Assessment of LTPP Friction Data

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LTPP

FOREWORD

From a safety standpoint, measures of pavement friction are THE most important indicators of pavement performance. For this reason, friction data are among the performance measures collected at the test sections being monitored for the Long Term Pavement Performance (LTPP) program. This report documents an assessment of the friction data available in the LTPP database as of 1997. Issues addressed include the availability, characteristics, and quality of the friction data, as well as the availability of related data on pavement characteristics. Recommendations for adjustments and refinements to current LTPP friction monitoring procedures are made.

This report will be of interest to those interested in using the LTPP friction data, as well as those involved in monitoring of pavement friction for routine highway agency purposes.

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NOTICE

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16. Abstract

A major goal of the Long-Term Pavement Performance (LTPP) study is the development of recommendations for improving the design and construction of new and rehabilitated pavements to make them longer lasting. As part of the condition monitoring of the LTPP test sections, friction data are being collected on a regular basis at each test site. Friction data collection is the responsibility of the specific highway agency under whose jurisdiction the pavements are located.

The LTPP data collection guidelines for friction data recommend using the ASTM E-274 (AASHTO T242) procedure as the preferred method for obtaining data. The ASTM E-274 procedure uses a locked-wheel skid tester in a trailer assembly. Friction test results are reported as Skid Numbers (SN's).

This report provides an assessment of the availability, characteristics, and quality of the friction data collected as part of the LTPP study. Also, the availability of related pavement characteristics data was assessed. The report also contains recommendations for adjustments and refinements to current procedures for the collection of friction and related data.

The LTPP database provides a one-stop source of reasonably good friction data collected in a systemic manner from a wide range of pavements subjected to a wide range of traffic loading and environmental conditions. The friction data will be of use for analyzing why some pavement surfaces retain good friction characteristics with time and why some surfaces show rapid deterioration in friction over time.

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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1. INTRODUCTION

Introduction

A major goal of the Long-Term Pavement Performance (LTPP) study is the development of recommendations for improving the design and construction of new and rehabilitated pavements to make them longer lasting. This is to be done through research based on pavement condition, design, site, and construction data collected as part of the LTPP program from test sites located throughout North America. As part of the condition monitoring of LTPP test sections, friction data are being collected on a regular basis at each test site. However, unlike other monitored data, friction data collection is the responsibility of the specific highway agency under whose jurisdiction the pavements are located. Also, the LTPP program has not been involved in direct implementation of calibration or other monitoring procedures for the test devices used in the friction data collection process.

The LTPP data collection guidelines for friction data collection recommend using the American Society for Testing and Materials (ASTM) E-274 (American Association of State Highway and Transportation Officials [AASHTO] T242) procedure as the preferred method for obtaining friction data, supplemented with appendix B of Federal Highway Administration (FHWA) Technical Advisory T 5040.17, dated December 23, 1980. The ASTM E-274 procedure uses a locked-wheel skid tester in a trailer assembly. Friction test results are reported as Skid Numbers (SN's). For the 152-m-long LTPP test sections, friction testing was to be performed:

- Once every 2 years and prior to and after placement of a rehabilitation or maintenance treatment.
- At the most appropriate time of the year for the locality (considering seasonal variations) and at the same time of the year for each round of friction testing.
- With a calibrated tester at 65 km/h, or less, if necessary.
- At two locations, one within the beginning 60 m and the other within the end 60 m.
- Along the center of the inner wheelpath (left wheel track for a two-wheel skid trailer).
- When the air temperature was in the range of 4 °C to 40 °C.

For the ASTM E-274 procedure, bias-related information has not been developed as a true value of sliding friction. With respect to precision of the results, ASTM E-274 uses repeatability of the results as a substitute. An acceptable standard deviation of 2 SN units has been obtained from numerous tests conducted using many skid trailers. It has been found that different skid trailers (used as per ASTM E-274) can be expected to measure similar values when the tests are performed by well-trained technicians and the equipment is calibrated regularly.

The following data are maintained in the LTPP database (in data table MON_FRICTION):

1. Test date.
2. Time of testing.
3. Skid number at the beginning location.
4. Skid number at the end location.
5. Test speed.
6. Test method used.
7. Equipment brand (or in-house equipment).
8. Equipment model.
9. State equipment number.
10. Date of last calibration of equipment.
11. Pavement surface type.
12. Air temperature at time of testing.
13. Comments (information relevant to the friction testing, including, if known, the number of days that have passed since the section was last rained on).

It should be noted that ASTM E-274 allows use of either a ribbed tire (as per ASTM E-501) or a smooth (bald) tire (as per ASTM E-524). The use of the two different tire types does result in different measured SN values. However, the LTPP friction data table does not have any provisions for identifying tire type used in the friction testing. ASTM E-274 requires the test speed and tire type to be cited when reporting the measured skid number. The friction test results are reported as follows:

SN (Test Speed) X

where	SN	=	Skid number.
	Test Speed	=	Test speed in km/h.
	X	=	R for ribbed tire or S for smooth tire.

ASTM E-274 also requires the reporting of the wheelpath tested, i.e., whether the inner or outer wheelpath is tested. However, ASTM E-274 does allow reporting of the skid number without qualification, only if the test vehicle was positioned along the inner wheelpath during the test. There is currently no provision in the LTPP database to allow reporting of the wheelpath tested. It is assumed that all LTPP friction testing is conducted along the inner wheelpath as recommended by ASTM E-274.

ASTM E-274 also requires measurement of friction test data for not less than 1 s nor more than 3 s in the wheel lock-up state. At 65 km/h, the test distance could be 20 to 60 m within the beginning and end 60 m of the LTPP test sections. It is likely that the test length varies somewhat from test to test. However, the variation in the measured skid number as a result of the longitudinal variation is likely to be less than the variation between the beginning and end of section test values.

Overall Highlights of Friction Test Data

Friction data used for the data assessment study reported here were obtained from the 7th release of the LTPP data, as of fall 1996. The following are the highlights of the data based on testing at General Pavement Study (GPS) test sections:

- A total of 2,441 measurements were reported.
- 96.8 percent of the 2,441 measurements were obtained using the ASTM E-274 procedure (Locked-Wheel Trailer). In fact, all U.S. agencies used the ASTM E-274 procedure. North Carolina started out with a different procedure, but switched to the ASTM E-274 procedure within a year. The Canadian agencies used several different procedures for friction testing.
- The skid numbers contained in the LTPP database had a high value of 94 and there were about 4.5 percent of the test results with SN values below 30.
- 95 percent of the differences between the beginning and end test values were within 6 SN, while 67 percent of the differences were within 2.5 SN.

Scope of Study

The objective of this study was to examine the availability, characteristics, quality, and potential uses of the friction data being collected as part of the LTPP program. The scope of the study included the following:

- A detailed evaluation of the friction data to determine data coverage in terms of pavement type, test procedure and equipment, and all other information within the database related to friction.
- Evaluation of the quality of the current data and identification of potential sources of variability during the data collection process.
- Establishing which pavement characteristics are required for friction data studies and analysis, but are currently not available in the LTPP database.
- Development of recommendations for adjustments and refinements to current procedures for the collection of friction and related data.

Scope of Report

This report addresses the work done in evaluating the influence of specific factors on variability in the friction test procedure. It also addresses the potential uses of the data currently available. Chapter 2 of this report provides a discussion of past research findings on factors that influence friction on the pavement surface. This is followed in chapter 3 by a detailed overview of the procedure and practices for collecting friction data for the LTPP database. Chapter 4 presents the results of the evaluation of the quality of the friction data and identifies some of the factors that may have contributed to the variability in the data. Chapter 5 identifies friction-related data in the LTPP database and the potential uses of the data. Chapter 6 discusses the usefulness of the LTPP friction data and presents recommendations for improving the current friction test procedure and protocol recommended by the LTPP program.

As part of the friction data assessment study, State and Provincial highway agencies were contacted to clarify information on specific procedures used by the agencies for LTPP-related friction data collection. Summaries of the agencies' practices related to LTPP friction data collection are given in appendix A. Appendix B presents a detailed assessment of the quality of friction data from test sites in the LTPP database. Appendix C presents an overview of friction and friction-related data available in the LTPP database, and appendix D provides a summary portion of FHWA Technical Advisory T 5040.17, Skid Resistance Reduction, relevant to skid-resistance testing. A copy of the proposed ASTM standard on the International Friction Index is given in appendix E.[1]

2. FACTORS THAT INFLUENCE PAVEMENT-TIRE FRICTION

Skid resistance is the force created when a tire that is prevented from rotating slides along the surface of the pavement. ASTM E-867, Standard Terminology Relating to Traveled Surface Characteristics, defines skid resistance as "the ability of the traveled surface to prevent the loss of traction."[(2)] Although skid resistance is often thought of as a pavement property, it is actually a property of both the pavement surface characteristics and the vehicle's tires. In this report, the terms *skid resistance* and *friction* are used interchangeably. Chapter 2 provides a summary of factors that influence pavement-tire friction. This is done to allow the reader a better understanding of issues that need to be considered for a comprehensive assessment of friction test data and the usefulness of the test data in investigating factors that affect loss in friction over time.

Reporting Skid Resistance

Skid resistance is measured and reported by various highway agencies using different test methods. The most common among these are Coefficient of Friction (μ), Skid Number (SN), Friction Number (FN), British Pendulum Number (BPN), and the International Friction Index (IFI). The procedure for obtaining some of these numbers for estimating skid resistance is described as follows.

Coefficient of Friction

The coefficient of friction is defined as follows:[(3)]

$$\mu = \frac{F_R}{W_V}$$

where F_R = Tractive force (horizontal force applied to the test tire at the tire-pavement contact patch).

W_V = Vertical load on test wheel.

Skid Number

Skid number or friction number is defined, according to ASTM E-867, Standard Terminology Relating to Traveled Surface Characteristics, as the number that is used to report the results of a pavement skid test conducted according to ASTM E-274. It is stated mathematically as follows:[(2, 3)]

$$SN = 100 * \frac{F}{W}$$

where F = Tractive force (horizontal force applied to the test tire at the tire-pavement contact patch).

W = Vertical load on test wheel.

FN and SN are often used interchangeably in the literature.

British Pendulum Number

The BPN is the resistance encountered when a pendulum to which a spring-loaded rubber shoe is attached is made to slide over the surface to be tested. BPN (as per ASTM E-303) tests may be conducted in the laboratory or in the field using pavement cores or in situ pavements. The results are reported as BPN to emphasize that they are specific to the tester and not directly equivalent to those from other testers or methods.[2, 3] The BPN is considered to be a surrogate test for determining the microtexture of the pavement surface.

International Friction Number

The IFI is a newly proposed method of standardizing all friction test measurements from various testing devices to a common index. The method covers the calculation of IFI from a measurement of pavement macrotexture and wet pavement friction at any speed. The pavement macrotexture is measured to estimate the speed constant, Sp. The macrotexture may be measured using ASTM E-965, Test Method for Measuring Pavement Macrotexture Depth (MTD) Using a Volumetric Technique, or using ASTM E-1845, Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth (MPD).

The measured friction (FRS, e.g., SN) at some slip speed (test speed), S, is used with the speed constant of the pavement, Sp, to calculate the friction at 60 km/h (FR60), and a linear regression is used on FR60 to determine the calibrated friction value at 60 km/h (F60). The values of F60 and Sp are then reported as the International Friction Index.

The IFI method is in an early stage of development. It has been adopted by Permanent International Association of Road Congresses (PIARC) and a standardization process is in progress in the United States through ASTM. It is expected that an ASTM standard will be available within a year and the standard is expected to gain widespread use in North America as the IFI method does not require any significant changes in equipment or procedures currently in use by most North American highway agencies. The method is compatible with ASTM E-274 and other common methods of friction testing. The method, however, does require collection of macrotexture data using volumetric techniques or using profiling equipment.

The IFI procedure allows harmonization of the commonly used friction measuring equipment and procedures. The F60 and Sp parameters have proven to be able to predict the speed dependence of wet pavement-related measurements of the various types of friction measuring equipment. Also, these two parameters have been found to be reliable predictions of the dependence of wet weather pavement friction on tire slip and vehicle speed. The IFI is a well-defined universal friction measurement that will make results from friction studies applicable in all parts of the world where international friction testing standards have been implemented.[5] Also, with respect to pavement management, the IFI procedure will allow establishment of realistic intervention levels for corrective work. For example, the requirements for a minimum texture level and a minimum friction measurement can be formulated for a particular device. As an example, it might be agreed that the hypothetical intervention (minimum) levels are F60 = 0.30 and Sp = 100 km/h. Then the criteria for minimum values of specific friction and texture devices can be developed.[5]

Pavement Characteristics That Provide Skid Resistance

Skid resistance between a rubber tire and a pavement is the sum of two components—adhesion and hysteresis (deformation losses).[3, 5] Adhesion is the product of the interface shear stress and contact area. Hysteresis is caused by damping losses with the rubber when it is flowing over and around the aggregate particles of the pavement surface. The relative contribution of the two components changes with the texture of the pavement surface.

Pavement texture can be defined as the deviation of the pavement surface from a true planar surface.[2, 5] Pavement texture is usually described at two levels, namely, microtexture and macrotexture, and they are the two primary factors responsible for pavement surface friction.

Microtexture

Microtexture influences the adhesion component of friction most strongly. It is defined according to ASTM E-867 as the deviation of a pavement surface from a true planar surface with characteristic dimensions of a wavelength and amplitude less than 0.5 mm.[2] These small deviations of a pavement surface from a true planar surface constitute the pavement surface microtexture, and they penetrate the small water film that remains between the tire and pavement to establish direct contact with the moving tire. In general, microtexture determines the frictional capabilities of a dry pavement.[5] Adequate microtexture is obtained by using aggregate with a harsh, angular, and rough surface in the pavement surface layer. Microtexture can be diminished when the surface layer is subjected to polishing by traffic, particularly in locations where vehicles frequently brake or accelerate. It is also diminished when the aggregate surface is completely covered by a lubricant. Microtexture varies from harsh to polished, as shown in figure 1.[6]

No direct methods of measuring microtexture are available. The BPN test is used as a surrogate for estimating microtexture of a pavement surface.

Macrotexture

Macrotexture strongly affects the hysteresis component of friction and is defined as the deviation of a pavement surface from true planar surface with characteristic dimensions of wavelength and amplitude from 0.5 mm up to those that no longer affect tire-pavement interaction.[2, 5] Deviations of the pavement surface from the true planar surface are determined chiefly by the shape, height, width, angularity, density, and the arrangement of the aggregate particles embedded in the matrix of the pavement surface course. A perfectly smooth pavement surface will reduce the macrotexture of the pavement and, hence, friction.[3] Macrotexture varies from rough to polished, as shown in figure 1.[6] Macrotexture contributes to the generation of friction in ways other than the damping losses provided when the tire rubber is flowing over and around aggregate particles of the pavement surface.[4] It provides drainage channels through which water at the surface of the pavement can escape quickly, making possible contact between the tread rubber of a vehicle's tires and the pavement surface.

Wet pavement surfaces generally have less tire-pavement friction than dry pavement surfaces.[5] Providing channels for draining excess precipitation from pavement surfaces reduces the period of time of wetness and the possibility of having thick films of water on the surface. The latter condition may result in hydroplaning, a phenomenon by which a tire sliding (or rolling) on a flooded surface buckles in slightly under the impact of the thick water layer that covers the pavement, greatly exaggerating the thickness of the water layer and ensuring the complete separation between the pavement surface and the vehicle tire. It is defined as a phenomenon that occurs when the load-bearing surface of a pneumatic tire is separated from a solid surface by a fluid, usually water.[2] Research indicates that an average texture depth of 0.7 mm is needed to reduce hydroplaning. A minimum texture depth of 0.4 mm has recently been suggested as the terminal value for a transversely tined portland cement concrete (PCC) pavement.

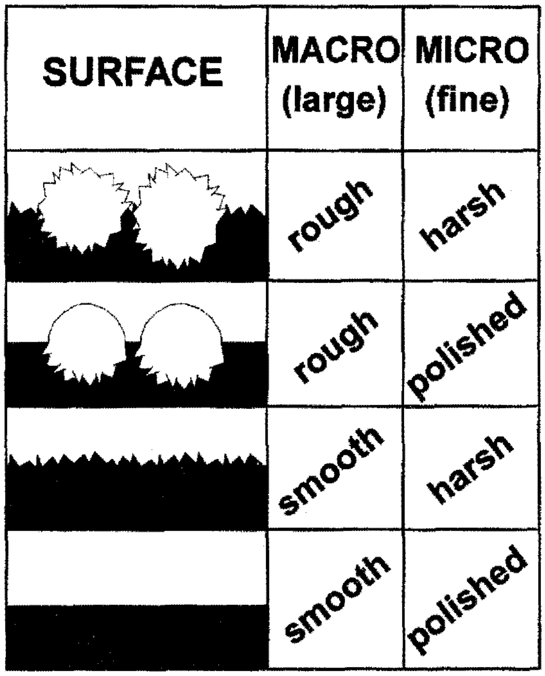

Figure 1. Pavement surface friction, scale of microtexture and macrotexture.[6]

Macrotexture may be determined using volumetric techniques (ASTM E-965) or profiling techniques (ASTM E-1845).

Factors That Result in Loss of Skid Resistance

The initial skid resistance of a pavement is provided by the properties of the surface mix. The two most important factors that provide friction are the microtexture and macrotexture of the pavement surface layer.[3] However, the surface condition of the original pavement changes as the pavement is subjected to the effects of traffic, climate, and aging. This generally results in the loss of surface friction. The factors and processes that cause the deterioration of the pavement microtexture and macrotexture are discussed in the next few sections.

Traffic

As traffic rolls over a pavement, various things happen. In flexible pavements, aggregate particles can become dislocated and reoriented and binder material can migrate to the surface, influencing surface friction. Also, as a tire rolls along a pavement, some of the tread elements in contact with the pavement surface move relative to the pavement surface. This normally occurs only after the prevailing local friction has been overcome and results in the smoothing or polishing of the aggregates at the pavement surface.(3)

The microtexture of the pavement surface is thus altered. Also, the shear forces that develop between the tire and pavement surface can dislocate the pavement's surface particles, or at least reorient them, altering the macrotexture of the pavement surface. The abrasion and changes in the surface characteristics of the aggregate particles on the pavement surface generally result in a reduction of surface friction. With the development of vehicles with greater horsepower, the torque applied to tires has increased tremendously, and this has amplified the phenomenon described due to increases in the shear forces between the tire and the pavement surface. Several studies have shown that traffic is the governing factor in the deterioration of the microtexture and structure of the pavement surface.(7) The aging of the pavement surface has little or no effect on the pavement's microtexture and structure, except for the fact that aging generally implies more traffic load applications.

This point is best illustrated by figure 2. It shows the skid resistance of one type of surface course that was installed at six different locations at the same time. The pavement was tested 3 years after construction, and skid resistance had stabilized at all locations after 2 years. The plot of the side friction factor measured versus the average daily traffic for the pavements shows clearly that there was less friction with more traffic passes.(3)

Both asphalt concrete (AC) and PCC pavement macrotextures change considerably with the application of traffic. For AC pavements, traffic tends to compact the pavement in the wheelpaths. The use of adequately designed AC mixes for expected traffic tends to minimize compaction. Compaction, however, tends to bring more binder material to the surface and into contact with the tires. This changes the macrotexture of the pavement, and it is detrimental to good skid resistance at all speeds. Another aspect of compaction is that it results in rutting. The ruts on the pavement surface, when filled with water, can result in hydroplaning.(3) With respect to PCC pavements, many new PCC pavements are now constructed with transverse tining, which improves surface drainage and reduces splash and spray during wet weather, resulting in a reduction in wet weather accident rates.

Wear

Wear on any kind of pavement surface (AC or PCC) is nonuniform and, in time, results in an unserviceable road, either because of the unevenness of the surface or because of the complete disappearance of the surface course. Wear can be gradual or can occur in a

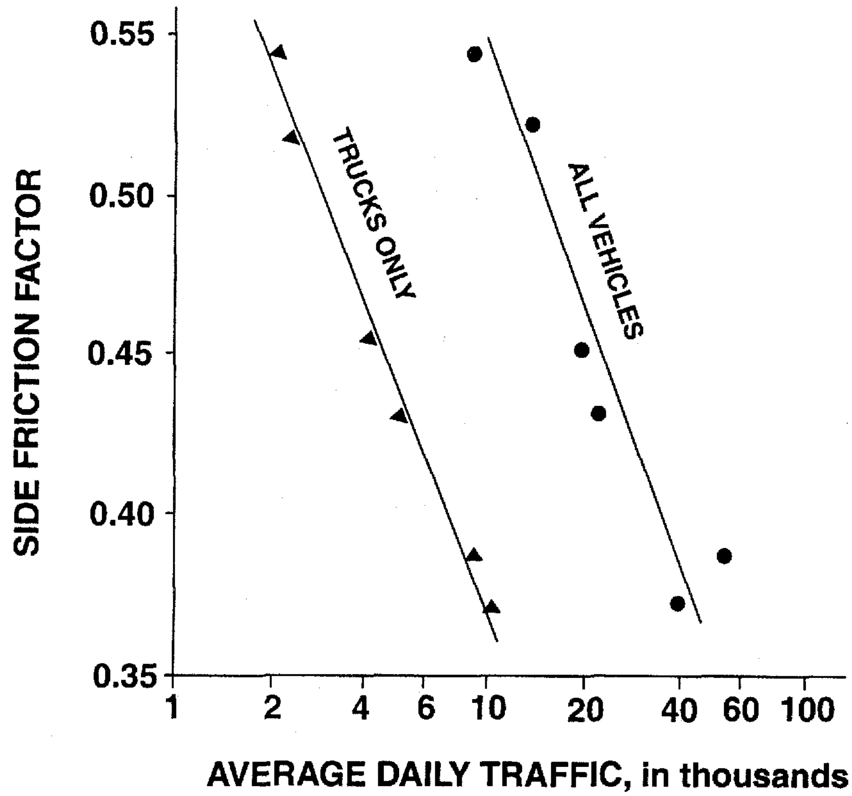

Figure 2. Deterioration of skid resistance with exposure to traffic.[7]

stepwise manner. In AC pavements, the removal of the asphalt binder in the mix through wearing or aging results in the exposure of the surface aggregates to the shear stresses developed between the tire and pavement surface. In most cases, these stresses are sufficient to break the bond between aggregate particles and the rest of the mix, thus increasing the rate of wearing of the AC material and distorting the macrotexture of the pavement. However, wear is more often gradual and continuous.[1, 4]

Wear is greatly accelerated by loose material on the pavement surface, whether generated by the pavement itself or blown there from elsewhere. The loose materials serve as abrasives and grind the pavement surface under the influence of shear stress generated from vehicles tires. The loose materials are generally the size of fine sand or finer.[3]

Wear is very much a function of aggregate characteristics. Past studies have shown that pavements with homogenous amorphous stone wear comparatively slowly, unless an outside source furnishes more abrasive material. Abrasive materials increase the potential for polishing and smoothing of the pavement's surface aggregates, decreasing skid resistance. Skid-resistant aggregates are rarely homogenous and amorphous.[3, 5] Debris from them contain particles that are harder than the aggregate matrix they are derived from. These hard aggregates help to wear the matrix away, releasing more hard particles to replace those that have been ground down and blown off the pavement surface. Several researchers have made attempts to relate the wear rates of aggregates to the aggregates' characteristics and have come to the following conclusions:[8]

- Aggregates wear by scratching and pitting.

