65
Missouri	ASTM E-274 Trailer	E-524	65
Montana	ASTM E-274 Trailer	E-501	65
Nebraska	ASTM E-274 Trailer	E-501	65 & 80
New Jersey	ASTM E-274 Trailer	E-501	65 & 80
New Mexico	ASTM E-274 Trailer	E-501	80
New York	ASTM E-274 Trailer	E-501	65
North Carolina	ASTM E-274 Trailer	E-501 & E-524	65
Oklahoma	ASTM E-274 Trailer	E-501	40–50
Oregon	ASTM E-274 Trailer	E-501	65
Pennsylvania	ASTM E-274 Trailer	E-501 & E-524	65
Rhode Island	ASTM E-274 Trailer	E-501	65
South Carolina	ASTM E-274 Trailer	E-501	65
South Dakota	ASTM E-274 Trailer	E-524	65
Texas	ASTM E-274 Trailer	E-524	80
Utah	ASTM E-274 Trailer	E-501	65
Vermont	ASTM E-274 Trailer	E-501	40 & 65
Virginia	ASTM E-274 Trailer	E-524	65
Washington	ASTM E-274 Trailer	E-501	65
Wisconsin	ASTM E-274 Trailer	E-501	65
Wyoming	ASTM E-274 Trailer	E-501	75
Puerto Rico	ASTM E-274 Trailer	E-501	65
NASA	DBV and others	Various	0–100
	Non-United States		
New Brunswick	Griptester & SFT	Griptester & SFT	65
Newfoundland	Griptester	Griptester	65
Nova Scotia	Griptester & BPT	Griptester	Not reported
Ontario	ASTM E-274 Trailer	ASTM E-501	80–100
Quebec	SCRIM & ROAR	Avon & ASTM E-1551	60
Saskatchewan	ASTM E-274 Trailer	ASTM E-501	80
South Australia	Griptester & BPT	Griptester	50
Victoria	SCRIM & BPT	Avon	20 & 50
New South Wales	SCRIM	Avon	20 & 50
Denmark	ROAR	ASTM E-1551	60
France	SCRIM	Avon	60

TABLE B1 (*continued*)

Hungary	SCRIM	Avon	50
Japan	Locked wheel tester	165 SR13	60–80
Netherlands, The	DWW tester	PIARC Smooth	50
New Zealand	SCRIM	Avon	50
Poland	Polish SRT-3	Patterned	60
Portugal	SCRIM	PIARC Smooth	50
Slovakia	BV-11	Trelleborg T49	Not reported
Slovenia	SCRIMTEX	Avon	40–80
Switzerland	BV-8 & SRM	PIARC Ribbed	40, 60 & 80
United Kingdom	SCRIM	Avon	50 & 20

Note: The test tires used outside the United States in this list are smooth treaded tires, with the exception of the ASTM E-501, PIARC Ribbed, and the Japanese 165 SR13 tires. DBV = diagonal braked vehicle; SFT = surface friction tester; BPT = British Portable Tester; SCRIM = Sideway-Force Coefficient Routine Investigation Machine; ROAR = Road Analyzer and Recorder; DWW = Dienst weg- en Waterbouwkunde friction tester; PIARC = Permanent International Association of Road Congresses; SCRIMTEX = SCRIM with macrotexture measurement instrumentation; SRM = Stuttgarter Reibungsmesser.