- Rapidly wearing aggregates exhibit both types of attrition, whereas slowly wearing aggregates showed mostly scratching.
- Hardness of the mineral relative to that of the abrasive is decisive for the rapidity of wear; that is, if the abrasive is harder than the aggregate mineral, wear is faster.
- Wear rates are generally well correlated to the hardness of the minerals in the aggregates.

However, aggregate wear (loss of microtexture) is not identical to pavement surface wear (loss of macrotexture).[3] This is especially true for PCC pavements. This is because hardness and other properties of the PCC concrete matrix (mortar and aggregates) are very different from those of either the mortar or the aggregates alone. From a skid resistance standpoint, different wear rates for the different materials and minerals that make up AC and PCC mixtures are desirable because differential wearing enhances the pavement's microtexture, increasing skid resistance.

PCC pavements are given a heavier initial microtexture than AC using such techniques as tining or brooming. This kind of texturing is done mostly in the mortar mix alone; therefore, the rate of initial wearing of the pavement macrotexture will depend on the properties of the mortar mix. The mortar must be hard and wear-resistant for the initial pavement macrotexture to remain intact. As stated in earlier sections of this chapter, wearing is dependent on, and enhanced by, the presence of abrasive materials on the pavement surface. The finer the abrasive particles, the smoother the wearing surface will be. However, the rate of wearing will be considerably less. Consequently, for similar materials, slower wear will result in more polishing and lower skid resistance.[3, 5]

Polishing

Polishing can be defined as a reduction in microtexture. It is difficult to measure, and the mechanism for polishing is complex and not fully understood. Also, polishing and wearing of mineral aggregate are very similar, and it may be difficult to distinguish between the two in some instances. Polishing and wearing are both greatly influenced by the presence of abrasive materials, and the degree of polishing is dependent on the size of the abrasive particles. This is shown in figure 3, which is a plot of the BPN, an estimate of microtexture versus polishing duration. The plot shows the effect of abrasive size on the polish obtained in the laboratory on limestone aggregate.[9] On an actual pavement surface, the process of polishing is similar to that shown in figure 3; however, there is a difference in the amount and nature of the abrasive material that aids in the polishing process on actual pavements. A major portion is probably debris from the aggregates making up the pavement surface. There is also material that is brought over by the traffic that uses the pavement. This makes it quite difficult to estimate the rate of polishing of pavements in the field or to relate laboratory aggregate polish tests to the process in the field.

The rate of polishing of a pavement surface material is a factor of the aggregate type or the mineralogy of the aggregate used in the surface layer (AC or PCC). The mineralogy and structure of the aggregate determine the ease and degree of polishing. Figure 4 shows the ranking of an aggregate material's susceptibility to polishing. This is based on the final friction

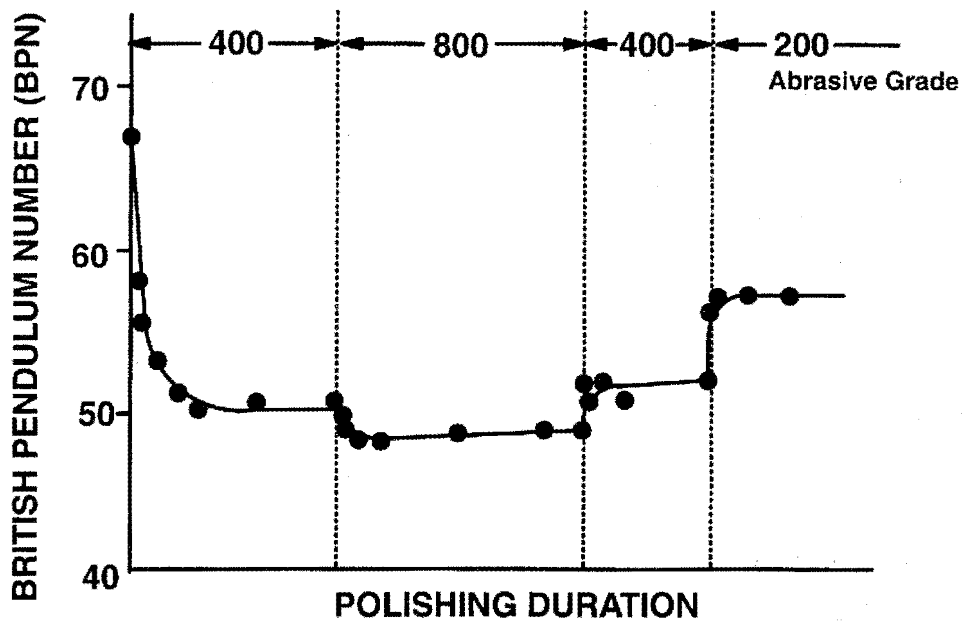

Figure 3. Effect of abrasive size on the polish obtained in the laboratory using limestone.[9]

factor, measured as the BPN after polishing in a laboratory machine.[10] Higher BPN values indicate higher skid resistance. It must be noted that these rankings are not absolute, because the range of BPN values measured has a large variability.

The variability may be due to the fact that friction is not just a property of the aggregate mineral composition, which also exhibits some variability. To a great extent, friction is a function of the physical properties of the aggregate, such as shape and size. There is still a lot to be learned about the mechanism of polishing and its effect on a pavement's skid resistance; however, the following generalizations of the process can be made:[10]

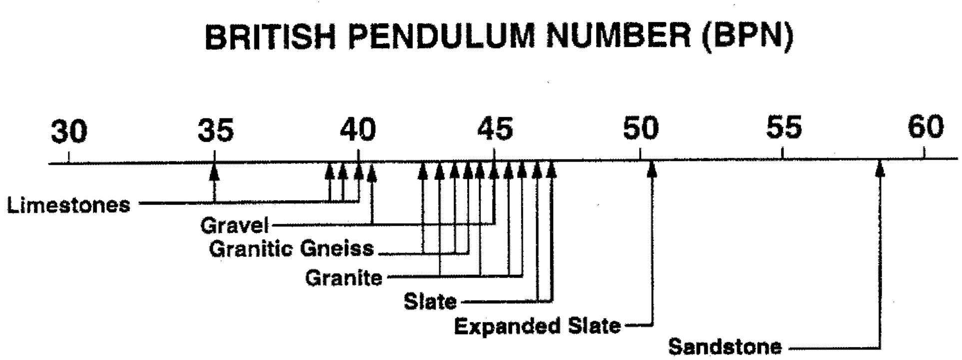

Figure 4. Ranking of various aggregates according to final friction factor after polishing in a laboratory machine.[10]

- The highest permanent skid resistance is obtained by aggregates whose surfaces are continuously renewed by the action of traffic.
- Sand-sized hard particles embedded in a softer matrix are highly beneficial for improving skid resistance.
- Aggregates with uniform mineral composition tend to have higher skid resistance the more angular and larger the grain size.
- Hardness for uniform aggregates, such as quartz pebbles, is not always beneficial to skid resistance.

A pavement will retain good microtexture and skid resistance if its irregularities are sand-sized and sharp-edged and if the surface wears fast enough to release the hard particles that form the irregularities before they are worn off or become rounded.

Contamination

A pavement surface can be contaminated by several different types of contaminants, liquid or solid, resulting in significant changes to surface characteristics and texture. Some of the common liquid contaminants are water and various kinds of oils leaked from vehicles that use the pavements. The most common types of solid contaminant are dirt and anti-skid materials that are left behind after snow or ice on the pavement surface has melted.

Several studies have reported the effect of water on the microtexture and skid resistance of a pavement.[11-12] Figure 5 shows the general effect of water applied to a pavement, measured as SN. Skid resistance generally drops as the rate of water applied to the pavement surface is increased. The application of higher rates of water to the pavement surface will cause hydroplaning and result in the rapid decrease in skid resistance again.

Also, with time, water applied to the pavement surface is absorbed by the aggregates. This can be described as the contamination of the pavement surface by the water particles. Retesting of previously wetted pavement surfaces (15 minutes after the initial wetting) shows a rapid decrease in skid resistance, as shown in figure 6.[10] This figure indicates that the absorption of water or other kinds of liquid generally results in the contamination of the surface aggregate material, distorting the microtexture and decreasing skid resistance.

Solid contaminants can also adversely affect the pavement's microtexture and skid resistance. They can act like balls in a bearing between the tire and the pavement surface when the vehicle's tires are locked. This reduces surface friction. The most common solid contaminants are deicing agents such as rock salt and calcium chloride. They are normally coarse and rough, with sharp edges, and do not necessarily contaminate the microtexture. However, deicing agents generally delay the drying process, and this could increase the period of time the pavement is subjected to low skid resistance when contaminated with water. Figure 7 shows the effect of deicing agents on the drying time of a pavement.[12]

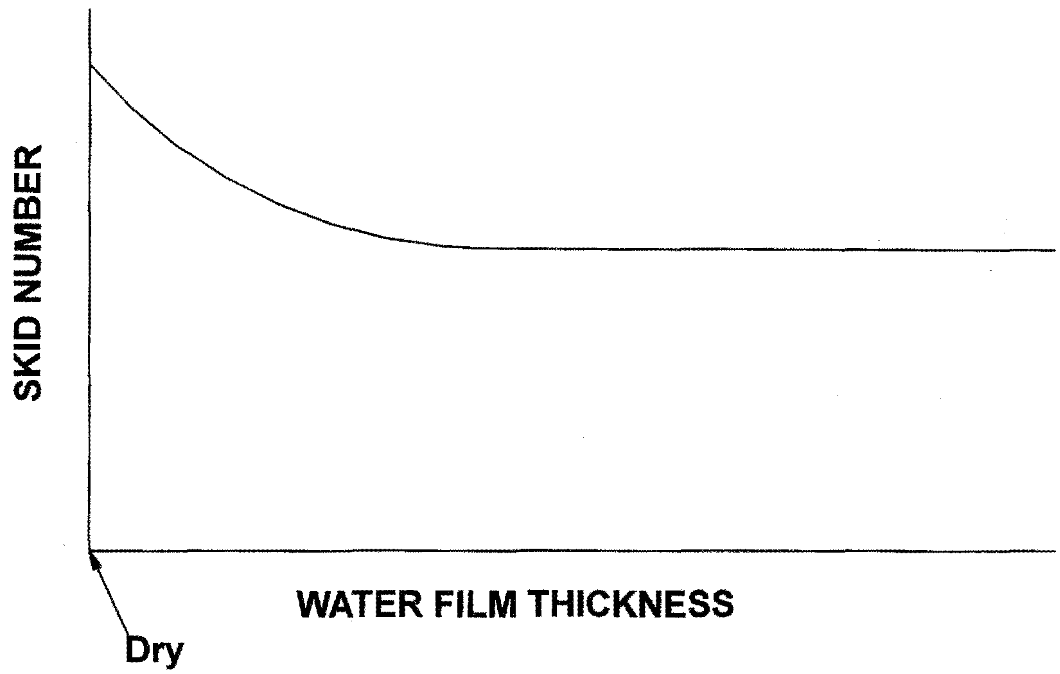

Figure 5. Skid resistance change caused by the rate at which water is applied to a dry pavement.(11)

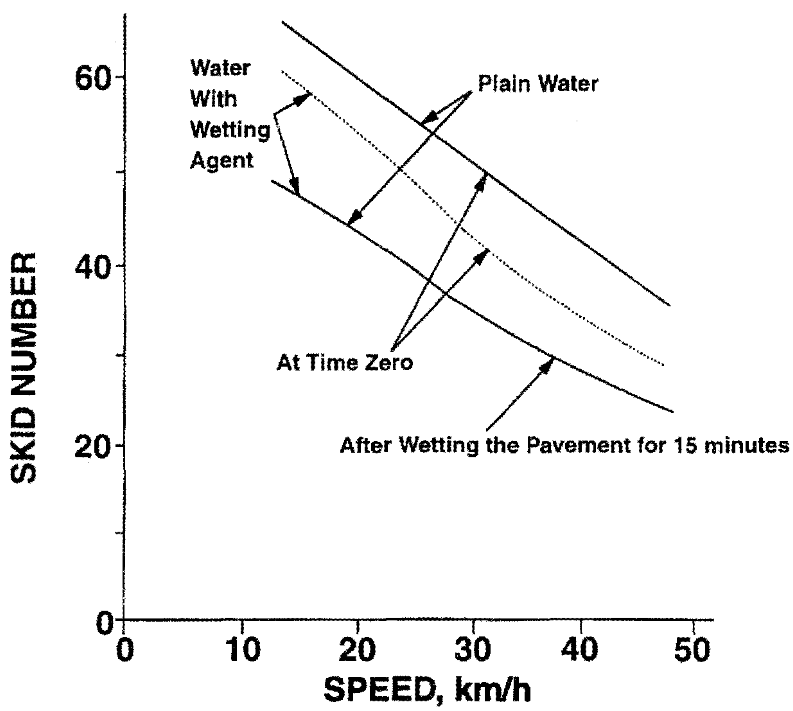

Figure 6. Effect of time and a wetting agent on the skid resistance of a smooth tire.(12)

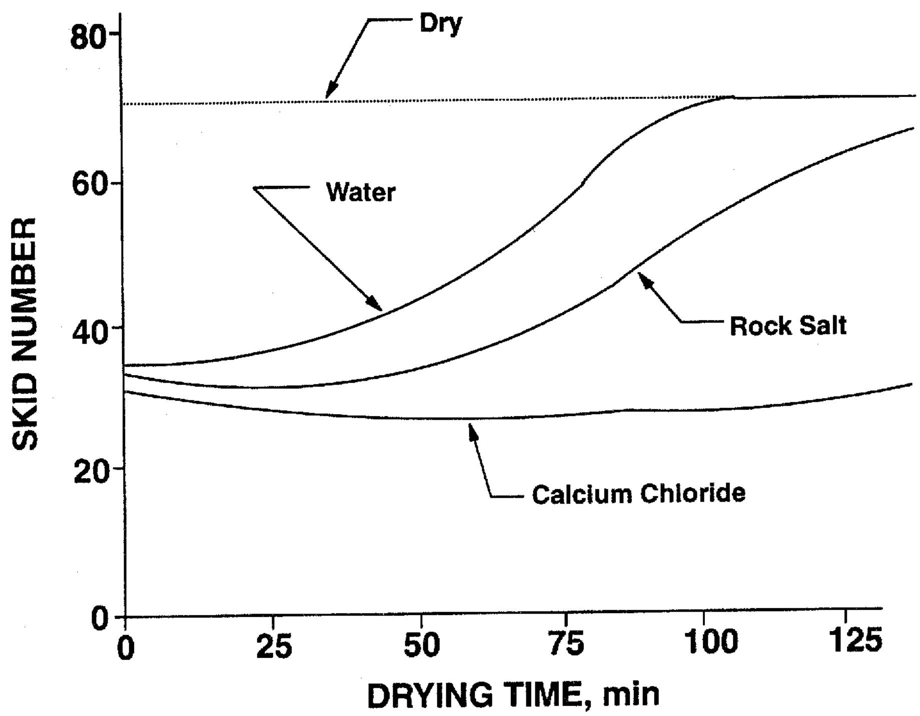

Figure 7. Effect of deicing agents on drying time.[3]

Climate

Climate-related factors are key to the amount of friction available on a pavement's surface at a given time and they also account for some of the variability in friction measurements. The key climatic factors that influence friction are wetness, season of testing, and temperature.

Precipitation and Wetness

Precipitation can affect friction in several ways. It can wash away contaminants, enhancing the surface texture of the pavement. It may also decrease pavement temperature, improving the tire-pavement interaction and increasing skid resistance. A decrease in pavement temperature also affects surface defects and distresses such as bleeding, reducing the influence of such surface defects on friction.[3, 5] However, prolonged precipitation increases the period of time the pavement surface is subjected to wetness. This has a negative effect on surface friction. The skid resistance of a dry pavement could be very different from that of a wet pavement.

Wetness can be defined loosely as the presence of a layer of water between the pavement surface and the vehicle tire. As explained in previous sections of this chapter, water between a tire and a pavement surface acts as a lubricant, substantially reducing the tire-pavement friction. It also distorts the microtexture of pavement, decreasing surface friction.

Pavements subjected to wet conditions therefore experience a temporary reduction in tire-pavement friction.[13] This results in fluctuating skid number values for skid resistance measurements conducted for a given pavement in a wet or dry period. Pavement surface friction decreases approximately exponentially as the water film thickness increases. Figure 8 is a graph of the effect of water film thickness on tire-pavement friction. The rate of loss of surface friction decreases as water thickness increases and eventually plateaus where any substantial increase in water film thickness has little effect on tire-pavement friction. A parameter called the critical water film thickness (d_{crit}) is used to measure the rate of decay of friction.[13-14] It is defined as the water film thickness at which tire-pavement fiction has fallen 75 percent of the dry surface value f(0) and the value for a thick water film.

A recent FHWA-sponsored study concluded that a very small amount of water can significantly reduce tire-pavement friction. In some tests conducted as part of the study, a 0.025-mm water film reduced friction 75 percent of the difference between the dry and the wet value. This level of wetness is likely to be exceeded during any hour in which at least 0.25 mm of rain falls.[15]

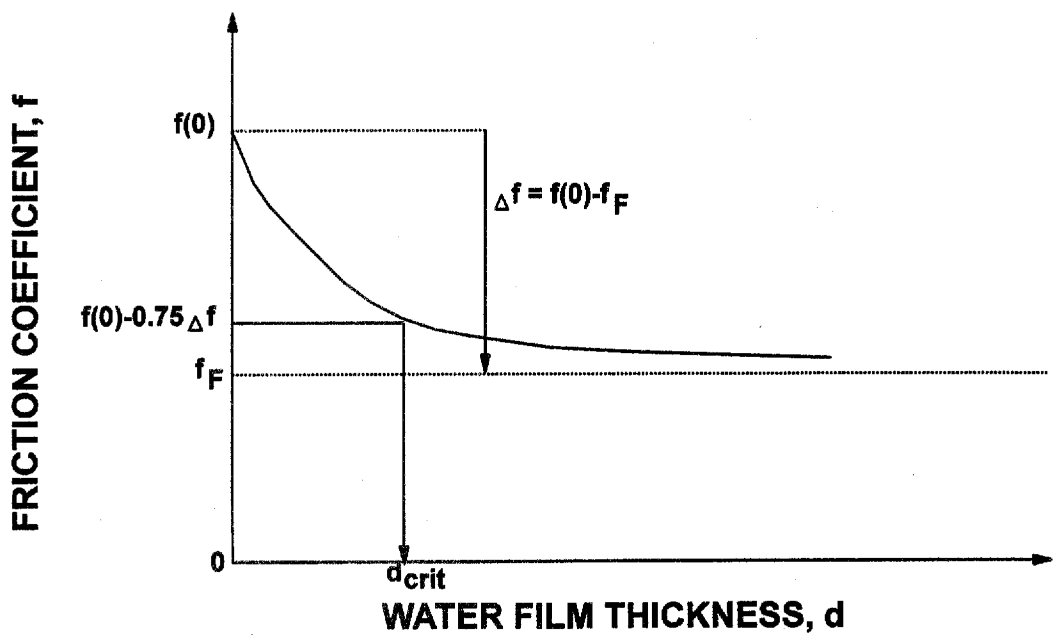

Figure 8. Relationship between tire-pavement friction and water film thickness.[13]

Thick films of water present on the pavement surface coupled with vehicles traveling at high speeds could result in hydroplaning.[5] Hydroplaning leads to a situation where there is virtually no friction between the two surfaces and increases the potential for accidents. The provision of grooves and channels on both the tire and pavement surface through texturing increases the rate at which water escapes from the pavement surface, thereby improving surface friction.[16-17]

Several States have developed methods and procedures for estimating the amount of time a pavement is exposed to wet conditions as part of accident reduction programs. A similar procedure has been developed by the FHWA in a study completed in 1990. The result of the study was the development of a model, WETTIME, that estimates wet pavement exposure from available pavement weather records.[5, 13, 18] The following elements were incorporated in the WETTIME model:

- Minimum level of wetness that reduces pavement surface friction.
- Rainfall intensity and duration.
- Runoff period following rainfall.
- Pavement drying period following rainfall and runoff.
- Pavement wetness due to fog.
- Estimation of exposure to ice and snow conditions.

Based on these data elements, the time during which a pavement is wet, T_w, is calculated as the sum of three components:

$$T_w = T_r + T_o + T_d$$

where T_r = Duration of rainfall.
T_o = Runoff time following rainfall.
T_d = Pavement drying time.

The WETTIME model is described in detail in the users guide for the WETTIME Exposure Estimation Model.[18] Table 1 shows the time a pavement is exposed to wet weather for the selected States within the United States, using data from the FHWA *Skid Resistance Manual* developed by the Pennsylvania Transportation Institute.[4]

Season of Testing

Friction is known to vary with the seasons because different seasons introduce different contaminants to the pavement surface. The variation in friction is therefore climate- and site-specific. The contaminants of interest are discussed as follows:[3]

- Particles of coarse rock salt and other deicing agents are used in clearing ice and snow during the winter season. The coarse material remains on the pavement surface after the winter season and temporarily increases the surface friction of the pavement.
- For pavements located in regions with high precipitation, available friction is lower during the period when the pavement surface is subjected to prolonged wetness.