TABLE B2

CALIBRATION TYPE AND FREQUENCY

Agency	Where	Frequency
	United States	
Arizona	In-house*	
Arkansas	In-house	Daily
California	In-house	Every 6 months
Colorado	Calibration center	Every 4–5 years
Connecticut	Calibration center	Every 2 years
Florida	Calibration center	
Georgia	In-house	Yearly
Hawaii	Calibration center	Every 4–5 years
Idaho	Calibration center	Every 3 years
Illinois	In-house	Monthly
Kansas	In-house	Yearly
Kentucky	Calibration center	Every 3 years
Louisiana	Calibration center	As needed
Maine	In-house	Yearly
Maryland	In-house	Every 4–6 weeks
Michigan	Calibration center	Yearly
Minnesota	Calibration center	Varies
Mississippi	Calibration center	Every 3 years
Missouri	Calibration center	As needed
Montana	Calibration center	As needed
Nebraska	Calibration center	Every 3 years
New Jersey	Calibration center	Yearly
New Mexico	Calibration center	Yearly
New York	Calibration center	Every 2 years
North Carolina	Calibration center	Every 2 years
Oklahoma	Calibration center	Yearly
Oregon	Calibration center	Every 3 years
Pennsylvania	Calibration center	Every 2 years
Rhode Island	Calibration center	Yearly
South Carolina	Calibration center	Yearly
South Dakota	Calibration center	As needed
Texas	Calibration center	Yearly
Utah	Calibration center	Yearly
Virginia	Calibration center	Yearly
Washington	Calibration center	Every 2 years
Wisconsin	Calibration center	Every 4–5 years
Wyoming	Calibration center	Every 2 years
Puerto Rico	In-house	
NASA	In-house	4 per year

TABLE B2 (*continued*)

	Non-United States	
New Brunswick	In-house	Not reported
Ontario	Calibration center	Every 8 years
Quebec	In-house	Monthly
Saskatchewan	In-house	Yearly
South Australia	In-house	Monthly
Australia–Victoria	In-house	Daily
New South Wales	In-house	Weekly
Denmark	By manufacturer	As needed
France	In-house	Twice Yearly
Hungary	In-house	Every 2 weeks
Japan	In-house	Yearly
Netherlands, The	In-house	Every 6 months
New Zealand	TRRL	Not reported
Poland	In-house	Weekly
Portugal	Calibration center	Not reported
Slovakia Road	AEC Sweden	Every 3 years
Slovakia Bratislava	In-house	Not reported
Slovenia	In-house	Yearly
Switzerland	Institute of Zurich	Yearly
United Kingdom	Calibration center	Yearly

*In-house calibrations are usually component calibrations or routine setup calibrations.

TABLE B3

USE OF FRICTION MEASUREMENTS

Agency	Management	Restoration	New Construction	Accidents	Snow/Ice
		United States			
Alaska	Y	N	N	Y	N
Arizona	Y	N	N	N	N
Arkansas	Y	Y	Y	Y	N
California	Y	Y	Y	Y	N
Colorado	N	N	N	N	N
Connecticut	Y	N	N	Y	N
Florida	Y	Y	Y	Y	N
Georgia	Y			Y	N
Hawaii	N				N
Idaho	Y	Some	Some	N	N
Illinois	N	Y	Y	Y	N
Kansas	N	1 year old	1 year old	N	N
Kentucky	Y	N	N	Y	N
Louisiana	Y	Y	Y	Y	N
Maine	N	Y	Y	Y	N
Maryland	Y	Y	Y	Y	N
Massachusetts	N				
Michigan	Y	Special	Special	Y	Y
Minnesota	N	Y	Y	N	Rcscarch
Mississippi	Y	Y	Y	Y	N
Missouri	Y	Y	Y	N	N
Montana	N	Y	Y	Y	N
Nebraska	Y	Y	Y	N	Y
New Hampshire	N			N	N
New Jersey	Y	Y	Y	Y	Y
New Mexico	Y	N	N	N	N
New York	N	Y	Y	Y	N
North Carolina	Y	Y	Y	By request	N
Oklahoma	Y	By request	By request	Y	N
Oregon	Y	Y	Y	Y	N
Pennsylvania	Y			Y	N
Rhode Island	Y			N	N
South Carolina	N	N	N	Y	N
South Dakota	N	N	N	N	N
Texas	Y	N	N	Y	N
Utah	N	Y	Y	N	N
Vermont	N	N	Some	Y	N
Virginia	Y	N	N	Y	N
Washington	Y	Y	Y	N	Y
Wisconsin	N	N	N	Y	N
Wyoming	Y	Y	Y	N	N
Puerto Rico	Y	N	Y	Y	N
NASA	Y	Y	Y	Y	Y

TABLE B3 (*continued*)

			Non-United States		
Alberta	N			N	N
British Columbia	N			N	N
Denmark	Y	Y	Y	N	N
France	Y	Sometimes	Sometimes	Y	Y
Hungary	N	Y	Y	N	N
Japan	N	Y	Y	N	Y
Manitoba	N				
Netherlands, The	Y	Y	Y	N	Y
New Brunswick	N	N	N	N	N
Newfoundland	N			N	N
New Zealand	Y	N	N	Y	N
New South Wales	Y	N	N	By request	N
Nova Scotia	N			Y	
Ontario	N	Y	Y		Y
Poland	Y	N	N	N	N
Portugal	N	Y	Y	N	N
Quebec	Y	Y	Y	Y	N
Saskatchewan	N	N	N	N	Y
Slovakia	Y	Y	Y	Y	Y
Slovenia	N	N	At 6 months	Sometimes	N
South Australia	Y	Y	Y	Y	N
Switzerland	N	Y	Y	Y	Research
United Kingdom	Y	N	N	N	N
Victoria	N	Y	Y	Y	N

Note: N = no; Y = yes.

TABLE B4

FREQUENCY OF SKID TESTING IN REGULAR SURVEYS

Agency	Interstate/ Motorways	Primary	Secondary
	United States		
Arizona	2	2	2
Arkansas	1	2	2
California	1	1	1
Florida	2	4–5	
Georgia	2	5	5
Idaho	1	2	2
Kansas	1	2	
Louisiana	3	4	
Maryland	1	1	1
Michigan	3	3	3
Missouri	2	2	
Nebraska	1	3	3
New Jersey	2	2	2
New Mexico	1	2	2
North Carolina	2	2	
Oklahoma	1	1	1
Oregon	2	2	2
Rhode Island	1	2	
South Carolina	1	2	As needed
Texas	2	4	4
Utah	2	2	2
Virginia	3	4	
Washington	1	2	2
Wyoming	1	2	2
Puerto Rico		Not specified	
	Non-United States		
Denmark	1	1	
France	5	3	5
Hungary	1	2	5
Japan	1–3	2	
Netherlands, The	1	1	Private companies
New South Wales	2	2	2
New Zealand	1	1	1
Ontario	<5%/year	<5%/year	
Poland	1	1	3
Quebec	Random sampling		
Slovakia		1–2	
South Australia	<5%/year	<5%/year	
United Kingdom	3	3	

Note: The frequency is the number of years between tests on a pavement.

TABLE B5

INTERVENTION LEVELS FOR FRICTION

Agency	Interstate/ Motorway	Primary	Secondary	Local
		United States		
Arizona	34 (MuMeter)	34 (MuMeter)	34 (MuMeter)	
Idaho	SN40S > 30	SN40S > 30	SN40S > 30	
Illinois	SN40R > 30	SN40R > 30	SN40R > 30	
Kentucky	SN40R > 28	SN40R > 25	SN40R > 25	SN40R > 25
New York	SN40R > 32	SN40R > 32	SN40R > 32	SN40R > 32
South Carolina	SN40R > 41	SN40R > 37	SN40R > 37	
Texas	SN40R > 30	SN40R > 26	SN40R > 22	
Utah	SN40R > 30–35	SN40R > 35	SN40R > 35	
Washington	SN40R > 30	SN40R > 30	SN40R > 30	SN40R > 30
Wyoming	SN40R > 35	SN40R > 35	SN40R > 35	
Puerto Rico	SN40R > 40	SN40R > 40		
		Non-United States		
Denmark	Speed < 80 km/h; μ = 0.4; Speed > 80: μ = 0.5 at 60 km/h			
Hungary	SCRIM > 0.50	SCRIM > 0.40	SCRIM > 0.33	
Japan Highways	Friction > 0.25			
Netherlands, The	DWW > 38	DWW > 38		
New South Wales	Varies (see Guidelines): SCRIM > 0.30–0.55			
New Zealand	SCRIM > 0.55 on event sites, 35 for no-event sites			
Poland	"Units not comparable with US standards"			
Quebec	SCRIM > 70%	SCRIM > 70%	SCRIM > 55%	SCRIM > 40%
South Australia	BPN > 45	BPN > 45	BPN > 45	BPN > 40
Switzerland	Same as for Construction and Rehabilitation (see Table 6)			
United Kingdom	Investigatory levels (*23*) (see Note)			
Victoria	Depends on conditions: SCRIM > 0.35–.55			

Note: SCRIM = Sideway-Force Coefficient Routine Investigation Machine; DWW = Dienst weg- en Waterbouwkunde friction tester; BPN = British Pendulum Numbers.