Figure 9 shows the mean and actual skid resistance expected for a pavement measured during summer and winter several years after construction. The figure shows that even after the skid number of the pavement has leveled off, there are still variations in the skid number values measured, primarily due to seasonal variations.[19]

Table 1. Percentage of wet time in selected States within the United States.[19]

State	Minimum wet time (%)	Maximum wet time (%)
Alabama	10	16
Arizona	1	5
Arkansas	10	16
California	5	40
Colorado	3	5
Connecticut	8	18
Delaware	8	18
District of Columbia	8	18
Florida	6	20
Georgia	12	26
Illinois	9	13
Indiana	9	15
Iowa	7	12
Maryland	8	18
Michigan	10	14
Ohio	9	12
Texas	2	14
Washington	5	30
West Virginia	8	18

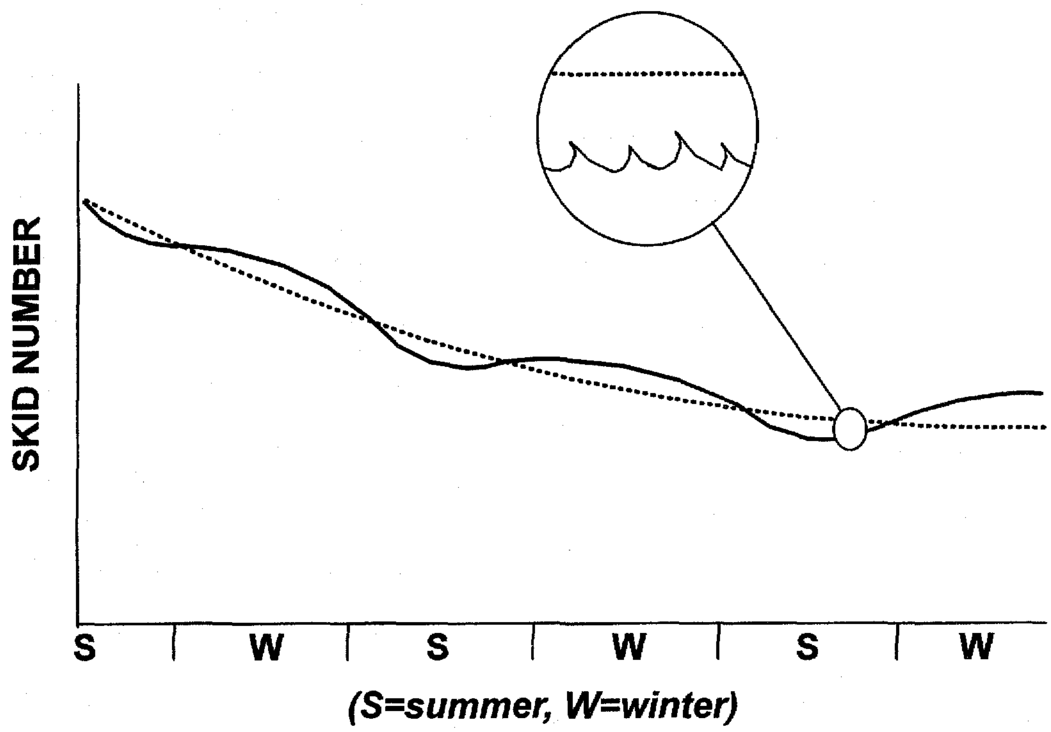

Figure 9. Mean and actual skid resistance of a pavement several years after construction.[3]

Temperature

Skid resistance is also affected by the temperature of the pavement at the time of measurement. Because tire rubber is a visco-elastic material whose properties are strongly affected by temperature, the frictional characteristics of tires are likewise affected by temperature. Field and laboratory studies show that tire-pavement friction decreases as temperature increases. However, the exact relationship between pavement temperature, tire temperature, and skid resistance values is not fully understood.[20]

AC Pavement Distress and Surface Condition

There are several distresses and surface condition features common to AC pavements that directly affect its macrotexture and, hence, skid resistance. The most common of these are bleeding, rutting, roughness, and particle loss. Their effects are discussed in the next few sections.

Bleeding

Microtexture of AC pavements can be affected detrimentally by the smoothing of the surface caused by bleeding. The pores of the aggregate material can be filled in and smoothed by the excess AC binder at the surface. This mostly occurs as a result of excess AC binder in the original surface mixture, hot weather or high temperature, and in AC mixtures with low surface void content.[3]

Rutting

The application of traffic on AC mixes tends to compact any flexible pavement, especially in the wheelpaths. A well-designed AC mixture should reduce compaction to a minimum. However, compaction is quite common, and this makes its effect on microtexture and skid resistance important. Compaction lowers the available air voids within the AC mixture, thereby increasing the probability of bleeding or the appearance of AC binder on the pavement surface. This affects the microtexture and macrotexture of the pavement surface in a manner similar to that of bleeding. Compaction results in rutting of the pavement surface or the creation of channels that could accumulate water to greater depths than otherwise would be present.

The channels or ruts interfere with the gradient (cross slope) provided for the removal of water from the pavement surface in the quickest possible time. This increases the probability of hydroplaning and lowers the speed at which it occurs because more water is available at the pavement surface for a longer time. Compaction can result in the reorientation of the AC pavement surface aggregate particles and this reorientation is likely to cause the large flat surfaces of the aggregates to be aligned to the pavement surface. If the aggregate is susceptible to polishing, reorientation can result in the polishing of the pavement surface aggregates and can reduce skid resistance considerably.

Roughness

Roughness, which is the large-scale deviations of a surface from the true planar surface with characteristic dimensions that affect primarily vehicle dynamics and ride comfort, can cause vehicles to bounce, reducing the effective tire-pavement friction. This is particularly pronounced in trucks.[5] Excessive roughness will therefore reduce the effective frictional capabilities of the pavement.

Particle Loss

The provision of excess AC binder in the mixture of the AC surface layer has been shown to change the microtexture of the pavement adversely. However, providing little AC binder can also be detrimental. The exposed aggregates in especially coarse-graded mixes reduce the bonding between the aggregates, resulting in aggregate particle loss when the pavement surface is exposed to the shear forces generated by moving traffic. This phenomenon is accelerated by vehicles with higher loads and speeds. It can lead to rutting or the exposure of the pavement surface to excess binder, thereby altering the microtexture and reducing skid resistance.

PCC Pavement Distress

The distresses that most directly affect the skid resistance of PCC pavements are polishing and roughness. The effects of these distresses are discussed as follows.

Polished Aggregate

Polishing is the loss of surface mortar through wear, resulting in the exposure of the coarse aggregate of the PCC pavement surface. Pavements with hard coarse aggregates are likely to polish when the pavement surface is exposed to the shear forces generated by moving traffic. This phenomenon is accelerated by vehicles with higher loads and speeds or pavements with softer coarse aggregates. It could lead to distortions in the pavement surface, resulting in ponding and hydroplaning.[3]

Roughness

Roughness, as discussed earlier, causes vehicles to bounce, reducing the effective tire-pavement friction.[5] Excessive roughness will therefore also reduce the frictional capabilities of PCC pavements.

Design and Construction of Skid-Resistant Pavements

Pavement surfaces are designed and constructed to provide the following basic skid resistance requirements:

- Ensure the availability of adequate levels of skid resistance on dry and moderately wet pavement surfaces.
- Provide friction between the tire and the pavement surface through adhesion.
- Provide friction between the tire and the pavement surface through hysteresis.
- Assist in draining water away from the pavement-tire interface.

Satisfying these four conditions ensures long-lasting skid resistance on pavement surfaces under varying environmental and traffic conditions. In order to satisfy these conditions, the following must be considered in the design and construction process:

- Aggregate properties.
- Mix design.
- Construction techniques.

These components of the design and construction process are discussed in greater detail in the next few sections.[3, 21-23]

Aggregate Properties

Several factors need to be considered to ensure long-lasting skid resistance. Some of these, such as resistance to wear and polishing, have been discussed in previous sections of this chapter. This section provides a summary of the aggregate properties required for constructing skid-resistant pavements.

The two significant factors required for constructing skid-resistant pavements are:[5]

- Using skid-resistant materials in constructing the pavement surface, especially the aggregate (coarse aggregate for AC pavements and fine aggregates for PCC pavements). For PCC pavements, the polish resistance of the coarse aggregates is very important if the PCC surface is diamond-ground to correct for roughness or to provide a smooth ride on new PCC pavements.
- Using pavement surface design and construction techniques that optimize surface texture (mix design for AC pavements and surface finish for PCC pavements).

The initial pavement surface is the primary factor in providing a skid-resistant surface. The durability of that surface will ensure the provision of long-lasting skid resistance. At the design stage, the designer should specify skid-resistant aggregates for pavement construction since they are the primary constituent of both AC and PCC mixtures. The properties of aggregates related to friction are as follows:[3, 5]

- Resistance to wear and polish.
- Texture.
- Shape.
- Size.

The beneficial effect of the resistance to wear and polish has been discussed in earlier sections of this chapter. Also, the effects of the aggregate's microtexture and the pavement's macrotexture on skid resistance have been discussed. The effects of aggregate shape and size are discussed as follows.

Shape

The shape and angularity of an aggregate particle significantly affects its skid resistance properties. An aggregate's shape depends on many factors, such as the natural source of the aggregate and the method of processing. As an example, aggregates from rivers and stream beds tend to be rounded and polished, while crushed aggregates have an angular shape. Some minerals will crush into mostly flat and elongated particles and have low skid resistance, while others crush into sharp-pointed edges and have greater frictional capabilities.

Size

Aggregate size also affects the frictional qualities of pavement surfaces. For AC mixtures, the large aggregates (coarse aggregates) influence overall skid resistance.[24] However, for PCC pavements, the sand-sized particles (fine aggregates) control the initial skid resistance of the pavement. The larger coarse aggregates assume a greater influence on the overall skid resistance of PCC pavements after the wearing off of the surface texture. However, the polish resistance of coarse aggregates is important if the PCC surface is diamond-ground to correct for roughness or to provide a smooth ride on new PCC pavements.

Mix Design

The two main pavement surfacing materials used are AC and PCC. Both AC and PCC pavement surface layer mixtures must be designed to obtain adequate tire-pavement friction. The elements in AC and PCC mixtures that provide surface friction are quite different and are therefore discussed separately.

AC Pavement

AC mixtures consist predominantly of asphalt cement, coarse aggregate, and fine aggregate. The material that chiefly determines the skid resistance of the mixture is the coarse aggregate. However, other mix properties, such as the asphalt content and void content, also influence skid resistance. An AC mixture will provide adequate skid resistance if the following requirements are met:(24)

- The coarse aggregate must be satisfactorily skid-resistant.
- Excess asphalt cement in the mix should be minimized as it could lead to bleeding, obscuring the coarse aggregates and the effectiveness of their skid resistance qualities.
- Inadequate amounts of asphalt in the mix or using a hard-grade asphalt should be minimized as it could lead to the raveling of the coarse aggregates, reducing skid resistance.
- Adequate level of internal voids should be designed for as it will reduce the possibility of bleeding and enhance drainage, reducing periods of wetness.

The type of mixture (e.g., dense-graded, open-graded, seal coat) also influences skid resistance, as shown by the mix properties listed. However, the decision on the type of mix most suitable for obtaining skid resistance (and good performance in general) depends on several factors, including the expected levels of traffic and speed.

PCC Pavement

PCC mixtures consist predominantly of portland cement, coarse aggregate, and fine aggregate. The material that chiefly determines the initial skid resistance of the mixture is the fine aggregate. The influence of the coarse aggregate increases as the initial surface texture provided by the mortar (fine aggregate and portland cement) mixture wears off. Also, the polish resistance of the coarse aggregate becomes important if the PCC surface is diamond-ground to correct for roughness or to provide a smooth ride on new PCC pavements. A PCC mixture will obtain adequate skid resistance by having the following:(5, 24-25)

- The fine aggregate material should be of high quality (gritty).
- The mortar used for texturing the pavement surface should be durable and should not wear off when subjected to traffic.
- The proportion of fine aggregate in the mix should be near the upper limit of the range that permits proper placing, finishing, and texturing.

- Research has shown that the siliceous particle content in the mix, as determined by the acid insoluble residual test, should not be less than 75 percent.
- Entrained air must be used in all concrete pavements to protect the textured surface from the effects of alternating cycles of freezing and thawing.
- The concrete must be durable (i.e., having the right amounts of portland cement, water-to-cement ratio, air content, aggregates). A durable concrete will resist wearing and disintegration, maintaining skid resistance.

Construction Techniques

The primary construction activity that influences skid resistance is texturing. Methods for obtaining surface textures that will provide adequate skid resistance are different for AC and PCC pavements and are discussed below.

AC Pavements

As stated previously, the material in the AC mixture that predominantly provides skid resistance is the coarse aggregate. A well-textured AC surface will therefore depend on the microtexture of the coarse aggregate and the gradation of the overall AC aggregate mixture to ensure that there are enough coarse aggregate particles at the pavement surface. Some studies have shown that mixtures with large-sized aggregates tend to provide more friction than those with smaller sized aggregates.[5] However, this differs from locality to locality, and local experience will be valuable in deciding which gradation is most suitable for obtaining the required skid resistance.

PCC Pavements

For PCC pavement, historically, finishes have exhibited a fine to medium texture rather than a coarse texture. This is because the final texture is done using mortar in a semi-fluid state brought to the slab surface during the casting and laying of the slab. This makes the properties of the mortar mix more important than the coarse aggregates for determining initial skid resistance. The method used to texture the semi-fluid mortar governs the texture of the finished pavement. It also provides an opportunity for controlling the final texture of the pavement. There are several common texturing methods, including the following:

- Burlap drag.
- Paving broom.
- Belt.
- Wire broom.
- Tining.

The average texture depths provided by these methods are given in table 2. A summary of the initial skid numbers corresponding to the different methods of finishing, and a summary of texture depth for the different methods of finishing computed from a study on the texturing of concrete pavements are given in tables 3 and 4, respectively. The study showed the following variations in pavement microtexture properties:[26]

Table 2. Texture depth on laboratory specimens.[27]

Method of finish	Texture depth, mm
Light belt	0.38
Light burlap	0.43
Heavy belt	0.51
Heavy burlap	0.635
Medium paving broom	0.74
Wire drag	0.91
Heavy paving broom	0.94
Stiff wire brush	1.905

Table 3. Summary of initial skid numbers.[26]

Method of finish	Initial SN		
	Minimum	Maximum	Mean
Burlap drag	38	64	52
Paving broom	46	72	58
Wire broom	51	72	61
Fluted float	40	72	61

Table 4. Summary of texture depths.[3]

Method of finish	Texture depth, mm
Burlap drag	0.48
Paving broom	0.79
Wire broom	1.06
Fluted float	1.14

- Textures produced by the different methods varied both in texture depth and initial skid number.
- Textures produced by the same methods varied significantly from site to site.
- The permanence of texturing varied, depending on cumulative traffic volume, initial texture depth, and the wearing characteristics of the particular texture and mortar mix.

These findings show that the final texturing of PCC pavement surfaces considerably influences initial skid numbers and the initial rate of pavement surface deterioration. However, after the textured surface wears off, the pavement surface characteristics are governed by the properties and mineralogy of the pavement's aggregate material.

Measuring Skid Resistance

Skid resistance measurements obtained from friction tests are highly influenced not only by the pavement's surface condition, but also by the test method and the state of the test equipment. To ensure accurate, reliable, and repeatable test results, the test method should be strictly adhered to and the equipment well calibrated and operated by highly skilled technicians. Also, care must be exercised in interpreting test data from new pavements. Early friction testing may provide misleading results regarding long-term durability of the skid characteristics of the surfaces.

There are several methods for testing the skid resistance of pavements. Some of these methods are field based, while others are measured on materials in the laboratory. The majority of the methods are based on the principle of moving a tire or rubber pad under a perpendicular applied load along a wetted surface and then measuring the horizontal resistance to moving the tire or rubber pad. There are some other nondirect methods of measuring friction, such as measuring the microtexture and the macrotexture parameters of the pavement surface and relating these to friction through the use of models. This section describes the different methods and procedures for estimating friction and discusses the advantages and disadvantages of each method.

Field Testing With a Locked-Wheel Testing Device

Skid testing in the United States is almost universally conducted in accordance with ASTM E-274.[(2)] This is also the method for friction testing specified for the LTPP test sections. This method uses a locked-wheel braking mechanism to measure the braking force coefficient. The measurement represents a steady-state friction force on a locked wheel as the tire is dragged over a wetted pavement surface under constant speed.

The vast majority of skid measurement systems consist of a towing vehicle and a two-wheel trailer. Most commonly, the left wheel of the trailer is locked during testing. The skid measurement system consists of the following features:[(3)]

- A transducer that senses the force developed between the sliding wheel and the pavement during testing.
- A computer system that transforms the raw measurements into skid resistance.
- A water supply system, usually 1.0 to 2.2 m^3, with the necessary apparatus to deliver approximately 0.018 m^3 of water per minute per wetted 25.4-mm width of pavement.
- Equipment to measure the speed at which the test is conducted.
- A standard tire for skid resistance testing so that measured SN's from different pavement types and surfaces can be compared.

The skid number is calculated as the braking force divided by the vertical force, measured when the vehicle is braking in a straight line and the tire is actually skidding.

Test Tire

The two test tires commonly used for skid resistance testing, Standard Ribbed Tire for Pavement Skid-Resistance Tests (ASTM E-501) and Standard Smooth Tire for Pavement Skid-Resistance Tests (ASTM E-524), measure different components of surface friction. The ribbed tire is sensitive primarily to the pavement's microtexture.[2, 5] Its effect on the pavement's macrotexture is limited because water on the pavement surface is expelled from the grooves of the ribbed tires even if the pavement has a poor macrotexture. Smooth tires, on the other hand, are affected by both the microtexture and macrotexture of the pavement.

Test Procedure

To take a measurement, the trailer is towed at a speed of 65 km/h over the dry pavement while water is applied in front of the test wheel. The test wheel is then locked up by a suitable brake. After the test wheel has been sliding on the pavement for a certain distance, the force that the friction in the tire contact patch produces and transmits as torque on the test wheel is measured and recorded for a specified length of time. The results of such a test are reported as SN.[1] The current recommendations are to perform skid testing at two speeds or using both the ribbed and smooth tires at one speed. This would allow determination of the speed gradient and the International Friction Index (IFI).

Test Personnel

It is essential that operators adhere to the standardized procedures for friction testing. Although measurements are essentially fixed, as far as skid resistance is concerned, surface characteristics change with time and are frequently far from uniform. Unless the test is repeated and measurements are made in an identical manner, the operators may conclude that changes occurred when they really did not. This could distort or hide the true value of the skid resistance or the magnitude of the change in skid resistance.

Possible Sources of Variability

The results of several research studies referenced in this chapter show that the possibility of error in skid resistance measurements is quite high. The sources of error can be random, such as operator error, or systematic, such as equipment error. Some of the potential error can be eliminated by using well-calibrated equipment and highly trained personnel. A study conducted by the Washington State Department of Transportation (DOT) identified various sources of random and systematic error and their effects on friction test measurements. A summary of the sources of error identified in the study is presented in table 5.[5]

Laboratory/Field Testing With the British Pendulum Tester

The British Pendulum Tester is an impact-type tester that measures the amount of kinetic energy lost when a rubber tester attached to the end of the pendulum arm is propelled over a test surface. The test surface can be a pavement or pavement cores taken from the field. The value measured by the tester is the skid resistance of the test surface. The British Pendulum Tester primarily reports the friction due to the microtexture of the surface. As such, the British Pendulum Tester is considered a surrogate for determining microtexture. Results are reported as BPN and the testing procedure used is described in ASTM E-303.[2, 5] The British Pendulum Tester is portable and easy to use; however, presently, there is no reliable procedure for correlating BPN with SN.

Table 5. Potential sources of random and systematic error.[6]

Error source	Random	Systematic	Effect on skid resistance
Speed holding	X		At 65 km/h ± 2 SN per km/h
Speed measurement		X	At 65 km/h ± 2 SN per km/h
Water temperature		X	Negligible
Air temperature		X	Indirect effect through pavement and tire temperature
Pavement or tire temperature	X		± 4% per 5.5 °C
Water film thickness	X	X	± 1 SN for ± 10% variation
Water flow		X	Strong
Pavement variability (lateral)	X		10 SN
Pavement variability (longitudinal)	X		10 SN per km
Tire variability		X	2.5 SN
Tire condition		X	Within wear range 1 SN
Inflation pressure		X	1 SN in operating range
Wheel load error		X	% SN error equal to % weight error
Wheel load range		X	1 SN per 45 kg
Instrumentation	X	X	Drift
Operating procedure	X	X	Controls other error sources

Surface Macrotexture Measurement

Several studies have attempted to model and correlate pavement macrotexture depth (a measure of macrotexture) and BPN (a measure of microtexture) to skid resistance. The success of such studies is varied. Strong relationships have been obtained by researchers at the Pennsylvania Transportation Institute, and skid resistance values may be predicted with some accuracy by using the models developed by them. Also, measuring texture depth as the pavement is subjected to traffic can give an indication of the rate of loss of macrotexture.[5, 28]

There are several methods for measuring pavement surface texture. Some of the traditional and recently developed methods are described and discussed as follows.

Measuring Pavement Macrotexture Depth Using Volumetric Technique

Traditionally, pavement macrotexture has been estimated by average surface macrotexture depth (previously, sand was used and the method was referred to as the sand-patch method). The procedure for measuring this parameter uses a known volume of homogeneous glass beads spread on a clean, dry pavement surface to calculate the average depth between the bottom of the pavement surface voids to the top of the surface aggregate. The result of the test is the average surface macrotexture depth calculated from the following equation.

$$MATX_d = \frac{4V}{\pi D^2}$$

where $MATX_d$	=	Average surface macrotexture depth, also referred to as MTD.
V	=	Volume of glass beads.
D	=	Average diameter of the area covered by the glass material.