United Kingdom investigatory levels for SCRIM at 50 km/h (*23*)

Site description	Level
Motorway (mainline)	0.35
Dual carriageway (all purpose) non-event sections	0.35
Single carriageway non-event sections	0.40
Dual carriageway (all purpose)—minor junctions	0.40
Single carriageway—minor junctions	0.45
Approaches to and across major junctions (all limbs)	0.45
Gradient 5 to 10% longer than 50 m, dual (downhill only)	0.45
Gradient 5 to 10% longer than 50 m, single (uphill and downhill)	0.45
Bend (not subject to 40 mph or lower speed limit) radius < 250 m	0.45
Gradient steeper than 10%, longer than 50 m dual (downhill only)	0.50
Gradient steeper than 10%, longer than 50 m single (uphill and downhill)	0.50
Approach to roundabout	0.55
Approach to traffic signals, pedestrian crossings, railway level crossings	0.55
United Kingdom investigatory levels for SCRIM at 20 km/h	
Roundabout	0.55
Bend (not subject to 40 mph or lower speed limit) radius < 100 m	0.60

TABLE B6

FRICTION LEVELS FOR CONSTRUCTION AND SURFACE RESTORATION

Agency	Friction Requirement
Maine	SN40R > 35
Minnesota	SN40R > 45; SN40S > 37
Washington	SN40R > 30
Wisconsin	SN40R > 38
Denmark	μ > 0.4–0.5
Hungary	SFC > 0.65 (motorways)
Japan Highways	$\mu_{80} > 0.35$
Netherlands, The	DWW > 52
Quebec	SCRIM > 70%
Switzerland	(See Note)
United Kingdom	Greater than Investigatory (see Table 2)

Note: SCRIM: Sideway-Force Coefficient Routine Investigation Machine; DWW = Dienst Weg- en Waterbouwkunde friction tester.

Switzerland: Using a Skiddometer BV-8 or the Stuttgarter Reibungsmesser

Speed Limit (km/h)	Speed	μ (locked wheel)
≤60	40	0.48
>60 and ≤100	60	0.39
>100	80	0.32

TABLE B7

FREQUENCY AND LOCATION OF SKID TESTING IN THE UNITED STATES

		Lane		Wheel Path	
Agency	Frequency	Driving	Passing	Left	Right
Alaska	2 per mile	X		X	
Arizona	1 per mile	X		X	
Arkansas	2 per mile	X	X	X	
California	1 per mile	X	X	X	X
Colorado	Varies	X		X	
Connecticut	4 per mile	X		X	
Florida	2–3 per mile	X	X	X	
Georgia	2 per mile	X		X	X
Hawaii	2 per mile	X		X	
Idaho	2 per mile	X		X	
Illinois	10 per mile	X		X	X
Kansas	5 per 2 miles	X		X	X
Kentucky	2 per mile	X		X	
Louisiana	(See Note)	X		X	X
Maine	Varies	X		X	X
Maryland	3 per mile	X			
Michigan	2.5 per mile	X	X	X	
Minnesota	Varies	X		X	
Mississippi	2 per mile	X		X	
Missouri	4 per mile	X			X
Montana	Varies	X	X	X	
Nebraska	2 per mile	X		X	
New Jersey	5 per km	X		X	
New Mexico	1 per mile	X			X
New York	10 per mile	X		X	
North Carolina	1 per mile	X		X	
Oklahoma	2 per mile	X		X	X
Oregon	2 per mile	X		X	
Pennsylvania	10 per mile	X		X	
Rhode Island	1–2 per mile	X		X	
South Carolina	3 per mile	X		X	
South Dakota	1 per mile	X		X	
Texas	2 per mile	X		X	
Utah	1 per mile	X		X	
Vermont	2–5 per mile	X	X	X	
Virginia	3–5 per mile	X		X	
Washington	1 per mile	X			X
Wisconsin	10 per site	X		X	
Wyoming	1 per mile	X		X	
Puerto Rico	Varies	X	X		X