Details of the testing procedure are given in ASTM E-965.

Road Surface Analyzer

Recently, FHWA sponsored the development of a laser-based Road Surface Analyzer (ROSAN) to record texture characteristics of pavement surfaces at normal highway speeds along a linear path.[30] ROSAN is currently undergoing enhancements to measure other pavement surface characteristics as part of a commercialization effort. An automated measuring system such as $ROSAN_v$ provides a larger quantity of valuable and less expensive texture data while greatly improving the safety of field personnel and reducing traffic control problems. The following areas of application are feasible with the aid of $ROSAN_v$:

- Surface texture measurements.
- Combining friction testing equipment such as skid trailer with $ROSAN_v$ to obtain simultaneous texture and friction data.

Prior to the completion of the $ROSAN_v$ research work, ASTM Committee E-17 approved ASTM Standard E-1845, Standard Practice for Calculating Macrotexture Mean Profile Depth, from a profile of a pavement macrotexture.[2] Using this standard and the output profile from $ROSAN_v$, the mean texture depth can be estimated.

Summary

A review of the literature indicates that many factors affect pavement surface friction characteristics and pavement friction measurements. Aggregate properties, mixture design, and construction are the key factors that affect the friction characteristics. With respect to friction testing, seasonal effects, test speed, and tire type are the key factors that affect the measured friction values. In addition to these factors, equipment calibration, operator training, adherence to specified test procedures, and consistently performing time-series measurements along the same lengths of the pavement section are important factors that may affect the reliability of test data.

3. LTPP FRICTION DATA COLLECTION: STATE OF THE PRACTICE

Introduction

Friction data collected as part of the LTPP data collection program are the responsibility of the highway agencies under whose authority the pavements are located. Because friction measurements are made by different agencies all across North America, there is a need to ensure that data are collected in a uniform manner, according to LTPP guidelines.

As part of the friction data quality evaluation study, procedures used by the participating highway agencies to collect friction data were reviewed and assessed. The information of interest was as follows:

- Actual procedures and equipment used.
- Quality control and calibration of equipment.
- Auxiliary climate-related data collection.
- Pavement design and construction characteristics.
- Equations and models for determining friction and skid number.
- Test tire type and specifications.

Participating highway agencies were contacted by the appropriate LTPP Regional Coordination Office (RCO) to clarify information on agency practices to allow an assessment of the quality of data collection at the LTPP sites. Responses to the clarification effort were received from 36 State DOT's, the Puerto Rico Highway and Transportation Authority, and 5 Canadian Provincial agencies. The respondents provided a good geographic representation across the United States and Canada. Summaries of the procedures and practices of the responding agencies are given in appendix A.

Quality Control and Calibration Methods

The first part of the information on agency practices concerned the quality control and calibration procedures used to check the accuracy and precision of friction testing equipment used at the LTPP sections. Information was also sought on the frequency or regularity of such procedures. A brief description of the calibration process was also requested. All of the agencies that responded, with the exception of Colorado and Hawaii, had a procedure in place for some type of calibration.

Internal Calibration

For most of the agencies, internal calibration consisted of a periodic on-site process carried out by agency personnel. The nature of the calibration process and the regularity of internal calibration differed widely from agency to agency. The calibration checks ranged from using the manufacturer's calibration software to calibrate the equipment just before testing to a more detailed check of the individual components of the friction testing system. However, based on the responses, internal calibration can be summarized as follows:

- System checks of the on-board computer systems using the manufacturer's internal calibration software.
- Using force plates to check the load measuring system of the equipment.
- Checking the water gauge and flow rates.
- Running test strips to check variability.

Most of these checks are simple and are carried out by trained personnel on site. The regularity of internal calibrations ranged from daily (during the period of testing) to once every 6 months. Twenty-one percent of the respondents performed internal calibration on a weekly basis, 28 percent on a monthly basis, and 12 percent once every 6 months. The remaining respondents provided no information on the frequency of calibration. A few of the agencies performed more sophisticated internal calibration, as described below.

Idaho

The Idaho DOT checks and calibrates the load measuring system, water gauge, speed measuring system, and the distance measuring system. This is done on a monthly to annual basis.

South Dakota

The South Dakota DOT runs test strips on a weekly basis to check for variability in measurements.

Puerto Rico

The Puerto Rico Highway and Transportation Authority checks and calibrates the speed measuring system monthly and checks the force measuring system every 6 months.

External Calibration

External calibration generally consisted of a periodic calibration of equipment at regional test centers located throughout the United States. The two most common calibration centers were the Ohio test center and the Texas Transportation Institute. The external calibration process was more rigorous and involved detailed checks of all measuring components of the friction testing system. Once again, the frequency of external calibration varied from agency to agency. Five percent of the respondents had their test equipment calibrated externally once every 6 months, 26 percent of the respondents did so annually, and 24 percent calibrated their equipment externally once every 2 years. Typically, most agencies had their equipment calibrated within a 2-year period. The reasons for calibration ranged from the need for regularly scheduled routine calibration (part of the testing guidelines for most agencies) to calibrating the equipment when important or extensive tests were to be conducted. Most of the test centers followed the calibration procedures outlined in ASTM E-274. Table 6 presents a summary of responses on quality control, calibration, and frequency of calibration.

Table 6. Summary of responses on quality control, calibration, and frequency of calibration.

Quality control practices		Number of respondents who indicated that this is done	Percentage of respondents
Perform regular calibration and quality control checks		38	95
Internal calibration		26	62
External calibration		26	62
Frequency of internal calibration	Weekly	9	21
	Monthly	12	28
	Every 6 months	5	12
Frequency of external calibration	Every 6 months	2	5
	Annually	11	26
	Once in 2 years	10	24
	Once in 3 years	3	7

Summary

There was no clear demarcation of what constituted internal and external calibration. It was also obvious that most of the testing agencies used guidelines different from those recommended by LTPP. To ensure the use of well-calibrated equipment and uniformity in testing procedures, greater conformity to LTPP recommendations is required.

Additional Data Collected as Part of Friction Testing

Because of the sensitivity of friction testing to pavement surface conditions, it is generally useful to collect data that can be used to document the state of the pavement surface at the time of testing. The information can be used to normalize or standardize friction test values for tests conducted at different times under various climatic and surface conditions. It can also be used to determine the effects of moisture, temperature, and distress on test results. As part of the data clarification process, information was obtained regarding additional data collected as part of friction testing at LTPP test sites. A summary of the additional information collected is presented in table 7.

All the testing agencies collected air temperature and test speed data as part of the process. Most of the testing agencies did not collect additional friction-related data. Twenty-six percent of the respondents collected data on pavement temperature at the time of testing. Three percent of the respondents collected data pertaining to distresses occurring on the pavement surface (such as rutting and patched areas). Two percent of the respondents collected data on the moisture condition of the pavement surface or evidence of wetness immediately before testing. Other information collected related to the possible contamination of the pavement surface by both solid and liquid contaminants, and the general weather condition at the time of testing.

Table 7. Additional data collected as part of friction testing.

Friction-related information	Number of respondents who collected data	Percentage of respondents
Any climate-related data	22	52
Air temperature at the time of testing	22	52
Pavement temperature at the time of testing	11	26
Number of wet days in 7 days preceding test	0	0
Average precipitation in 7 days preceding test	0	0
Pavement condition rating	3	7
Reports of hydroplaning	1	2
Surface moisture	2	5
Tire condition	1	2
Wind speed/direction	3	7
Weather condition	3	7

Guidelines for Addressing Skid Resistance

This section summarizes information on specific guidelines adopted by the highway agencies to address potential skid resistance problems. Forty percent of the respondents (17 of 42) had specific guidelines to address skid resistance. The guidelines address a wide range of issues that could affect skid resistance.

Mix Design of Surface Course

Thirty-six percent of the respondents designed pavement surface mixtures to obtain the required minimum friction and to resist friction loss. The specific tests and specifications used to ensure that the mixture will provide the required friction included:

- Aggregate type and geological class.
- Petrographical analysis.

- Abrasion test.
- Soundness test.
- Hardness test.
- Polish resistance test.
- Aggregate gradation.
- Percent aggregate with fractured faces.
- Percent natural sand.
- Percent crushed aggregate.

Aggregate Type and Geological Class

Aggregate type and geological class are used to determine and classify the frictional properties of an aggregate. However, such a classification process is not expected to be very accurate because of the variability in purity and composition of minerals from different sources.

Petrographical Analysis

Petrographical analysis, which determines the composition and nature of the minerals present in a given aggregate, is a more accurate procedure for classifying the frictional characteristics of aggregate based on mineralogy. Iowa used a detailed petrographical analysis to classify aggregates by their frictional characteristics, and Kentucky used a chemical analysis to determine aggregate suitability. However, these procedures require the use of very skilled personnel and equipment and are not widely used by other highway agencies.

Abrasion, Soundness, Hardness, and Polish Resistance Tests

Quite a number of the highway agencies use tests such as resistance to abrasion, soundness, polishing, and the hardness of the aggregates to determine their ability to provide adequate skid resistance and to resist the loss of skid resistance. Georgia specified the use of only hard siliceous metamorphic aggregates in the design of surface mixtures, and most of the respondents use the L.A. Abrasion test and various forms of soundness tests to determine the susceptibility of aggregates used in construction to smoothing and polishing.

Gradation, Percent Fractured Faces, Percent Natural Sand, and Percent Crushed Aggregate

Other common tests and specifications that were used by some of the highway agencies to determine the frictional properties of aggregates included aggregate gradation, percent aggregate with fractured faces, percent natural sand in mixture, and percent crushed aggregate. Iowa specified the use of natural sand in mix design, while Nevada and New Mexico specified the percentage of fractured faces for aggregates used in mix design.

Test Specifications

Specifications for aggregate materials based on these tests differed from agency to agency because most of the specifications were developed from the past performance and local experience of the engineers in the State. Some agencies' specifications were also based on the functional class, traffic application, pavement location, speed limit, and other functional properties of the pavement. A summary of issues related to skid resistance identified as part of the data clarification effort is presented in table 8. Table 9 presents a summary of the responses on the specific tests and specifications used for addressing skid resistance. The number of highway agencies with specific design or construction guidelines for addressing skid resistance is low, but the reason for this is not obvious.

Table 8. Summary of responses on guidelines for addressing skid resistance.

Issues addressed in guidelines	Number of DOT's involved in activity	Percentage of respondents
Specific activities to address skid resistance	17	40
Conducting friction-related research	17	40
Mix design of surface course	15	36
Pavement grade and alignment	10	24
Aggregate type	14	33
Speed limit	5	12
Surface distress condition	2	5
Pavement location/classification	5	12
Traffic	3	7

Table 9. Summary of responses on tests and specifications used for addressing skid resistance.

Test activity	Number of DOT's involved in activity	Percentage of respondents
Aggregate geological class	2	5
Abrasion test	12	29
Soundness test	5	12
Percent crushed aggregate	1	2
Gradation	1	2
Hardness test/specification	1	2
Petrographical analysis	2	5
Natural sand specification	2	5
Polish resistance	3	7
Test for percent fractured faces	2	5
Surface texture depth test	1	2
British Pendulum Tester	1	2

Friction-Related Research

Only 40 percent (17 of 42) of the respondents were currently or recently involved in friction-related research. The research topics investigated by the DOT's varied. The most common research topics were the effects of aggregate properties on skid resistance, the effect of traffic on skid resistance, and the effect of both liquid and solid contaminants on skid resistance.

Test Tire Type and Specifications

A summary of the tire types used in friction testing by the highway agencies is presented in table 10. Most of the respondents (18 of 25) used ribbed tires for AC and PCC pavement friction testing. Arkansas and Ontario used smooth tires exclusively for both AC and PCC pavements friction testing. Colorado and Illinois used ribbed tires for AC pavements and smooth tires for PCC pavement testing.

Table 10. Tire type used in friction testing of AC and PCC pavements.

Pavement type	Number of SHA's using smooth tires	Number of SHA's using ribbed tires
Asphalt	3	21
Portland cement	4	18

Alaska tested only AC pavements using ribbed tires, while Nova Scotia used smooth tires for AC pavement testing. Louisiana used both ribbed and smooth tires interchangeably for both AC and PCC friction testing. For the respondents using ribbed test tires for friction test measurements, the test tires were in compliance with ASTM E-501. Those using smooth tires complied with ASTM E-524.[2] A few of the highway agencies had switched to alternate friction test methods in recent years. Some examples of these are British Columbia, which now uses the British Pendulum Tester; Nova Scotia, which switched to the grip tester from the SAAB friction tester in 1996; and Ontario, which has been using the grip tester since 1995.

4. LTPP FRICTION DATA QUALITY AND AVAILABILITY

Introduction

The evaluation of the quality of the friction data collected in the United States and Canada was based on recommendations given in ASTM E-274. Data quality was assessed by observing trends in time-series plots of skid resistance measured as skid number (i.e., plot of SN versus traffic). This chapter presents a summary of the entire LTPP friction database classified into three categories—as expected, questionable, and sections that could not be classified because of a lack of time-series data. As-expected data are those data that show a decrease in skid number with time.

Criteria for Determining Data Quality

Pavement sections within the LTPP database with time-series friction data (i.e., repeated friction measurements as traffic is applied to the pavement) were classified into as-expected and questionable data. The classification was based on the level of variability in the time-series data. ASTM E-274, Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire, states the following:

> *The acceptable precision of SN units can be stated in the form of repeatability. As there is no significant correlation between standard deviation and arithmetic mean of sets of test values, it appears that standard deviations are applicable to this test method regardless of the average locked-wheel sliding friction of the surface. An acceptable standard deviation, σ, of 2 SN units was obtained from numerous friction tests conducted on a variety of systems.*

The following criteria for assessing data quality were thus developed based on the ASTM guidelines and past research findings:

- Old pavements with constant SN may exhibit seasonal or weather-related variations.
- SN values are expected to remain the same or decrease as traffic is applied to the pavement.
- An increase in skid number within the 95-percent confidence interval ($1.96\sigma \simeq 4$ SN) of the initial test measurement is possible and may be attributed to random error in the test process (precision of testing).
- An increase in SN values of more than 4 SN units (greater than the recommended 95-percent confidence interval) would be considered questionable. This would imply that there is more variability than acceptable (at the 95-percent confidence level) in the test measurements.

Figure 10 presents a flow chart of the data quality classification procedure. Figure 11 shows the as-expected and questionable data. Time-series plots were developed for all pavement sections in the LTPP database that had friction data. The plots clearly show the trends of the

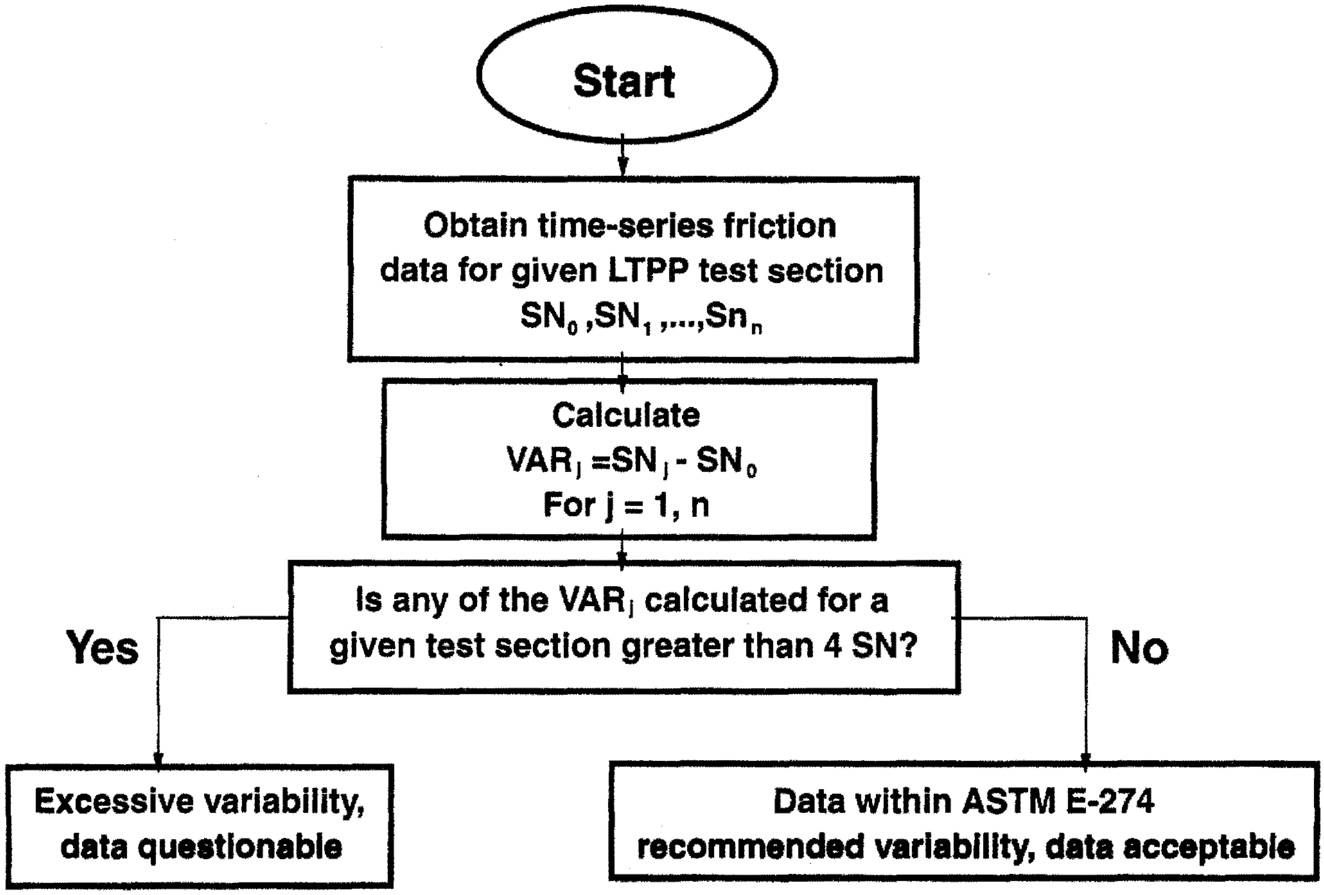

Figure 10. Flow chart of friction data quality classification procedure.

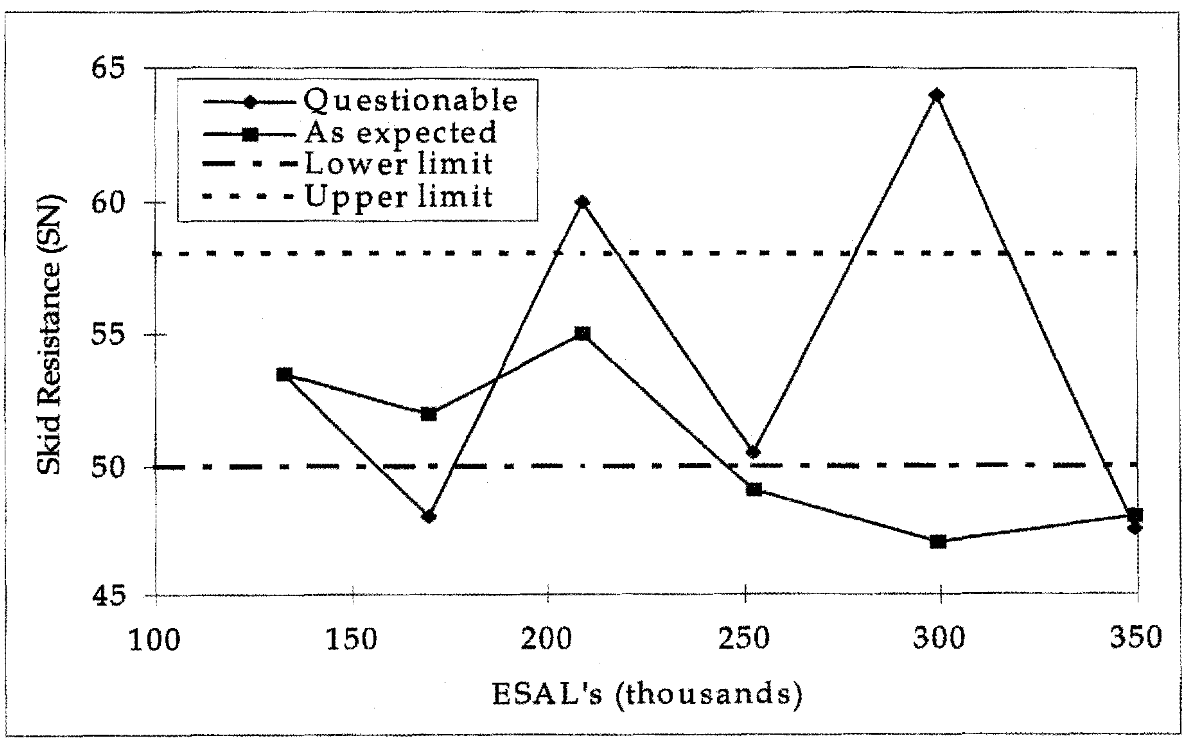

Figure 11. Plot showing time-series friction data with as-expected and not-as-expected data.

measured skid numbers. Pavement sections with as-expected trends based on the criteria discussed were identified. A detailed summary of the results is presented in appendix B. Typical time-series plots showing data with as-expected and questionable variability are illustrated in figures 12 and 13, respectively.