Note: Louisiana

Section Length	*Frequency*
0–1 mile	5 per mile
1–3 miles	3 per mile
3–5 miles	2 per mile
>5 miles	1 per mile

TABLE B8

SEASONAL CORRECTION FACTORS

Month	SLA Multiplier	VDOT Reduction (SN)
January	0.86	–3.7
February	0.87	–3.7
March	0.87	–3.1
April	0.88	–1.7
May	0.92	–0.7
June	0.98	–0.3
July	1.00	0.0
August	1.00	0.0
September	0.96	–0.6
October	0.90	–1.7
November	0.87	–3.1
December	0.86	3.7

Note: VDOT = Virginia Department of Transportation; SLA = Slovak Road Administration; SN = skid number.

TABLE B9

USE OF TEXTURE MEASUREMENTS

Purpose	Routine Survey	Accident Analysis	Construction	Rehabilitation	Pavement Management	Method
Louisiana	X					ICC Laser, MTD
Minnesota			X			MTD
Mississippi	X				X	Laser–Contracted
Pennsylvania						MTD
Virginia	X				X	MTD, MPD
NASA	X	X	X	X	X	MTD, MPD, Grease
Denmark						ISO MPD
France	X	X	X	X	X	ETD, ISO MPD
Hungary	X		X	X		RMS (RST-Laser), MTD
Japan Highways			X			SMTD by MTM
Morocco			X	X		MTD
Netherlands, The			X			MTD, ISO MPD
New South Wales		X	X			MTD
New Zealand	X		X			MTD, ISO MPD
Ontario			X			MTD
Portugal			X	X	X	MTD
Quebec	X	X	X	X	X	MTD
Saskatchewan			X			MTD, Visual
Slovakia		X	X	X		MTD
Slovenia	X					ISO MPD
South Australia	X	X	X	X	X	MTD
Switzerland		X				Outflow meter
United Kingdom	X		X	X	X	MTD and SMTD
Victoria	X	X		X	X	MTD

Note: ICC = International Cybernetics Corporation; MTD = Mean Texture Depth; MPD = Mean Profile Depth; ISO = International Standards Organization; ETD = Estimated Texture Depth; RMS = root mean square; RST = Road Surface Tester; MTM = Mini Texture Meter; SMTD = Sandpatch Mean Texture Depth.

TABLE B10

INTERVENTION LEVELS FOR TEXTURE

Road Category	Motorways	Primary	Secondary
Denmark		Collecting data; levels are being developed	
Hungary	RMS < 0.22 mm	RMS < 0.14 mm	RMS < 0.10 mm
New Zealand	MTD < 0.90 mm	MTD < 0.90 mm	MTD < 0.90 mm
Quebec	MTD < 0.60 mm	MTD < 0.60 mm	MTD < 0.60 mm
Slovakia Road		Specified according to design speed	
South Australia	0.4 < MTD < 0.8 mm	0.2 < MTD < 0.4 mm	0.2 < MTD < 0.4 mm
Switzerland		(See Note)	
United Kingdom		Advisory levels	

Note: Switzerland—Using the British Portable Tester and the outflow meter

Speed Limit (km/h)	BPN	OFT
≤60	65	150
>60 and ≤100	65	100
>100	65	50

BPN = British Pendulum Number; OFT = outflow time (s).

TABLE B11

RELATIVE IMPORTANCE OF DESIGN CONSIDERATIONS

Agency	Noise Interior	Noise Exterior	Splash and Spray	Wet Friction	Durability	Rolling Resistance	Tire Wear	Other
United States								
Alaska	3	3	3	2	1	3	1	1-Fatigue, rutting
Arizona	2	2	2	1	1	3	3	
Arkansas	3	3	2	1	1	3	3	
Connecticut	3	2	2	1	1	3	2	1-Drainage
Florida	2	2	1	1	1	1	3	
Georgia	2	2	2	1	1	3	3	
Hawaii	2	2	2	1	1	2	2	
Idaho	3	3	3	1	1	3	3	
Illinois	2	2	2	1	1	3	3	
Kansas	2	2	3	2	1	3	2	
Kentucky	2	2	2	1	1	3	3	
Louisiana	2	3	1	1	1	1	3	
Maine	3	3	3	2	1	3	3	1- Rutting, smoothness
Maryland			1	1	1	3	3	
Massachusetts	1	1	1	1	2	3	3	
Michigan	3	2	2	1	1	3	3	2 - Permeability
Minnesota	1	1	1	1	1	3	2	
Mississippi				2	1		3	
Missouri	2	2	2	1	1	3	3	
Nebraska	2	2	2	2	1	3	3	
New Hampshire	1	1	2	1	1	2	2	
New Jersey	3	3	2	1	1	3	3	
New Mexico	3	3	2	1	1		3	
New York	3	2	2	1	1	3	3	
North Carolina	3	2	2	1	1	3	3	
Oklahoma	2	3	2	1	1	3	3	
Oregon	3	3	3	2	3	1	1	
Pennsylvania	2	2	2	1	1	2	2	
Rhode Island	2.5	2.5	2	1	1	3	3	
South Carolina	3	3	1	1	1	3	3	
Texas	2	2	1	1	1	2	3	
Utah	3	3	1	1	1	3	3	
Vermont		3	2		1		3	
Virginia	3	2	2	1	1	2	3	
Washington	2	2	2	1	1	2	3	
Wisconsin	2	2	3	1	1	3	3	
Wyoming	3	3	2	1	1	3	3	
NASA	2	3	2	1	1	2	1	
Non-United States								
British Columbia	3	3	2	2	1	2	2	
Denmark	3	2	2	1	1	3	3	
France	3	2	1	1	1	2	2	
Hungary	3	2	2	1	1	2	2	
Japan–Nippon Hodo	2	1	1	2	1	3	3	Night visibility
Japan Highways	2	2	1	1	1	2	3	
Netherlands, The	3	1	1	1	1	2	3	
New Brunswick	3	3	2	1	1	2	2	
New South Wales		2	2	1	2			2- Hydroplaning
New Zealand	2	2	2	1	2	2	3	
Nova Scotia					1			
Ontario	3	1	2	1	1	3	3	
Poland	2	2	1	1	2	3	3	
Portugal	2	2.5	1	1	1	3	3	
Quebec	2	3	2	1	1	3	3	
Saskatchewan	3	3	2	1	1	3	3	
Slovakia	3	3	2	1	1	2	3	
Slovenia	2	2		3	3	2	2	
South Australia	3	3	2	2	1			
Switzerland	3	1	1	1	1	3	3	
United Kingdom	3	2	3	1	2	2	3	

Note: 1 = very important; 3 = relatively unimportant. Where no rating is given, a value of 4 was assigned for the purpose of computing an average rating.