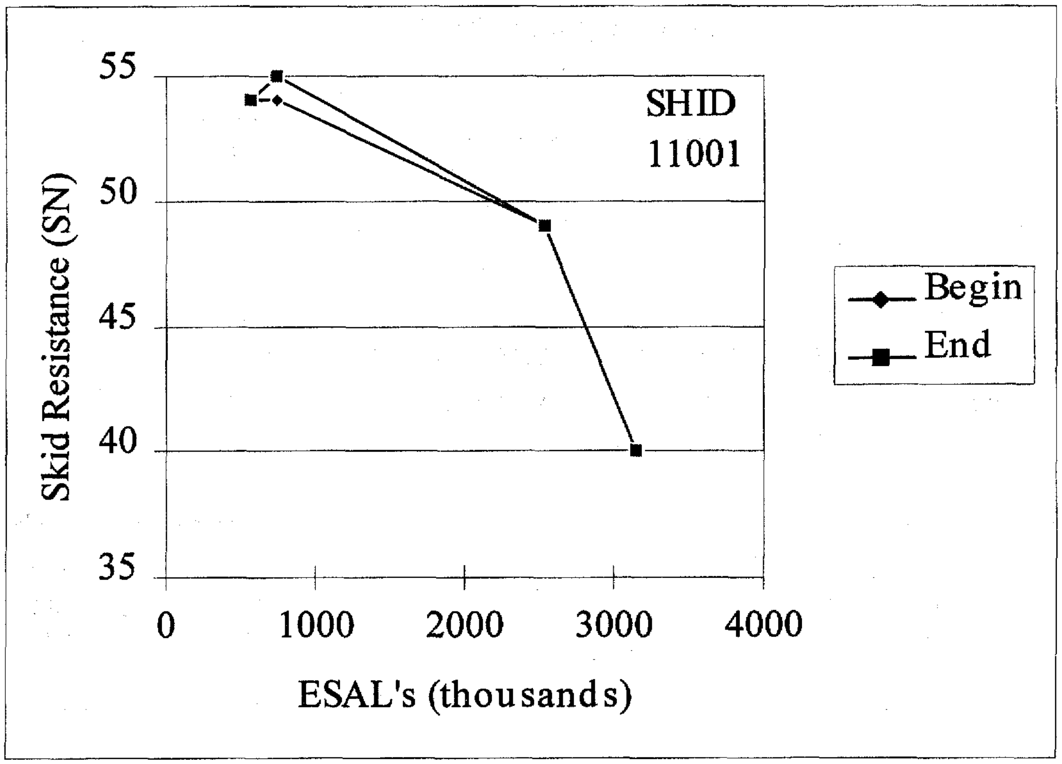

Figure 12. Plot of SN versus ESAL's showing data with expected variability.

Summary of Friction Data Quality by State, Territory, or Province

As indicated previously, friction data used for the data quality assessment were obtained from Release 7.0 of the LTPP data (Fall 1996). There were a total of 2,441 observations from a total of 723 GPS sections. A summary of the friction data quality by State, Territory, or Province is given in table 11. It should be noted that test sections refer to experimental test sections and not just physical test sections. A section with a construction number of 2 or 3 (indicating that the pavement surface has been altered since the start of the LTPP monitoring) is treated as a separate section.

Probable Causes of Questionable Data

It is obvious that a high number of pavements in the database have questionable data. It is therefore necessary to determine the probable causes for the questionable data. Table 11 is a summary of the percentage of as-expected and questionable data from all the States and Provinces. The testing methods, equipment, friction data, and all other relevant information for these sections were reviewed to determined the probable causes for the questionable data.

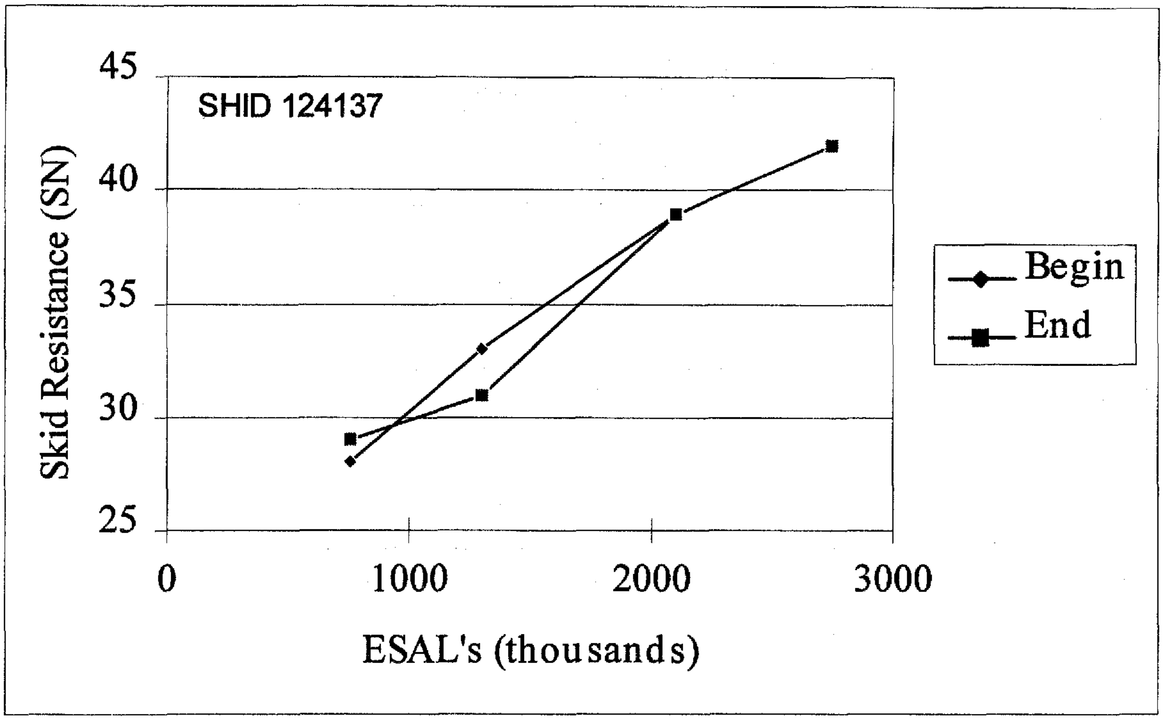

Figure 13. Plot of SN versus ESAL's showing data with not-as-expected variability.

Test Location

A review of the literature shows that skid number measurements can exhibit large variations in values for tests conducted at different locations on a given pavement, even if those locations are very closely spaced. Therefore, to obtain accurate data with the repeatability recommended by ASTM E-274, tests should be performed at the same location within the test section. There should be no lateral or longitudinal deviations from the spot of the initial friction test and the same spot should be tested over the time and traffic applications in order to obtain the kind of data that can be evaluated to determine changes in SN.

Equipment

The friction test system is made up of different pieces of equipment, all of which should be well calibrated to obtain reliable test results. A review of the supporting data for pavement sections with questionable data showed that in a number of cases, the differences in the test results may have been due to the use of different test equipment. For example, results were different for tests conducted on some sections in Texas before or after 1991. This may be due to a change in test equipment. Arizona conducted repeated friction measurements using similar test equipment but with different test tires, which resulted in a difference in measurements ranging from 6 to 50 percent. Figure 14 is a chart comparing measured skid numbers from smooth and

Table 11. Summary of LTPP data quality classification.

State/Province	Total number of test sections	Data quality classification			Comments
		As expected (%)	Questionable (%)	NC* (%)	
Alabama	18	72	16	11	11 percent (2 of 18 pavements) could not be classified because they had no time-series data.
Arizona	24	83	17	0	None.
Arkansas	14	0	0	100	None of these sites had time-series data. Therefore, the quality of the data could not be assessed using the criteria outlined in this report.
California	36	52	34	14	The questionable data generally exhibited increasing skid number values. This may be due to the use of different types of test equipment for performing the tests.
Colorado	16	0	0	100	None of these sites had time-series data. Therefore, the quality of the data could not be assessed using the criteria outlined in this report.
Connecticut	5	100	0	0	Data collected on August 27, 1991, were out of the expected range for three of the four pavement sections. With these measurements taken out, all the data from the four test sections were classified into the as-expected category. The reason for the poor data was not obvious.
Delaware	5	100	0	0	
Dist. of Columbia	1	0	0	100	The test pavement had no time-series data.
Florida	37	51	32	16	Six pavement sections had no time-series data and the remaining 32 percent (12 of 37 pavements) had questionable data.
Georgia	24	96	4	0	The questionable data generally exhibited increasing skid number values with an increase in age.

Table 11. Summary of LTPP data quality classification (continued).

State/Province	Total number of test sections	Data quality classification			Comments
		As expected (%)	Questionable (%)	NC* (%)	
Idaho	13	0	0	100	None of these sites had time-series data.
Illinois	20	65	5	30	The questionable data generally exhibited an increase in skid number with an increase in age or traffic applications.
Indiana	20	55	35	10	The questionable data generally exhibited an increase in skid number with an increase in age.
Iowa	10	30	70	0	The questionable data generally exhibited increasing skid number values with an increase in age.
Kansas	18	55	33	11	The questionable data generally exhibited an increase in skid number with an increase in age. The possible reasons for the questionable data may be attributed to the use of different test equipment and performing tests at speeds other than the standard 65 km/h.
Kentucky	8	87	0	13	One section had no time-series data.
Louisiana	2	100	0	0	None.
Maine	11	10	63	27	The remaining seven sections were classified as questionable because all the tests performed in October 1988 were out of trend.
Maryland	6	67	33	0	None.
Massachusetts	3	33	67	0	None.
Michigan	11	63	27	10	The questionable data generally exhibited increasing skid number values with age.
Minnesota	22	0	0	100	None of the test sites had time-series data.
Mississippi	24	25	0	75	18 sections had no time-series data.
Missouri	25	64	24	12	The questionable data generally exhibited increasing skid number values with age.

Table 11. Summary of LTPP data quality classification (continued).

State/Province	Total number of test sections	Data quality classification			Comments
		As expected (%)	Questionable (%)	NC* (%)	
Montana	7	71	14	14	The questionable data generally exhibited increasing skid number values with age.
Nebraska	11	54	46	0	The questionable data generally exhibited increasing skid number values with age.
Nevada	7	42	28	28	The questionable data generally exhibited increasing skid number values with age.
New Hampshire	1	0	100	0	None.
New Jersey	9	33	67	0	None.
New Mexico	12	50	50	0	The questionable data generally exhibited increasing skid number values with age. The data measured in 1992 were generally out of trend. Removing these data would improve the status of the data from some of the test sites.
New York	7	28	72	0	None.
North Carolina	28	60	35	5	The questionable data generally exhibited increasing skid number values with age.
North Dakota	5	0	0	100	None of these sites had time-series data.
Ohio	10	60	20	20	The questionable data generally exhibited increasing skid number values with age.
Oklahoma	20	40	55	5	The questionable data generally exhibited increasing skid number values with age.
Oregon	12	58	17	25	The questionable data generally exhibited increasing skid number values with age.
Pennsylvania	18	17	0	83	Fifteen pavements had no time-series data.
Rhode Island	1	100	0	0	None.
South Carolina	9	0	0	100	Data could not be classified because they consisted of single data entries.

Table 11. Summary of LTPP data quality classification (continued).

State/Province	Total number of test sections	Data quality classification			Comments
		As expected (%)	Questionable (%)	NC* (%)	
South Dakota	13	38	15	46	There was an increase in skid resistance with age for the questionable pavement sections.
Tennessee	18	78	6	16	There was an increase in skid resistance with age for the questionable pavement sections.
Texas	95	23	73	4	Four sections had no time-series data.
Utah	12	67	8	25	There was an increase in skid resistance with age for the questionable pavement sections.
Vermont	7	14	28	58	There was an increase in skid resistance with age for the questionable pavement sections.
Virginia	13	61	31	8	There was an increase in skid resistance with age for the questionable pavement sections.
Washington	19	42	48	10	There was an increase in skid resistance with age for the questionable pavement sections.
Wisconsin	14	57	43	0	There was an increase in skid resistance with age for the questionable pavement sections.
Puerto Rico	4	75	25	0	There was an increase in skid resistance with age for the questionable pavement sections.
Alberta	5	0	0	100	Data could not be classified because they consisted of single data entries.
British Columbia	4	75	0	25	
Manitoba	5	100	0	0	None.
New Brunswick	4	25	75	0	There was an increase in skid resistance with age for the questionable pavement sections.
Newfoundland	3	33	67	0	There was an increase in skid resistance with age for the questionable pavement sections.
Nova Scotia	1	0	0	100	Data could not be classified because they consisted of single data entries.

Table 11. Summary of LTPP data quality classification (continued).

State/Province	Total number of test sections	Data quality classification			Comments
		As expected (%)	Questionable (%)	NC* (%)	
Ontario	7	71	0	28	There was an increase in skid resistance with age for the questionable pavement sections.
Prince Edward Island	3	67	33	0	There was an increase in skid resistance with age for the questionable pavement sections.
Quebec	9	0	0	100	Data could not be classified because they consisted of single data entries.
Saskatchewan	7	28	43	28	There was an increase in skid resistance with age for the questionable pavement sections.
Total	773	45	29	25	

*NC = Not classified

ribbed tires using data from Arizona. The level of variability is high, and it strongly suggests that SN values are influenced by the type of test tires used since they measure different components of friction. Also, figure 14 shows that the effect of the test tire varies by pavement type.

Available information shows that most of the highway agencies use ribbed tires for friction testing; however, because a minority of the testing agencies use smooth tires, data from the different testing agencies must be used with care. Combining SN values for ribbed and smooth tires may be meaningless. Also, the use of different types of tires for testing within the same highway agency must be discouraged unless both tires are used at a given speed during a test sequence. Finally, the test equipment must be calibrated such that there is continuity and minimum variability for SN values with time.

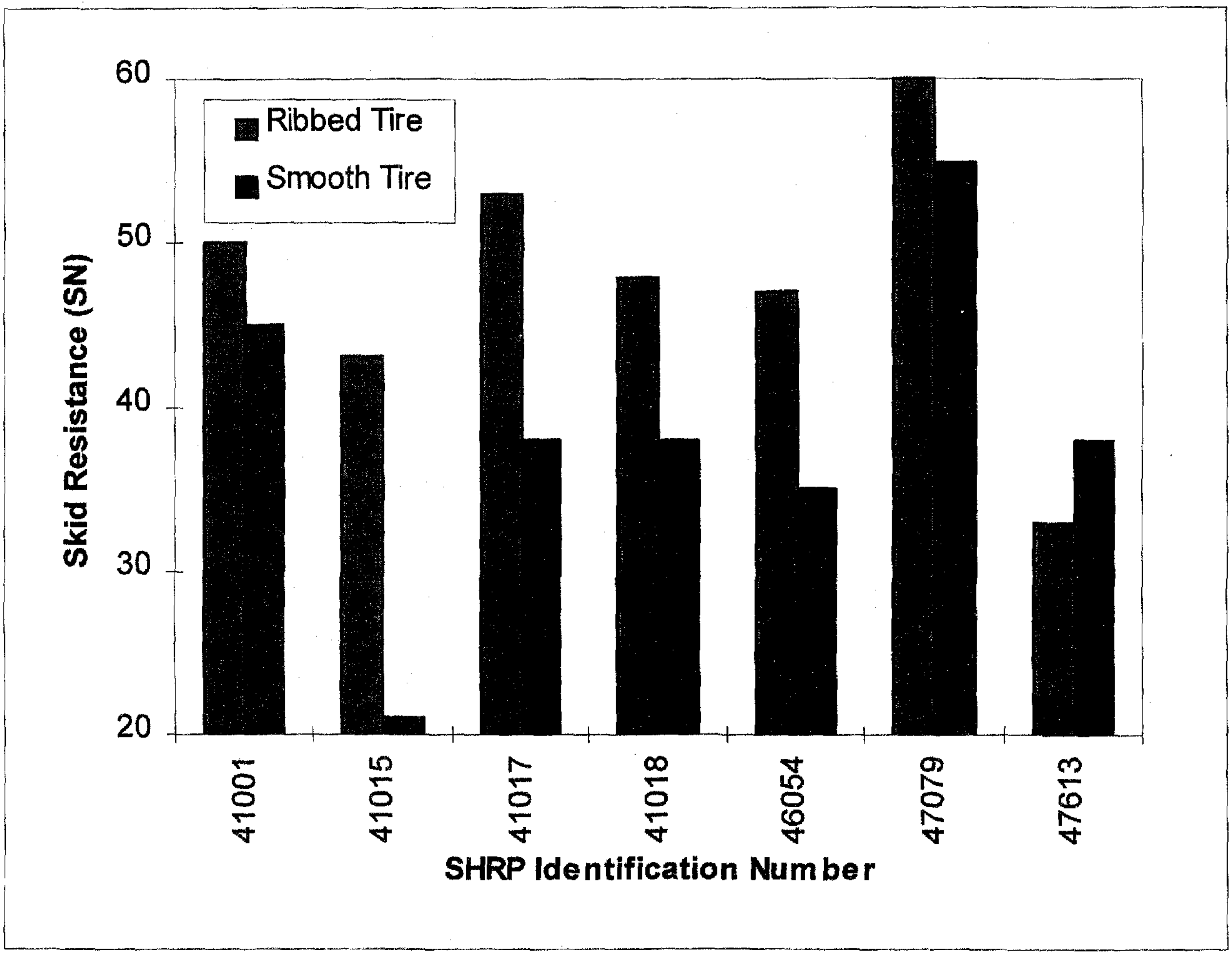

Figure 14. Skid numbers for tests conducted using ribbed and smooth tires.

Test Temperature

The influence of temperature on friction measurements is still under investigation, and there is no procedure currently available for correcting test results for the effect of temperature variation. The LTPP database showed significant differences in the temperatures at which tests were conducted for a given pavement at different times. This could be one of the contributors to the variability observed in the LTPP database. Variability could be limited if tests are conducted within a more tightly specified temperature range.

Operator Error

For some of the data classified as questionable, there was no apparent reason for the high level of variability. Such variability may exist because different operators test pavements over time. Such variability can be minimized by providing adequate training to the operators.

Distress and Surface Contamination

The surface characteristics of in-service pavements change with the application of traffic. Most pavements exhibit some differences in surface characteristics, such as the onset of distress or the contamination of the surface by solid or liquid contaminants, between consecutive skid resistance measurements. Such differences affect the measured skid resistance values and could result in an increase in variability. Some highway agencies document the moisture condition of the pavement surface. This practice should be encouraged. Also, the possible contamination of a pavement surface by dry contaminants should be noted. To minimize and understand possible sudden increases in variability in friction test measurements, the condition of the pavement surface during testing should be documented.

Effect of Beginning and End Skid Resistance Values

For the LTPP program, friction measurements are made along two 60-m subsections (one at the beginning and one at the end) within the 152.4-m LTPP test pavement section. It is reasonable to expect that for most test pavement sections, the surface characteristics, climate conditions, and the state of the testing equipment and operators will be the same for tests conducted at approximately the same time. Table 12 is a summary of the difference in the beginning and end skid number values for the LTPP data evaluated. A large difference in skid number for the beginning and end tests within the test section indicates large variability in the pavement surface condition. It should be noted that the difference in 92 percent of the testing was 4 SN or less, indicating reasonable consistency in pavement surfaces between the beginning and end portions of the test sections.

Weather Conditions

The weather condition prior to friction testing (e.g., wetness during the preceding 7 days before testing) may significantly affect skid resistance. The state of the pavement surface just prior to testing should therefore be documented. This information can be used to normalize the data or to explain excess variability.

Table 12. Difference in beginning and end SN values for LTPP data.

Difference	Number of observations	Percentage of total observations
0	619	25
1	821	34
2	443	18
3	220	9
4	141	6
5	71	3
6	72	2
7	17	1
8	15	1
9	10	0
Greater than 9	24	1

Date of Testing

The date of friction testing could also explain the presence of variability. Pavement surfaces tend to be contaminated by different contaminants according to the season and, therefore, the date of testing. It is well known that testing soon after the end of the winter season may result in higher skid resistance values in northern environments because the use of abrasives during the winter season may rejuvenate the pavement surface with respect to frictional properties.

5. POTENTIAL USES OF LTPP FRICTION TEST DATA

Introduction

Friction data are collected and used by many State highway agencies (SHA's) to monitor safety and to obtain performance-based data to research the effect of pavement mixture and aggregate properties and constructed surface texture properties on skid resistance. The use of friction data can therefore be categorized as follows:

- Accident and risk assessment analysis.
- Evaluation of the effect of pavement design features, material properties, and construction techniques on skid resistance.
- Evaluation of the need for intervention to improve skid characteristics.

To use the friction data obtained from skid testing effectively, there must be other relevant and complementary data available. Such data are used with the friction data to develop models and procedures for identifying potential risk and accident areas that will need rehabilitation and to develop strategies for designing and constructing long-lasting pavements with adequate skid resistance for the expected service life of the pavement.

Also, as discussed previously, the use of the International Friction Index (IFI) procedure for LTPP friction data collection will allow harmonization of the different friction measuring equipment and procedures and will make results from all test sites globally applicable with respect to data analysis.

This chapter summarizes the complementary data required for analysis and discusses how much of this type of data is currently available in the LTPP database.

Complementary Data Required for Accident and Risk Assessment Analysis

Pavements are designed in general to have adequate skid resistance to satisfy the demand for tire-pavement friction. Friction demand depends on several factors, e.g., the driver's skills, driving habits, and the vehicle's performance and capabilities. The data elements required for a complete analysis of friction demand at a given site are listed below:[5, 34]

- Speed.
- Road geometry.
- Traffic volume.
- Percentage of trucks in traffic.
- Vehicle characteristics.
- Driver skills.

A primary reason for friction testing is to provide an indicator of wet weather accident rate. As such, total and wet weather accident rate data should also be considered.

No further discussion on this topic is presented here as the evaluation of site-specific friction demand was not an objective of the reported study. Additional discussion on this topic is presented in references 43 and 44.

Complementary Data for Assessing Pavement Skid Resistance Performance

Several pavement design features, material properties, and construction techniques influence the availability of friction and loss of friction for AC and PCC pavements. These variables were discussed in detail in chapter 2 of this report. A summary of the needed complementary data is presented in table 13.

Friction Data Availability in LTPP Database

The LTPP database is the most comprehensive national database in the United States. It has friction measurements reported as SN and other complementary data that could be used for analysis. This section summarizes the friction data available in the LTPP database and the extent of complementary data available for comprehensive data analysis.

The LTPP database has 723 GPS pavement sections with friction data. Of these, 454 were AC sections and 269 were PCC. The quality of the friction data available for the 723 sections has been discussed and presented in chapter 4 of this report. The following is a summary of the quality of the data available:

- Of the total number of pavement sections with friction data, 23 percent (162 of 723 sections) could not be classified using the criteria outlined in chapter 4 because they lacked time-series data.
- Of the remaining 561 GPS sections with time-series data, 58 percent (327 of 561 sections) were classified as "as expected" and the remaining 42 percent (234 of 561 sections) were classified as questionable.
- Of the 327 pavement sections with as-expected data, 60 percent (194 of 327 sections) were AC and 40 percent (133 of 327 sections) were PCC.

Complementary Data Availability

The LTPP database has a wide range of friction-related data that could be useful for analysis. Tables 14 through 16 present a description of the data in the LTPP database and its availability. The information available in tables 13 through 17 was obtained from the review of the LTPP database. A detailed description of the data available is presented in appendix C of this report and the highlights of the review are summarized here.

Table 13. Complementary friction-related data required for analysis.

Data Classification	Data Element
General and test process	Pavement age
	Cumulative traffic at the time of testing (ESAL's, ADT)
	Test method (e.g., ASTM E-274, ASTM E-303)
	Test equipment
	Wheelpath tested
	Test speed
	Tire type
For performance evaluation (material properties)	Aggregate geological class
	Soundness (Insoluble residue)
	Hardness (fine and coarse aggregates)
	Polish value
	Binder type, grade
	Percent voids and AC binder content
	Coarse and fine aggregate content and aggregate gradation
	Aggregate shape and size
For performance evaluation (pavement surface condition)	Macrotexture depth
	Pavement condition rating at the time of testing
	Presence of liquid or solid contaminant at the time of testing
	Initial texture method (PCC pavements)
	Current surface texture type (PCC pavements)
	AC pavement type (e.g., dense-graded, open-graded, seal coat)
	PCC pavement type
For performance evaluation (maintenance)	Frequency of snow removal
	Frequency of deicing
	Patching, diamond-grinding, and other repairs
For performance evaluation (climate)	Annual number of freeze-thaw cycles and freezing index
	Precipitation and annual number of wet days
	Mean annual/daily temperature
	Air temperature during testing
For performance evaluation (construction)	Texture method (PCC pavements)
	Roller type, weight, frequency of application (AC pavements)

Table 14. General data description and availability.

Data Element	Data Availability (%)
Pavement age	100
Traffic (ESAL's, ADT)	66*
Test method (ASTM E-274, ASTM E-303, etc.)	100
Test equipment	100
Test speed	100
Test tire type (ribbed or smooth)	0
Wheelpath tested (inner or outer)	0

* Historical data

Table 15. Data description and availability for AC pavement friction evaluation.

Data Element	Data Availability (%)
Acceptable friction data (with expected trends)	194 sections
AC pavement type	100
Coarse aggregate geological class	36
Coarse aggregate specific gravity	36
Fine aggregate specific gravity	36
Hardness	Not available
Polish value	3
Soundness	Not available
Binder type, hardness, grade	Negligible
Mineral filler type	37
Pavement condition rating at the time of testing	Not available
Pavement surface moisture condition	Not available
Potential for solid contamination	Not available
Frequency of snow removal	36
Aggregate shape and size	Not available
Aggregate gradation	Negligible
Average annual temperature	85
Air temperature during testing	88
Annual precipitation	85
Freeze-thaw cycles	85
Roller type	Negligible
Roller weight	Negligible

Table 16. Summary of friction and pavement design, material, and construction variables available for PCC pavements.

Data Element	Data Availability (%)
Acceptable friction data (with expected trends)	133 sections
PCC pavement type	100
Coarse aggregate geological class	70
Coarse aggregate specific gravity	67
Fine aggregate specific gravity	67
Hardness	Not available
Soundness	Not available
Coarse aggregate content	85
Fine aggregate content	85
Cement type	85
Pavement condition rating at the time of testing	Not available
Pavement surface moisture condition at the time of testing	Not available
Potential for solid contamination at the time of testing	Not available
Frequency of snow removal	21
Aggregate shape and size	Not available
Aggregate gradation	Negligible
Average annual temperature	95
Air temperature during testing	95
Annual precipitation	95
Freeze-thaw cycles	95
Paver type	82
Texture method	82
Curing method	82

General Data

The LTPP database has information on the friction test results (measured as skid number); test speed; air temperature at the time of testing; and the methods, standards, and procedures used in testing. However, to assess the accuracy of the data and possibly to normalize the data, taking into account the prevailing condition of the pavement at the time of testing, there is the need for additional information, such as the following:

- Testing at two speeds or testing at one speed with both the smooth and the ribbed tires.
- Pavement surface moisture condition.
- Information on surface contamination (solid and liquid).
- Surface distress condition.

This list is not meant to be exhaustive, but the provision of such information in the database will enhance the ability of analysts to make decisions on the usefulness and accuracy of the friction data. All the pavement sections reviewed had information on the construction date and history, such as the date for major reconstruction events.

Approximately 70 percent of the LTPP pavement sections with friction data have traffic data in the form of equivalent single-axle loads (ESAL's). However, the data collected were not for the entire life of the pavement and had to be supplemented with projections and historical estimates. This has a negative effect on ESAL data accuracy.

Material Data

The material-related data in the LTPP database were inadequate. First, most of the pavements with friction data lacked information on material properties of the surface layer, such as specific gravity, gradation, geological classification, binder type, and polish value. Information, such as aggregate hardness, soundness, aggregate shape index, and mineralogy, was not provided at all. Since most past studies have shown that friction is directly related to these properties, the provision of this information will greatly enhance the usefulness of the data.

Maintenance

Pavements are subjected to different kinds of maintenance activities that affect skid resistance temporarily or permanently. Some of the temporary maintenance activities are snow removal and deicing procedures during winter. Approximately 20 percent of the sections within the LTPP database have data on such activities. The permanent maintenance activities on pavement sections within the LTPP database, such as patching and diamond-grinding, are well documented, and almost all pavement sections subjected to major construction events have data describing them.

Climate Data

There are enough climate-related data in the LTPP database for analysis.

Construction Data

The range of PCC construction variables in the LTPP database related to the pavement's surface characteristics is adequate. For AC pavements, two construction variables related to the pavement's surface characteristics were provided, namely roller type and weight. However, for most of the pavements with friction data, data on construction-related variables were missing, and no reasonable analysis can be made with what is currently available. For PCC pavements, there was some information on the method used for surface texturing. The information provided (i.e., tining, burlap drag, brooming) was not detailed enough. Past research studies have shown that there is a lot of variability in texture depths from these methods. Also, friction loss depends not only on the initial texturing method, but also on the properties of the mortar used in texturing. Providing in-depth information, such as texture depth and pattern, and mortar strength and material properties, will greatly enhance the usefulness of the data.

Preliminary Evaluation of Friction Data

To assess the overall quality of the friction and complementary data as part of evaluating friction data quality, the relationship between SN and some of the friction-related variables was investigated. The aim of the investigation was to:

- Determine the scope and extent of the data available.
- Determine if there were gaps in the data available.
- Determine trends between SN and some of the complementary data and compare to trends observed in past studies.

This was achieved through the use of bivariate plots and bivariate correlation analysis. This section presents a summary of the results of the investigation. It must be noted that the results presented are preliminary. It was beyond the scope of this study to investigate in-depth the mechanism and processes that result in the deterioration of skid resistance in pavements. It must also be noted that the data used in the preliminary analysis presented here make no differentiation with respect to what tire types were used during the friction testing. Results from smooth tire tests and ribbed tire tests cannot be compared directly.

Statistical Analysis

The bivariate plots and correlation analysis presented throughout this chapter are from the raw LTPP data. At this stage of the analysis, some of the results may be misleading because of confounding effects and interactions between the data elements. However, reasonable trends imply good reliable data and show that these data can be used for more in-depth analysis and research.

Bivariate Plots

Bivariate plots present a graph of data points based on two variables, where one variable defines the horizontal axis and the other the vertical axis. The pattern generated by the data points plotted could give an insight into the relationship between the two variables. Figures 15 some of the complementary data for both AC and PCC. A brief discussion of the trends observed are presented later in this chapter. It should be noted that even though clear trends cannot be observed in figures 15 through 31 because of the confounding effects of other variables not considered, these figures are useful as they do identify the inference space of the specific variables considered.

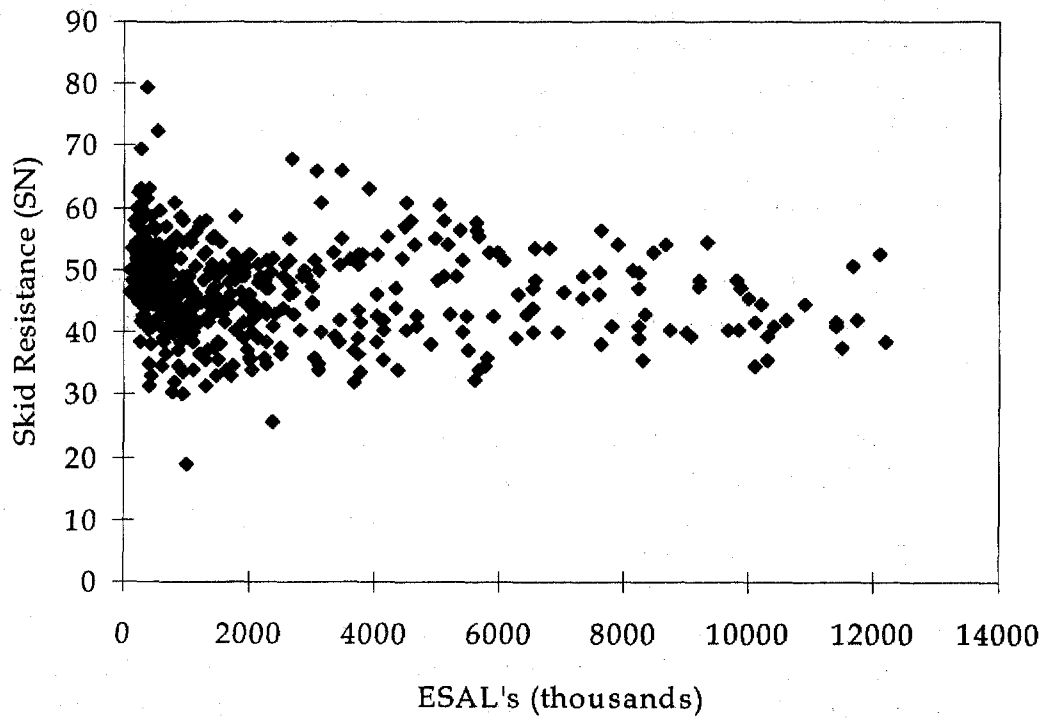

Figure 15. Plot of skid number versus cumulative ESAL's for AC-surfaced pavements.

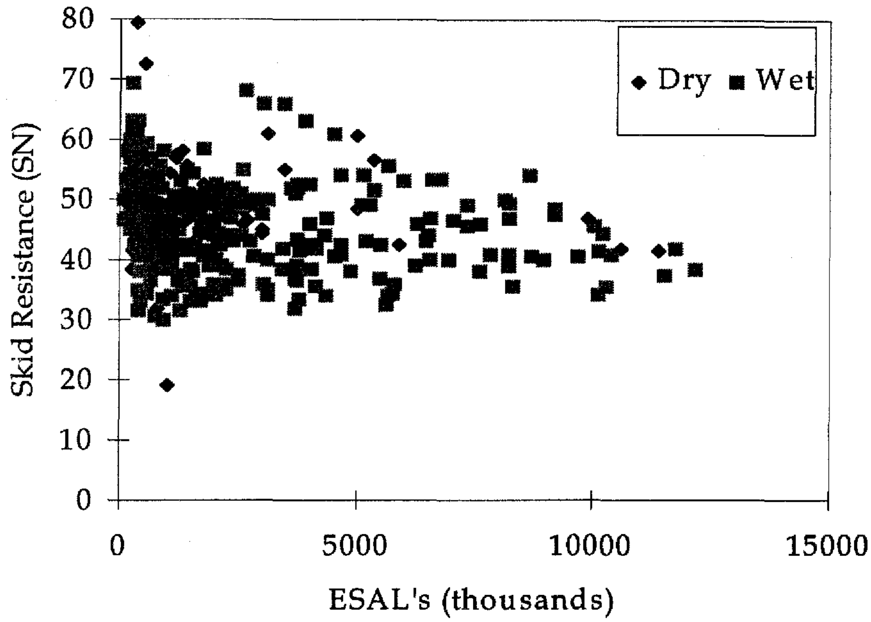

Figure 16. Plot of skid number versus cumulative ESAL's for AC-surfaced pavements showing the effect of climate (wet or dry).

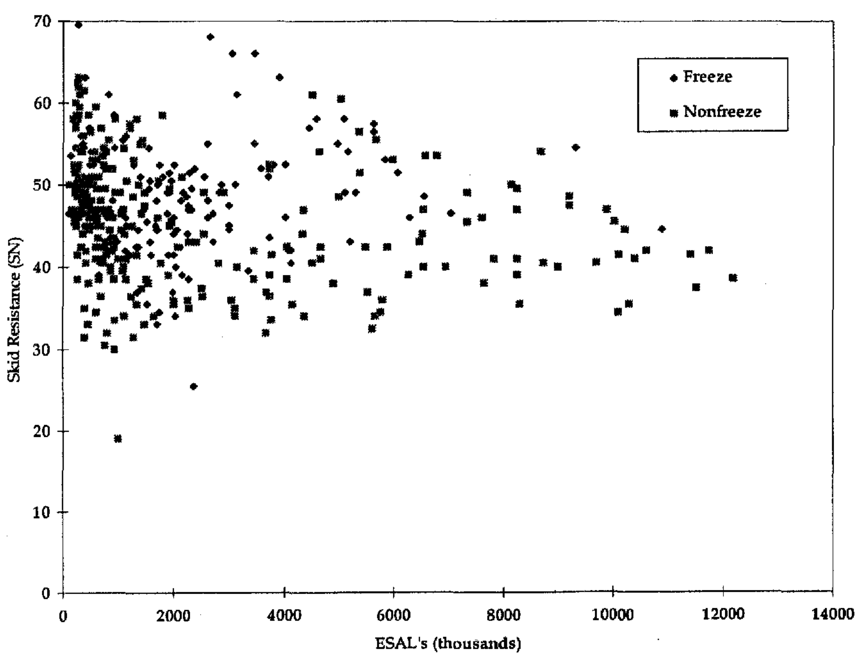

Figure 17. Plot of skid number versus ESAL's for AC-surfaced pavements showing the effect of climate (freeze or nonfreeze).

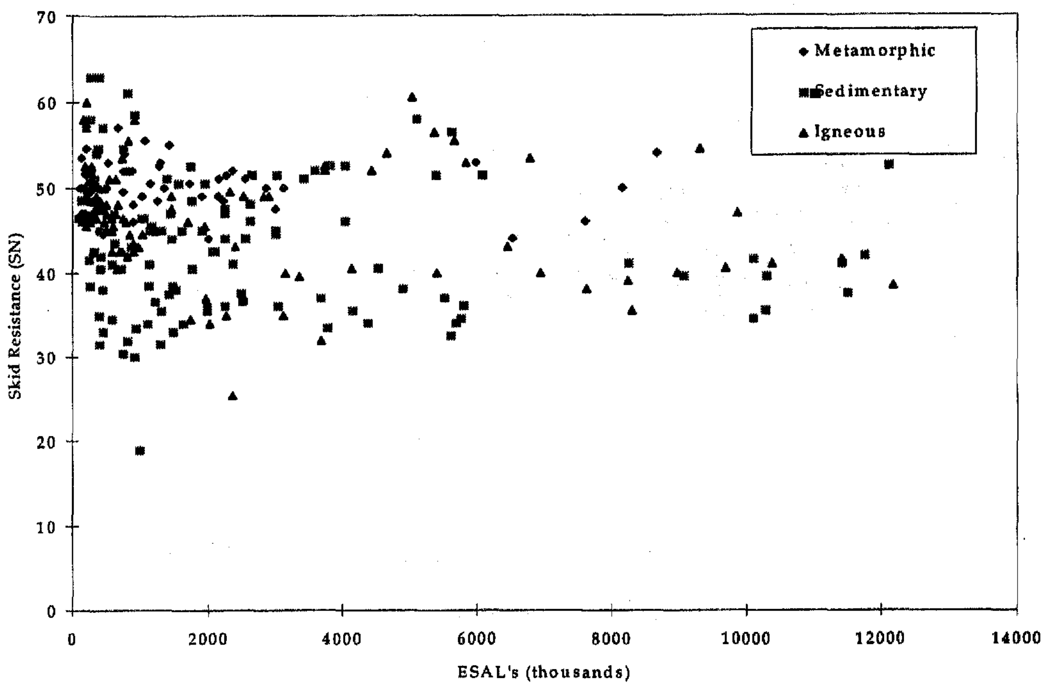

Figure 18. Plot of skid number versus ESAL's showing the effect of AC mix coarse aggregate geologic classifications.

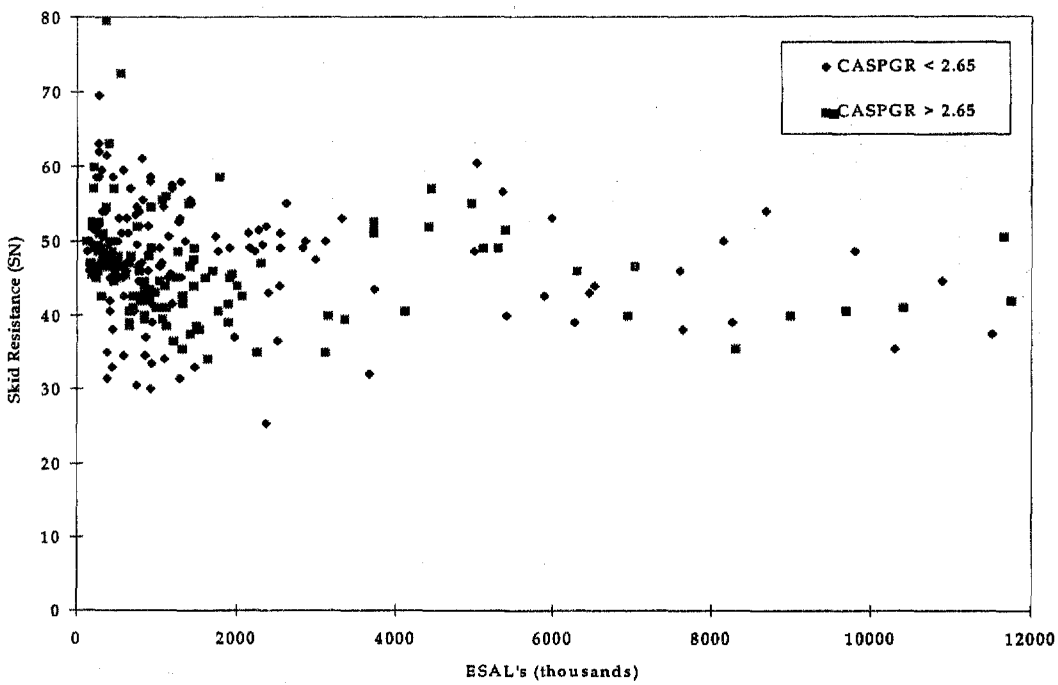

Figure 19. Plot of skid number versus age for AC-surfaced pavements showing effect of coarse aggregate specific gravity (CASPGR).

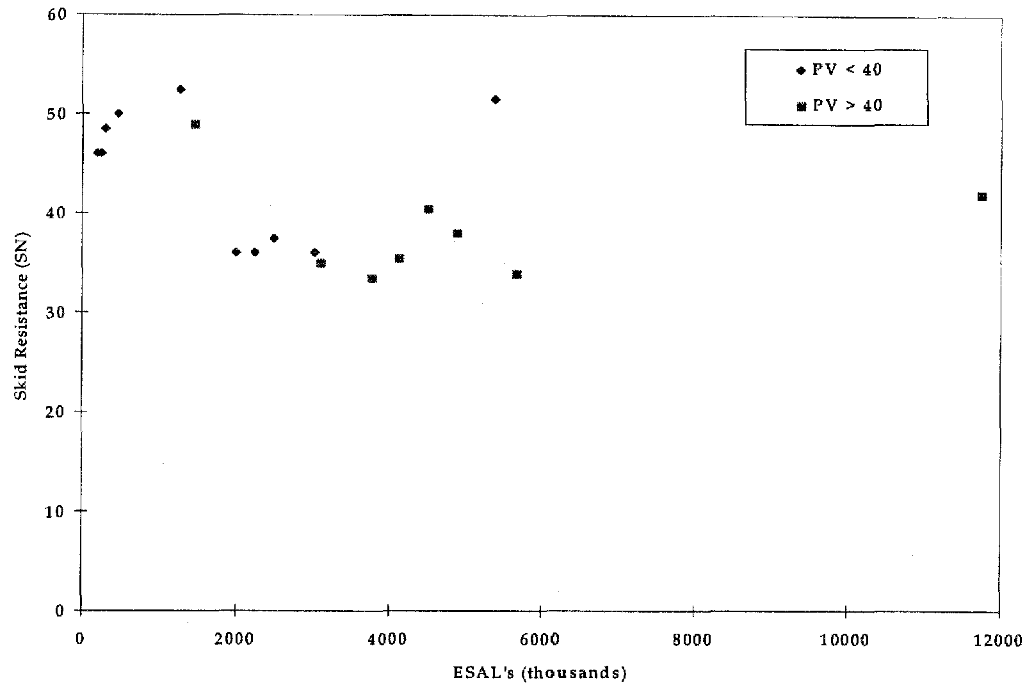

Figure 20. Plot of skid number versus ESAL's showing effect of AC material coarse aggregate polish value (PV).