TABLE B12

AGGREGATE EVALUATION

Agency	Mixture Evaluation	Aggregate Polishability
United States		
Alaska		LA abrasion
Arizona		LA abrasion
Arkansas		PSU reciprocating
Florida		LA abrasion
Hawaii		LA abrasion
Illinois		Variable speed tester
Kansas		LA abrasion
Kentucky		LA abrasion
Louisiana	BPT	AASHTO T-96
Maryland		Br. Wheel/LA abrasion
Massachusetts		LA abrasion
Michigan		MI wear index
Minnesota		LA abrasion
Mississippi		LA abrasion
Missouri		LA abrasion
Nebraska		LA abrasion
New Jersey	BPT	British wheel
New Mexico		LA abrasion
North Carolina		LA abrasion
Oklahoma		LA abrasion
Oregon		LA abrasion
Pennsylvania	BPT	LA abrasion
Rhode Island		LA abrasion
South Carolina		LA abrasion
Texas		British wheel
Utah	BPT	British wheel
Virginia		LA abrasion
Washington		LA abrasion
Wisconsin		LA abrasion
Wyoming		LA abrasion
Non-United States		
Denmark	BPT	LA abrasion
France	BPT	British wheel
Hungary	BPT	LA abrasion
Japan	BPT & DFT	LA abrasion
Netherlands, The	BPT	LA abrasion
New Brunswick		LA abrasion
New South Wales	BPT	British wheel
New Zealand		British wheel
Ontario	BPT	LA abrasion
Poland		LA abrasion
Portugal	BPT	British wheel
Quebec	BPT & MTD	LA abrasion
Saskatchewan		LA abrasion
Slovakia	BPT & MTD	British wheel
Slovenia	BPT	Br. Wheel/LA abrasion
South Australia		LA abrasion
Switzerland		Br. Wheel/LA abrasion
United Kingdom		British wheel

Note: LA = Los Angeles; PSU = Pennsylvania State University; BPT = British Portable Tester; MI = Michigan; DFT = DFTester; MTD = Mean Texture Depth.

TABLE B13

POROUS ASPHALT FRICTION COURSES

Agency	Void Content (%)	Thickness (mm)	Life (years)
UNITED STATES			
Arizona	16–20	16	10
Connecticut		19	4–15
Florida		13–19	8–10
Georgia	18–20	19–32	10
Idaho	20	19–25	7
Illinois		16–19	5–10
Massachusetts		19–25	10–15
New Mexico	12–15	16	8–15
Oklahoma	20	19	7
Oregon	14–20	50	12–15
South Carolina		25	10–12
South Dakota	7–10	32	10
Texas		13–19	12–15
Vermont		19	10
Wyoming	8–12	19	15–20
CANADA			
Ontario		25	8–12
Quebec	10–20	30	7–10
PACIFIC			
South Australia	20–25	35	12
Victoria	20–25	25–30	12–15
New South Wales	18–23	35–40	
New Zealand	20–25	25–40	8
Japan–Nippon Hodo	20	25	>5
Japan Highways	~20	40	
EUROPE			
Denmark	>20		
France	20	40	8–10
Netherlands, The	>20	50	12
Portugal	3–6	40	
Slovakia	6	40–50	>7
Switzerland	>22		12
United Kingdom	~20	50	8

TABLE B14
TINE SPACING

Agency	Tine Spacing (mm)
United States	
Arizona	13–25
Connecticut	12
Florida	20 maximum
Georgia	Not reported
Hawaii	19
Idaho	12–20
Illinois	20
Kansas	18
Kentucky	Not reported
Louisiana	25
Massachusetts	Not reported
Michigan	13
Mississippi	12
Missouri	Not reported
Nebraska	19
New Jersey	50
New Mexico	Longitudinal
New York	Random
North Carolina	Depth 3–6
Oklahoma	12–15
Oregon	Random
Pennsylvania	10–20
South Carolina	12.7
South Dakota	Not reported
Texas	25
Utah	Random
Virginia	19
Washington	13
Wisconsin	Not reported
Wyoming	20–25
NASA	Not reported
Non-United States	
Japan	30
New Brunswick	10
New South Wales	Not reported
Nova Scotia	Not reported
Ontario	Not reported
Quebec	Longitudinal
Victoria	10–21