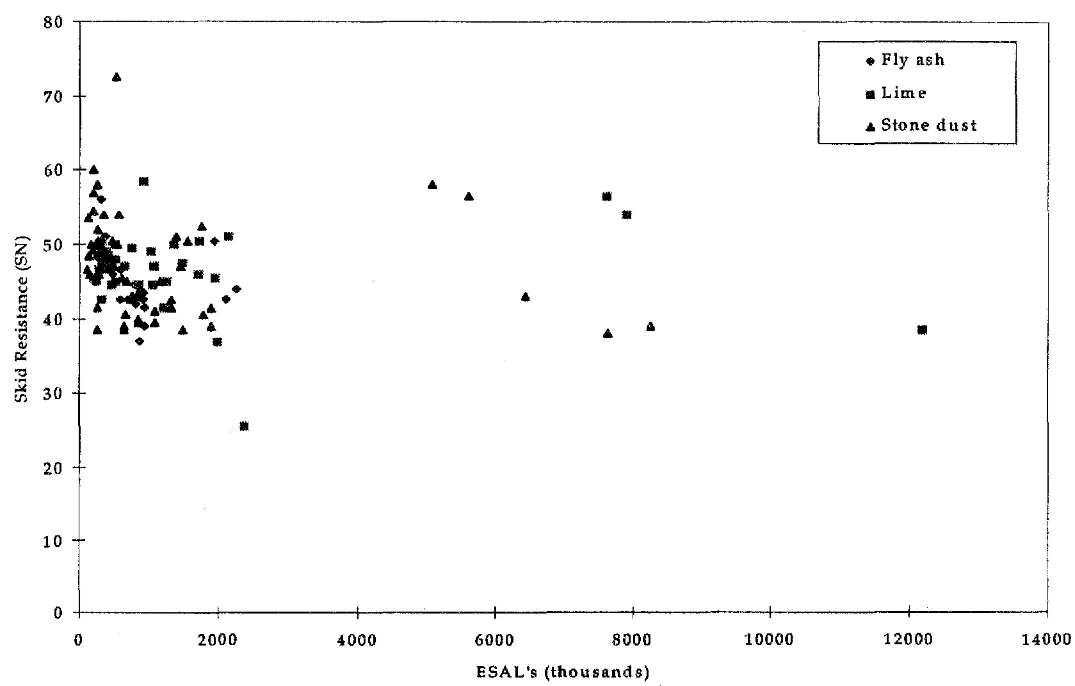

Figure 21. Plot of skid number versus ESAL's showing effect of AC mix mineral filler type.

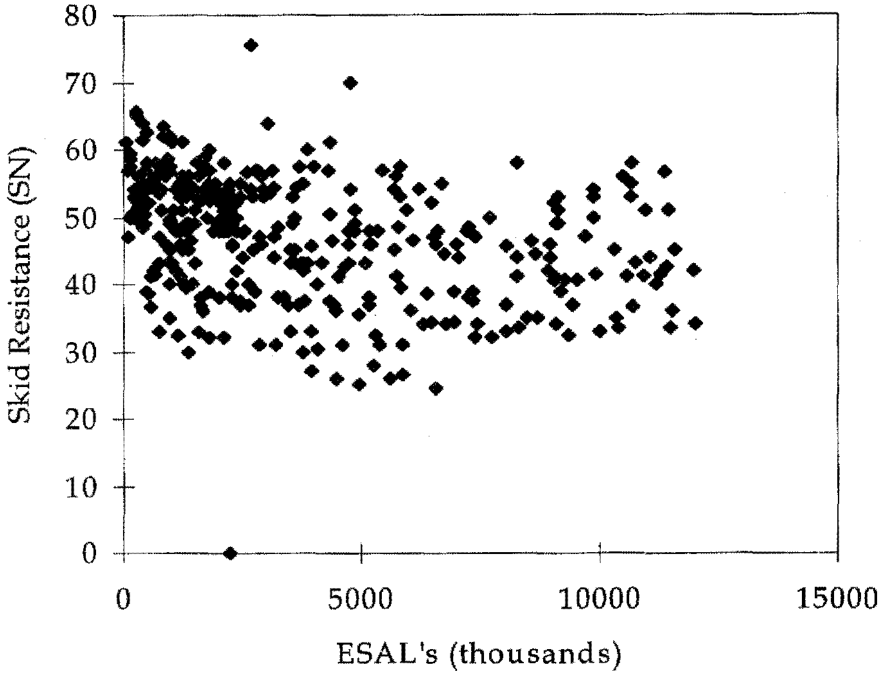

Figure 22. Plot of skid number versus ESAL's for PCC-surfaced pavements.

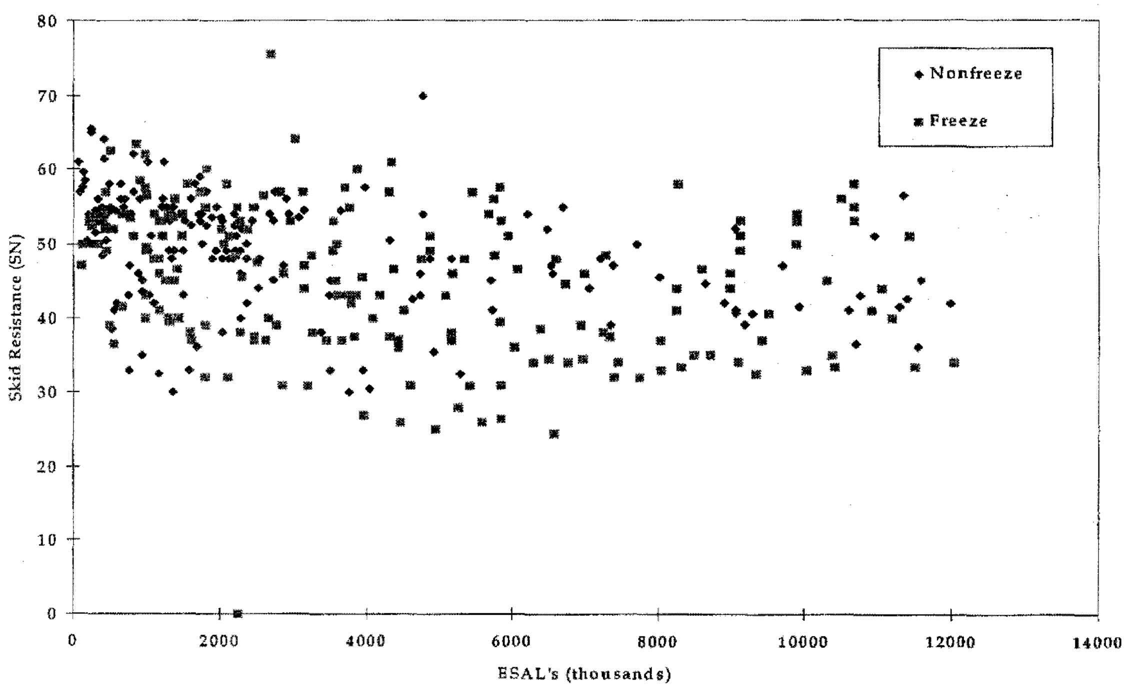

Figure 23. Plot of skid number versus ESAL's for PCC-surfaced pavements showing effect of climate (freeze or nonfreeze).

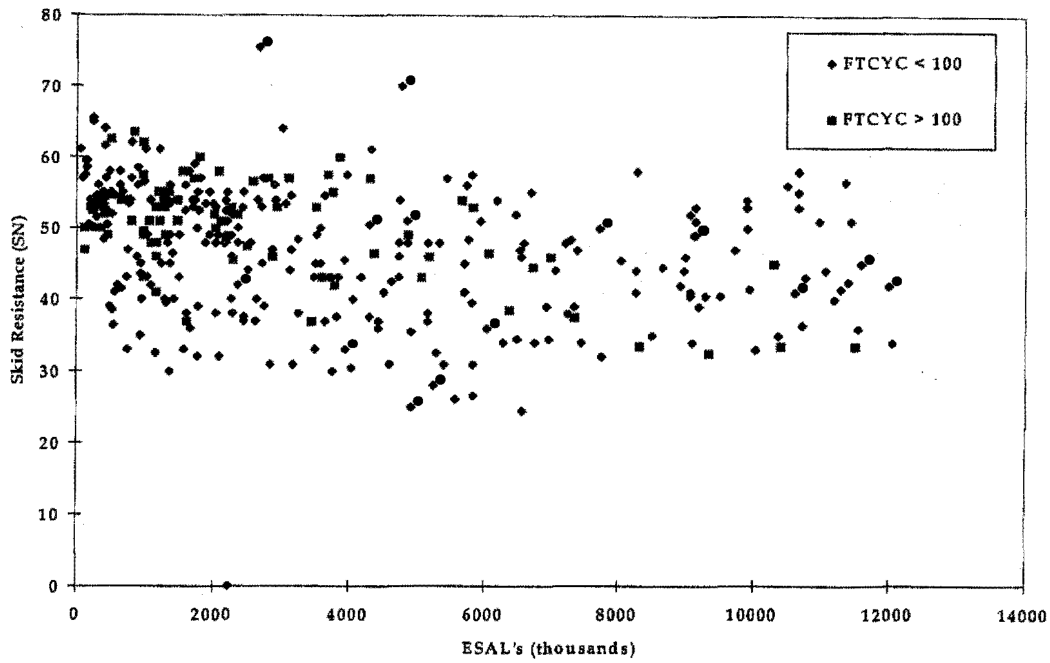

Figure 24. Plot of skid number versus ESAL's for PCC-surfaced pavements showing effect of freeze-thaw cycles (FTCYC).

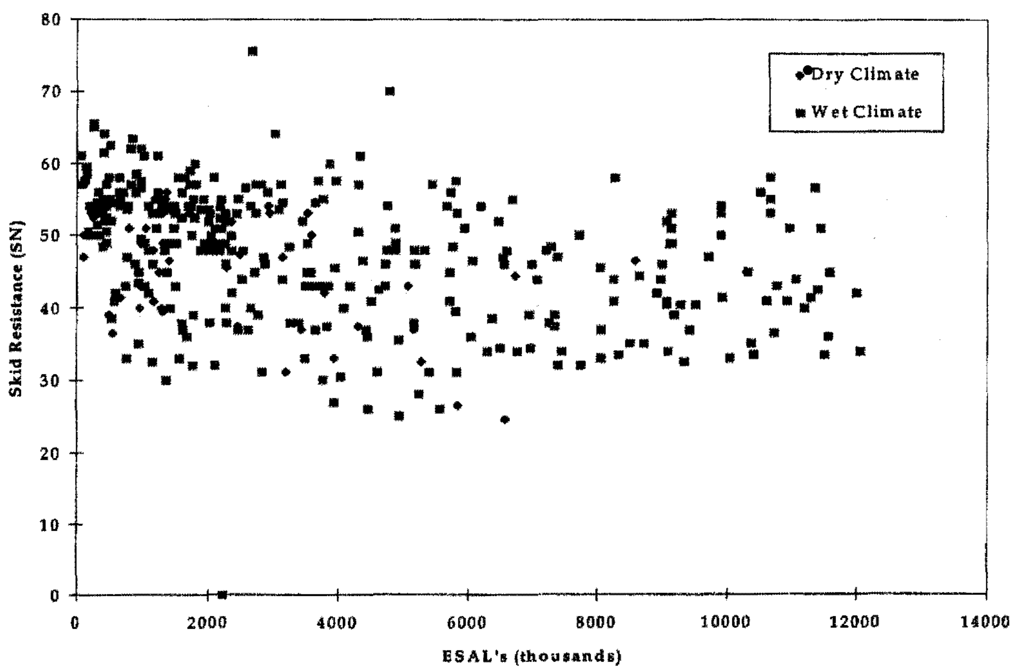

Figure 25. Plot of skid number versus ESAL's for PCC-surfaced pavements showing effect of climate (wet or dry).

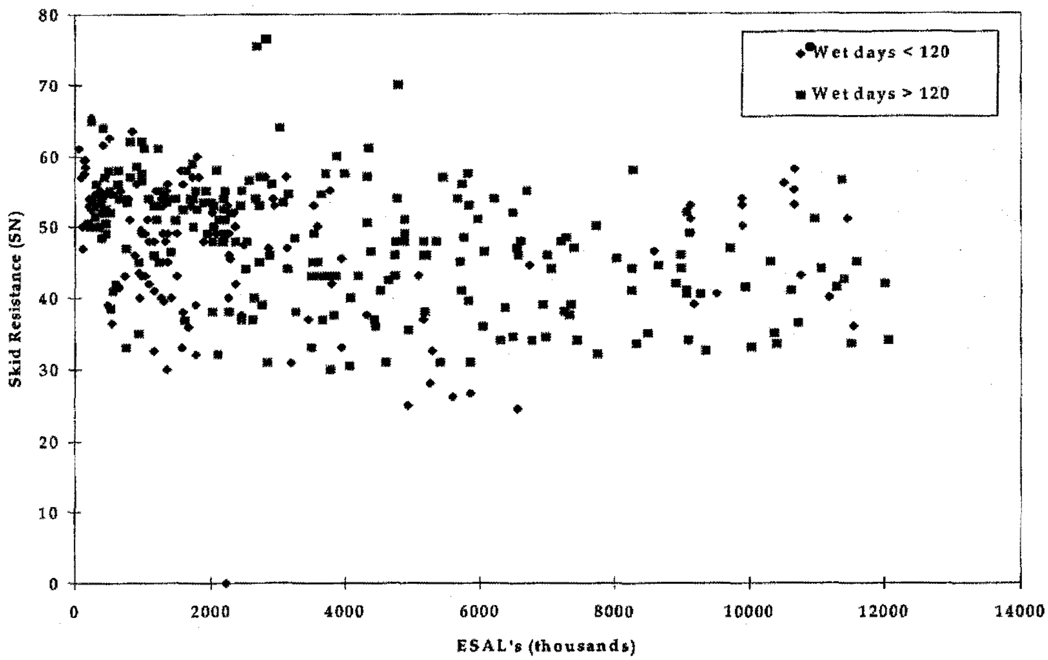

Figure 26. Plot of skid number versus ESAL's for PCC-surfaced pavements showing effect of wet days.

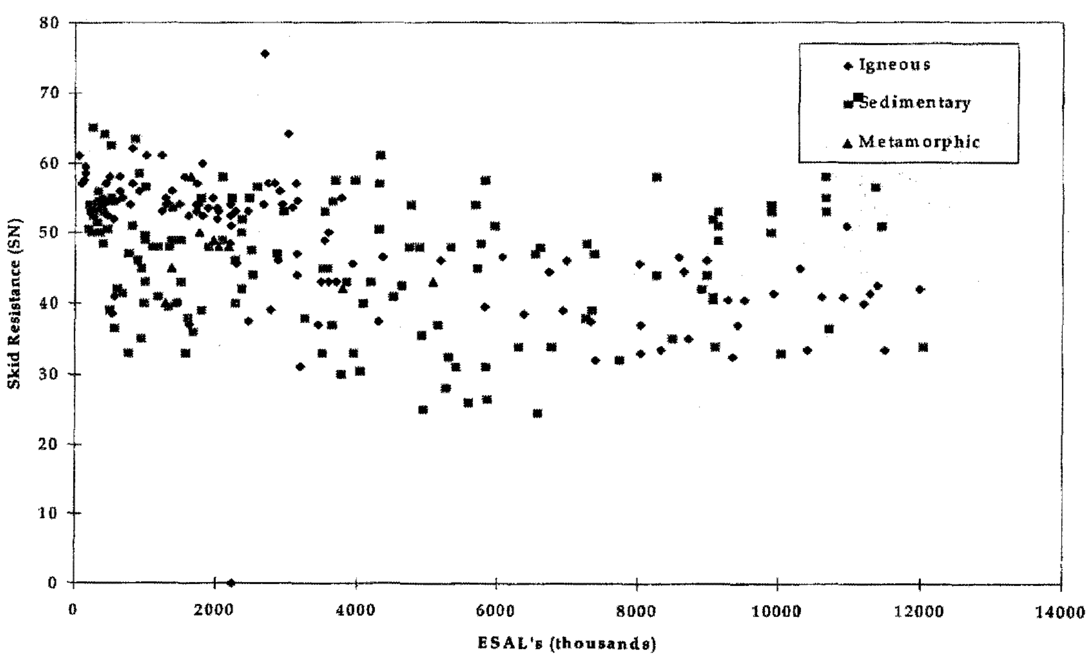

Figure 27. Plot of skid number versus ESAL's for PCC-surfaced pavements showing effect of coarse aggregate geologic classifications.

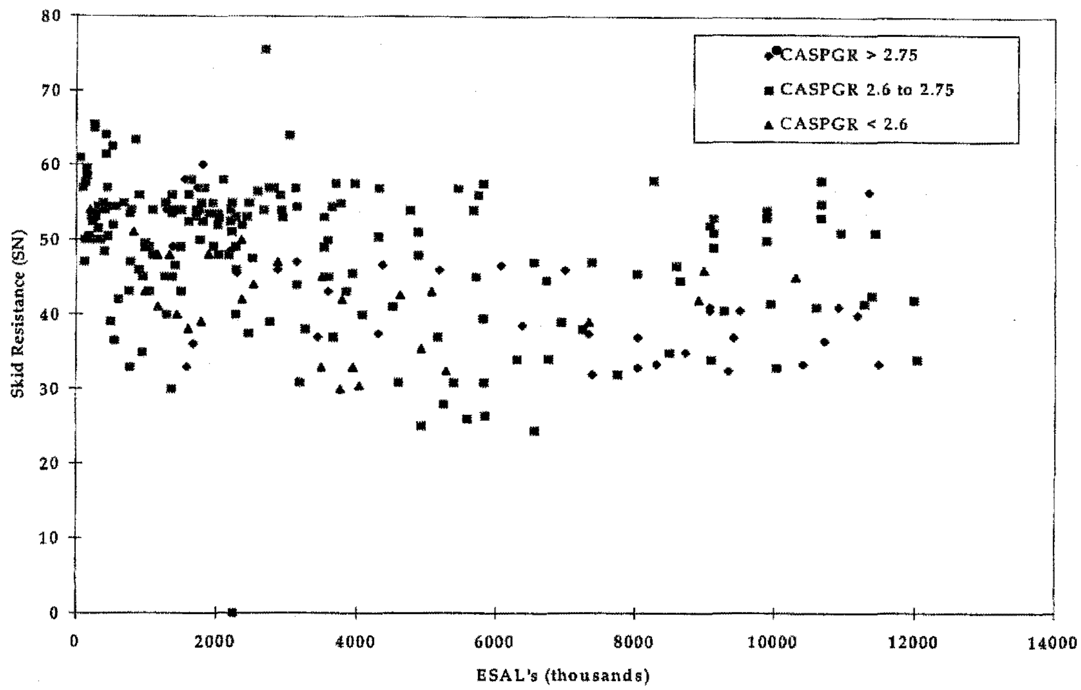

Figure 28. Plot of skid number versus ESAL's for PCC-surfaced pavements showing effect of coarse aggregate specific gravity (CASPGR).

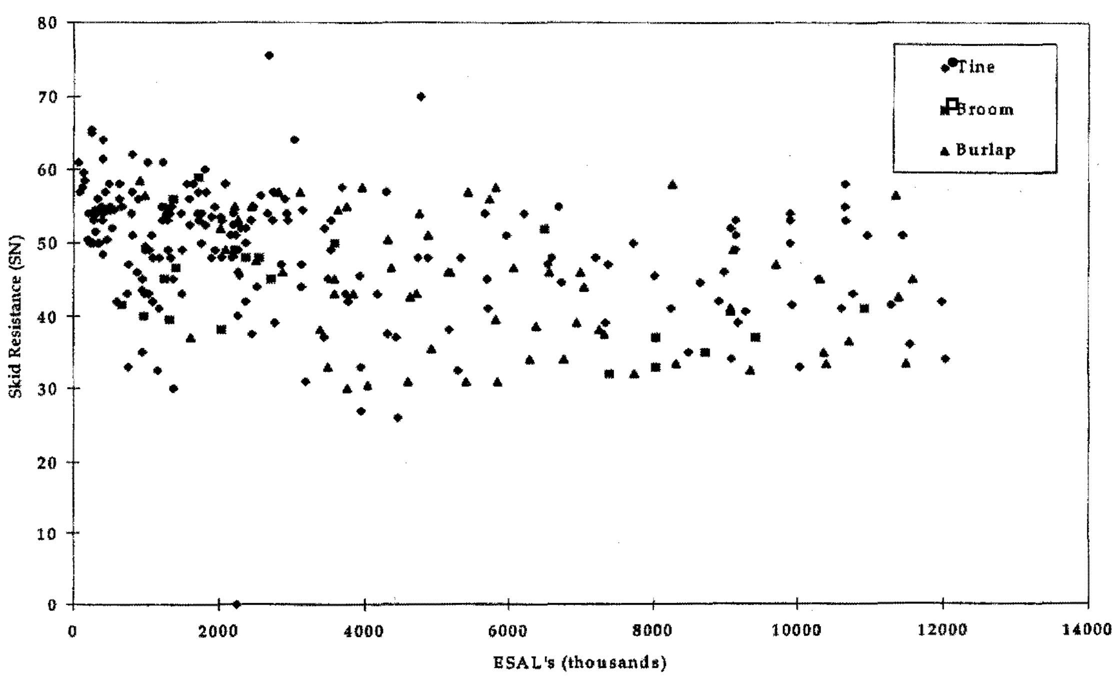

Figure 29. Plot of skid number versus ESAL's showing effect of surface texture.

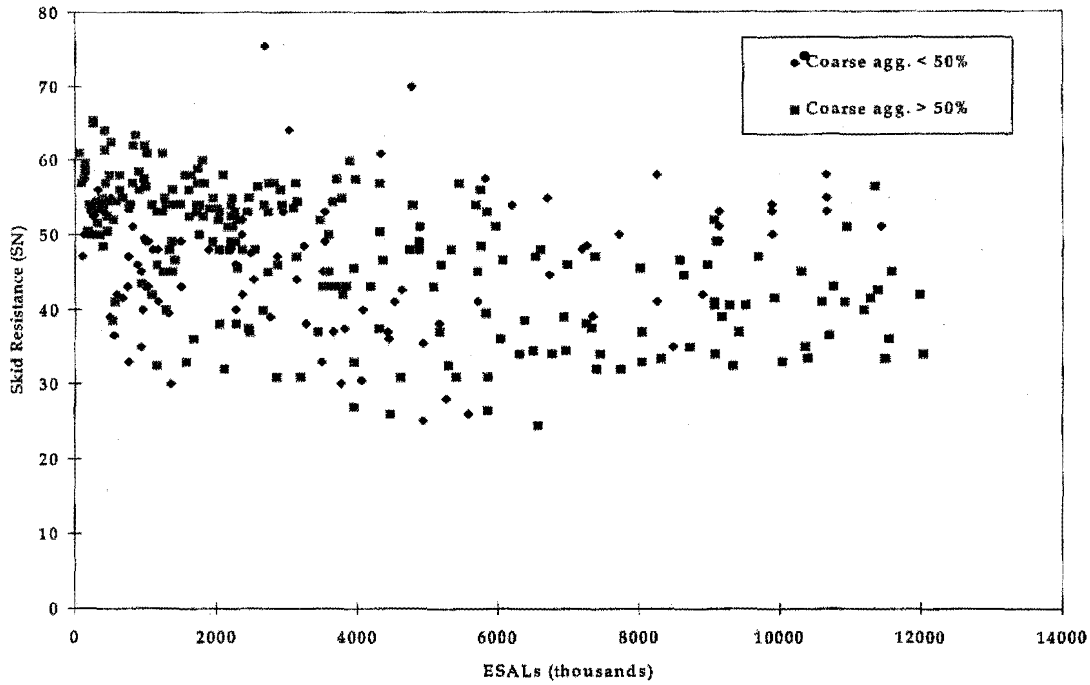

Figure 30. Plot of skid number versus ESAL's showing effect of percentage of coarse aggregate.