TABLE B15
REHABILITATION PRACTICES

	Longitudinal Groove		Transverse Groove		Microsurface		Shot Peen		Seal Coat		Grinding	
Agency	AC	PCC	AC	PCC	AC	PCC	AC	PCC	AC	PCC	AC	PCC
United States												
Alaska									Y			
Arizona		Y					Y					
Colorado		Y		Y	Y				Y			
Connecticut					Y				Y	Y		
Florida												Y
Georgia		Y			Y				Y			Y
Hawaii		Y				Y						
Idaho		Y			Y				Y			
Illinois												
Kansas					Y				Y			
Kentucky		Y			Y							
Louisiana					Y			Y	Y			Y
Maryland					Y		Y					
Massachusetts		Y		Y								
Michigan	Y	Y		Y	Y						Y	Y
Minnesota		Y			Y				Y			
Mississippi		Y		Y	Y			Y	Y			
Missouri		Y			Y				Y			
New Hampshire												
New Jersey					Y	Y	Y	Y				
New Mexico				Y	Y				Y			
New York		Y		Y	Y	Y		Y				
North Carolina		Y			Y				Y			
Oklahoma		Y			Y	Y			Y			
Oregon									Y			
Pennsylvania				Y	Y				Y			
Rhode Island					Y							
South Carolina				Y								
South Dakota									Y			
Texas				Y	Y			Y	Y	Y		
Utah									Y			

TABLE B15 (*continued*)

Virginia	Y	Y		Y	Y	Y			Y		
Washington									Y		Y
Wisconsin	Y	Y	Y	Y							
Wyoming		Y			Y				Y		
NASA	Y	Y	Y	Y	Y	Y	Y	Y			
Non-United States											
Alberta									Y		
British Columbia	Y				Y				Y		
Denmark											
France							Y	Y			
Hungary					Y				Y		
Japan–Nippon	Y			Y	Y	Y			Y	Y	
Japan Highways			Y					Y			
Manitoba					Y				Y		
Netherlands, The		Y		Y				Y	Y		
New South Wales				Y	Y				Y		
New Zealand	Y	Y									
Nova Scotia				Y	Y						
Ontario					Y					Y	Y
Portugal					Y				Y		
Quebec	Y	Y	Y	Y	Y	Y	Y				
Saskatchewan					Y				Y		
Slovakia					Y				Y		
Slovenia							Y				
Switzerland		Y		Y	Y	Y		Y	Y		
United Kingdom				Y	Y	Y	Y	Y	Y	Y	

Note: AC = asphalt concrete; PCC = portland cement concrete; Y = yes.

TABLE B16
ECONOMIC CONSIDERATIONS

Agency	Have a Program for Wet Friction	Adequate for Litigation	Aggregate Cost Considered	Incentive Program
United States				
Alaska	N			
Arizona	Y	Y	Minor	N
Arkansas	N	Y		N
Connecticut	N		N	N
Florida	Y	Y	Some	N
Georgia	Y	Y	N	N
Hawaii	N			N
Idaho	N			N
Illinois	Y	Y	Y	N
Kansas	N			N
Kentucky	N			N
Louisiana	Y		Reduce Tort Liab.	N
Maine	N			
Maryland	N		Y	N
Massachusetts	N			N
Michigan	Y	Y	N	N
Minnesota	N	Y	Some	N
Mississippi	N			N
Missouri	N	N		N
Montana	N			
Nebraska	N			N
New Hampshire	N			N
New Jersey	Y	N	N	N
New Mexico	N		Y	
New York	Y	Y	Y	N
North Carolina	N		N	N
Oklahoma	N		Longer life cycle cost	N
Oregon	N			N
Pennsylvania			Y	N
Rhode Island	N			N

TABLE B16 (*continued*)

South Carolina	N		Some	
South Dakota	N	N		N
Texas	Y	Y	Y	N
Utah				N
Vermont	N			N
Virginia	Y		Y	N
Washington	Y	Y		N
Wisconsin	N	Y	Slight	N
Wyoming	N		Minimal	N
NASA	Y			
Non-United States				
Alberta	N			
British Columbia	N	N	Y	N
Denmark	N	N		N
France			Y	Y
Hungary	N			N
Japan	Y	N	N	N
Netherlands, The	N			N
New Brunswick	N			N
Newfoundland	N			N
New South Wales				N
New Zealand			Y	N
Nova Scotia	N			
Poland	N			
Portugal	N			
Ontario	N	Y	Y	N
Quebec	Y	Y	Y (Justifiable)	Y
Saskatchewan	N		N	N
Slovakia	N	N		Y
Slovenia	N			Y
South Australia	N	N		N
United Kingdom	N			N

Y = yes; N = no.

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