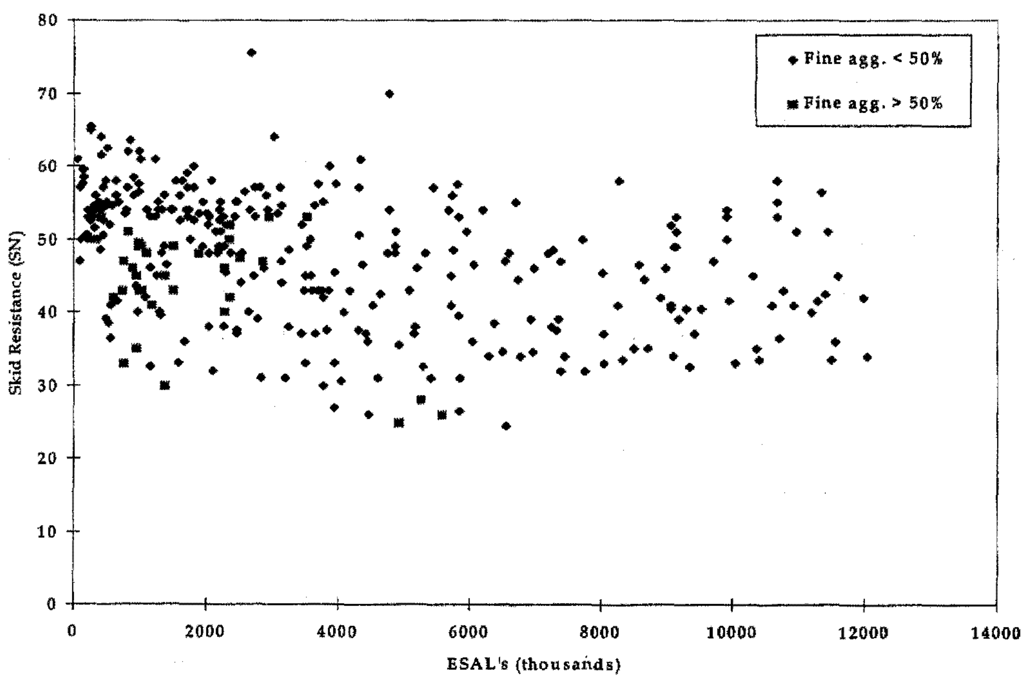

Figure 31. Plot of skid number versus ESAL's showing effect of percentage of fine aggregate.

Bivariate Correlation

Bivariate correlation provides a single number that summarizes the relationships between two variables (friction and friction-related variables). The correlation coefficients indicate the degree to which variation (or change) in one variable is related to variation in another. A correlation coefficient not only summarizes the strength of the association between pairs of variables, but also provides an easy means for comparing the strength of the relationship between one pair of variables and a different pair.

For this study, a comprehensive bivariate correlation analysis was conducted between the friction and friction-related variables in the LTPP database. The results are presented in tables 17 and 18. The results are also compared to observations from past research studies. Agreement with past research and basic engineering principles would show that the data are useful and can be used for research purposes. The definitions of the acronyms used to describe the variables used in the correlation analysis presented in tables 17 and 18 are provided in table 19.

Summary of Statistical Analysis

The bivariate plots showed trends between skid resistance and some of the key friction-related variables. The bivariate correlation results gave an indication of the strength of the correlation between the variables and also whether there was a positive or negative correlation between skid resistance and other friction-related variables. Results of the correlation analysis showed that the correlations with the key variables were quite low; however, the values were not significantly lower than those of LTPP data used in past analyses.[38-41] The analysis showed some interesting trends and correlations, which are summarized in the following sections.

AC-Surfaced Pavements

Effect of Traffic Applications

Figure 15 shows the effect of traffic on skid resistance. Skid resistance generally was reduced with increases in traffic load applications. Moving wheels impose shear stresses on a pavement's surface, which, in turn, cause the aggregate surface to smooth, polish, or disintegrate. This situation leads to a reduction in skid resistance.

Effect of Freeze and Nonfreeze Climates

Figure 17 shows the effect of climate (freeze or nonfreeze) on skid resistance. Pavements located in nonfreeze climates had a higher rate of friction loss than those in freeze climates. There was a fair to strong correlation between skid resistance and temperature-related variables such as maximum, minimum, and mean temperature; freezing index; and freeze-thaw cycles. Pavements located in regions with higher temperatures are likely to exhibit more skid resistance, while those with a higher freezing index or annual freeze-thaw cycles are likely to exhibit less skid resistance. Past research has shown that the temperature at the time of testing influences skid resistance; however, the exact nature of the effect of temperature on the testing process and friction loss is not fully understood.

Table 17. Summary of correlation analysis for AC pavement complementary data.

Data element	No. of observations	Correlation coefficient	Prob > |R|
Skidno	722	1	0
Age	725	-0.0274	0.4617
Speed	718	-0.0875	0.0192
AIRTEMP	637	-0.2057	0.0001
ESAL's	473	-0.1566	0.0007
MAXT	659	-0.1716	0.0001
MEANT	659	-0.2184	0.0001
MINT	659	-0.1995	0.0001
PRECIP	617	-0.0761	0.0593
D32	617	0.20006	0.0001
D0	617	-0.1491	0.0002
WTDYS	617	0.017	0.674
FTCYC	617	0.1858	0.0001
FI	617	0.1095	0.0066
SNOWREM	263	0.1932	0.0017
DEICING	263	0.1469	0.0178
IGNEOUS	437	0.0276	0.5643
SEDI	437	-0.1505	0.0016
META	437	0.1756	0.0002
LIME	264	0.1502	0.0145
FLYASH	264	-0.08607	0.1632
STONEDUST	264	-0.0418	0.4989
MF	264	-0.05356	0.3861
PV	22	-0.50307	0.017
CASPGR	428	-0.19536	0.0001
FASPGR	400	-0.06998	0.1635
MSPGR	178	0.02201	0.7706
CSPGR	391	-0.10777	0.0336
EFFSPGR	268	-0.13536	0.0267
RWT	129	-0.12371	0.1625
RPRESS	10	-0.05592	0.8781
RFREQ	23	0.0514	0.8159

Table 18. Summary of correlation analysis for PCC pavement complementary data.

Data element	No. of observations	Correlation coefficient	Prob > |R|
Skidno	485	1	0
Age	487	-0.3466	0.0001
AIRTEMP	423	-0.06569	0.1786
ESAL's	428	-0.35814	0.0001
MAXT	481	0.03254	0.4774
MINT	481	-0.00808	0.86
MEANT	481	0.0125	0.7851
PRECIP	472	0.0186	0.6872
D0	472	0.02782	0.5469
D32	472	0.09132	0.0476
WTDYS	472	-0.055	0.2338
FTCYC	472	0.02952	0.5228
FI	472	0.03144	0.496
SNOWREM	100	-0.1704	0.0934
DEICING	100	-0.0952	0.3511
LW	487	0.1842	0.0001
CA	419	0.07492	0.126
FA	419	-0.07775	0.1124
CEMENT	421	-0.17557	0.0003
WATER	410	-0.00775	0.8758
WCRATIO	410	0.09343	0.059
TYPEI	407	0.14427	0.0036
TYPEII	407	-0.17755	0.0003
TYPEIA	407	0.0274	0.6626
ENTAIR	394	0.16959	0.0094
SLUMP	327	-0.1007	0.0698
CASPGR	326	-0.0238	0.6692

Table 18. Summary of correlation analysis for PCC pavement complementary data (continued).

Data element	No. of observations	Correlation coefficient	Prob > |R|
FASPGR	326	0.01556	0.7799
IGNEOUS	341	0.12307	0.0232
SEDI	341	-0.12324	0.023
META	341	0.00336	0.9507
INSLORES	8	0.37023	0.3666
SLIP	399	0.2254	0.0001
SIDE	399	-0.24087	0.0001
CUREM	398	0.22091	0.0001
CUREO	399	-0.09882	0.0491
TINE	399	0.38208	0.0001
BROOM	399	-0.13828	0.0058
BURLAP	399	-0.29231	0.0001
TEXTO	399	-0.09882	0.0491

Table 19. Definitions of acronyms used to describe variables in correlation analysis.

Acronym	Definition
Age	Pavement age since construction
AIRTEMP	Ambient air temperature during testing
Alkali	Alkali content of PCC mixture, percent
BROOM	PCC brooming finishing method
BURLAP	PCC burlap finishing method
CA	PCC coarse aggregate content, kg
CASPGR	Coarse aggregate specific gravity
CEMENT	PCC mixture portland cement content, kg
D0	Annual number of days with temperature below 0 °C
D32	Annual number of days with temperature above 32 °C
DEICING	Frequency of deicing pavement during winter season
EFFSPGR	AC mixture effective specific gravity
ENTAIR	PCC mixture entrained air
ESAL's	Cumulative 80-kN axle load applications since construction
FA	PCC fine aggregate content, kg
FASPGR	PCC fine aggregate specific gravity
FI	Annual freezing index, °C days
FLYASH	AC mixture mineral filler type (fly ash)
FTCYC	Annual number of freeze-thaw cycles
IGNEOUS	Coarse aggregate derived from igneous rock
INSLORES	Percent insoluble residue of coarse aggregate (soundness test)
LIME	AC mixture mineral filler type (lime)
LW	Pavement lane width
MAXT	Annual average maximum temperature, °C
MEANT	Annual average temperature, °C
MEMBRANE	Membrane curing method
META	Coarse aggregate derived from metamorphic rock
MF	AC mixture mineral filler not specified in database
MINT	Annual average minimum temperature, °C

Table 19. Definitions of acronyms used to describe variables in correlation analysis (continued).

Acronym	Definition
MSPGR	AC mixture mineral filler specific gravity
PRECIP	Annual average precipitation, m
PV	Aggregate polish value
RFREQ	Roller frequency
RPRESS	Roller tire pressure
RWT	Roller weight
SEDI	Coarse aggregate derived from sedimentary rock
SIDE	Side-form paver
Skidno	Friction reported as Skid Number (SN)
SLIP	Slip-form paver
SLUMP	PCC mixture slump value
SNOWREM	Frequency of snow removal
Speed	Friction test speed
STONEDUST	AC mineral filler (stone dust)
TINE	PCC tining finishing method
TYPEI	Type I cement
TYPEIA	Type IA cement
TYPEII	Type II cement
WATER	PCC mixture water content, kg
WCRATIO	PCC mixture water-to-cement ratio
WTDYS	Annual number of wet days

Effect of Dry and Wet Climates

Figure 16 shows the effect of climate (wet or dry) on skid resistance. As expected, the pavements located in dry climates had a higher level of skid resistance than those in wet climates. Precipitation also had a negative correlation with skid resistance. This implies that pavements located in wet regions are more likely to exhibit lower skid resistance. Correlation analysis on the effect of annual number of wet days on skid resistance was not conclusive. Most of the current literature confirms that wet pavements generally have lower skid resistance than dry ones; however, precipitation also washes dirt and other solid contaminants off pavement surfaces, and that could improve skid resistance. The LTPP data show that there is some correlation between the moisture-related variables and skid resistance.

Effect of Aggregate Geological Classification

Figure 18 shows the effect of aggregate geological classification on skid resistance. The aggregate geological classification is an indication of the aggregate hardness, mineralogy, and soundness. The LTPP database categorizes the aggregates as igneous, metamorphic, or sedimentary. The plots show that AC mixtures with metamorphic coarse aggregates generally experienced little or no loss in skid resistance with traffic applications, while AC mixtures with igneous and sedimentary coarse aggregates did experience a loss in skid resistance.

Sedimentary aggregate materials are generally softer than other kinds of aggregates and tend to lose their skid resistance properties readily. Extremely hard aggregates, such as igneous coarse aggregates, smooth or polish as shear stresses from wheels are applied to them. This situation leads to a decrease in friction.

Effect of Coarse Aggregate Specific Gravity

Figure 19 shows the effect of coarse aggregate specific gravity on skid resistance. Pavements with a coarse aggregate specific gravity of greater than 2.65 had a lower rate of loss of skid resistance than those with a specific gravity of less than 2.65. The aggregate's specific gravity is an indication of hardness and durability; therefore, aggregates with higher specific gravities are expected to provide more lasting friction.

Effect of Polish Value

Figure 20 shows that coarse aggregates with a polish value of greater than 40 generally had a lower rate of friction loss than those with a polish value of less than 40. Polish value is an indication of the polishing characteristics of aggregates, which are partially responsible for friction loss. The trends are as expected.

Effect of Mineral Filler Type

Figure 21 shows that other components of AC mixtures, such as mineral filler, could affect surface friction. AC mixes with lime as a mineral filler showed little change in skid resistance with traffic application, while mixes with fly ash as a mineral filler showed the greatest changes in skid resistance. This trend was confirmed by the results of the correlation analysis.

PCC-Surfaced Pavements

Effect of Traffic Applications

Skid resistance generally is reduced with increases in traffic load applications. Figure 22 shows clearly that there is a decrease in skid resistance as traffic is applied to the pavement. Moving wheels impose shear stresses on a pavement surface, which, in turn, cause the aggregate surface to smooth, polish, or disintegrate. This situation leads to a reduction in skid resistance.

Effect of Freeze and Nonfreeze Climates

The correlation analysis for the effect of climate (freeze or nonfreeze) and the trends shown in figure 23 were not conclusive; however, figure 24 shows that pavements located in climates with higher freeze-thaw cycle rates experienced a higher rate of friction loss than those in climates with little or no freeze-thaw cycles. Freeze-thaw cycles affect the durability of the coarse aggregates in the surface mix. Aggregates that undergo freezing and thawing over long periods of time tend to weaken and disintegrate. This process could result in a loss of surface friction.

Effect of Dry and Wet Climates

The trends shown in figures 25 and 26 and the correlation analysis on the effect of climate (wet or dry) were not conclusive.

Effect of Aggregate Geological Classification

The aggregate geological classification is an indication of the aggregate hardness, mineralogy, and soundness. The LTPP database categorizes the aggregates as igneous, metamorphic, or sedimentary. Figure 27 shows that PCC mixtures with sedimentary coarse aggregates generally experienced a lower rate of loss in skid resistance with traffic applications than PCC with igneous or metamorphic coarse aggregates. Both plots and correlation analysis show that the geological classification of coarse aggregates influences skid resistance.

Effect of Coarse Aggregate Specific Gravity

Figure 28 shows the effect of coarse aggregate specific gravity on skid resistance. Pavements with a coarse aggregate specific gravity of greater than 2.7 had a higher rate of loss of skid resistance than those with a specific gravity of less than 2.6. The aggregate's specific gravity is an indication of hardness and durability, and harder aggregates tend to polish, reducing skid resistance.

Effect of Surface Texturing Method

There are various methods of surface texturing for PCC pavements, namely, tining, burlap drag, and brooming. Figure 29 shows plots of the influence of texturing method on surface friction. The plots and correlation analysis results show that tining provides good skid resistance that is maintained over time. This is in agreement with past research results that show that skid resistance is related to texture depth. Tining provides more texture depth than most other texture methods.

Effect of Coarse and Fine Aggregate Content

There was a positive correlation between coarse aggregate content and skid resistance and a negative correlation between fine aggregate content and skid resistance. It is normally expected that PCC mixtures with a higher percentage of coarse aggregates will exhibit more skid resistance. This, however, depends on the properties of the aggregates.

Summary

The bivariate and correlation analysis results show various trends between friction and friction-related variables. Most of the trends were reasonable and agree with engineering expectations. The results presented suggest that the LTPP friction data collected to date can generally be considered reliable and can be used for in-depth analysis and research. The purpose of this study was not to investigate the mechanisms of skid loss; therefore, only general observations were investigated and are reported.

6. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This study was intended to determine the availability, characteristics, quality, and potential uses of the friction data being collected by highway agencies for the LTPP database. The characteristics and quality of the LTPP friction data have been presented and discussed. The quality and potential uses of the friction data in the LTPP database were assessed using statistical and engineering principles. Based on the findings obtained, the following conclusions can be made:

- Sixty percent of the pavements with time-series data in the LTPP database with friction data were classified as having as-expected data.
- Forty percent of the pavements with time-series data in the LTPP database were classified as having questionable data.
- Twenty-five percent of the pavements in the LTPP database with friction data were not classified because they lacked time-series data.
- Various factors related to the testing process were identified as probable causes of the observed variability in the test data.
- The LTPP database is not detailed enough to identify all possible sources of variability.
- There is a need to collect data on additional friction-related variables to enhance the usefulness of the friction data.
- Additional data needs to be collected for friction-related variables within the database with a high percentage of missing related data.
- There are enough quality data in the LTPP database for use in future analysis of friction data.

The friction data assessment was undertaken to determine the quality and availability of friction data and the availability of related data to allow in-depth investigations in the future of factors that affect friction loss. Wet weather accidents are a significant concern to all highway agencies and any improvement in pavement-tire friction characteristics can lead to significant savings monetarily and in terms of human lives. Any knowledge gained on factors that affect friction loss from the LTPP program will contribute significantly to reducing wet weather accidents in heavily trafficked urban areas.

The maintenance of friction data in the LTPP database is considered to have only a minor financial impact on the LTPP program. Friction testing is performed by participating highway agencies and the LTPP program's role is to receive the data, perform basic quality assurance (QA) checks on the data, and store the data in the LTPP database. Only a single friction data table is maintained, which has just over 3,100 observations as of February 1998 (up from about 2,500 as of Fall 1996). The friction data table is, therefore, not utilizing much space in the database.

It is the opinion of the DATS team that friction test data currently maintained in the database are of acceptable quality and that future efforts should have an active focus on friction data quality, collection of complementary data needed to relate friction characteristics to factors that affect friction, and the adoption of the newly proposed International Friction Index (IFI) procedure that will require the measurement (or estimation) of the macrotexture characteristics of the pavement surface. The adoption of the IFI will eliminate concerns related to the use of different tire types (smooth or ribbed), equipment/procedures, and test speeds. The team feels strongly that the benefits that will accrue to the participating highway agencies from collecting quality friction data warrant the investment these agencies would be required to make to collect quality data by upgrading their data collection procedures.

Some important findings on the potential sources of variability in the friction database were identified, and recommendations to improve the current data collection procedures based on these findings are presented as follows.

Recommendations—Friction Testing Process

Test Equipment Calibration

A review of the data collection process presented in chapter 3 of this report shows that many of the participating agencies do not adhere strictly to the guidelines developed by the FHWA. Compliance with the recommendations in Technical Advisory T 5040.17 and adherence to the procedures of ASTM E-274 will greatly improve data quality. As a minimum, the following must be checked and determined to be working satisfactorily on a daily basis or after any period when the testing system is off for more than 30 minutes.

- Check if all power subsystems are on and are providing the proper level of power.
- Check if all signal conditioning subsystems have been put on for an adequate period of time to reach stable operation (typically 10 to 30 minutes).
- Check if all recording systems are on and are functioning properly.
- Check if instrument calibration has been performed.
- Check tire pressure and adjust if necessary.
- Test tire checked for wear.
- Fill water tank adequately.
- Determine that the water nozzle (nozzles), when in the testing position, assumes the proper angle with respect to the pavement (ASTM E-274 requires an angle of 25 ± 5 degrees).
- If the measurement system has a provision for raising and lowering the nozzle between tests, determine that the mechanism is working properly and that the nozzle assumes a fully lowered position during the test sequence.
- Determine that the nozzle, when in the test position, will discharge water directly in front of and centered on the test wheel.
- Examine the nozzle outlet orifice to determine that it is free from damage or distortion.
- Connect, position, and protect safety chains and all other connections between the trailer and the towing vehicle.
- Make sure all auxiliary equipment (e.g., air compressors, lights) is functioning properly.

These checks are not meant to be exhaustive and other procedures that can enhance the data collection process and improve data quality should be implemented.

Test Personnel

There is no indication of formal training and certification of the personnel involved in LTPP friction testing. Formal training conducted for the personnel involved in LTPP friction testing should help reduce the occurrence of discrepancies. The training could be in the form of well-documented guidelines for LTPP friction testing.

Test Location

A review of past literature shows that there could be high variability in friction results for pavements tested at different locations, no matter how close these locations are. To reduce variability due to differences in test locations, the same locations (laterally and longitudinally) should be tested each time.

Test Tires

The LTPP test guidelines recommend using a locked-wheel tester with a ribbed tire as specified by ASTM E-501. However, a review of the state of the practice for friction shows that a considerable number of States use different tires (smooth or ribbed) for the different pavement surface types (AC or PCC). Data obtained to date from different tires cannot be used interchangeably for analysis. Therefore, only the recommended ribbed tire should be used in LTPP testing, preferably at two different speeds to allow computation of the speed gradient. Also, testing could be conducted at one speed, but using both the smooth and the ribbed tires. However, it should be noted that in the future, if LTPP adopts the International Friction Index procedure for friction data reporting, the use of a specific tire type for friction testing would not be an issue as the IFI procedure allows standardization of friction tests using different procedures and different tire types.

Other Recommendations

The following is a list of some general information that will be useful for calibration and friction testing:

- Friction tests should be conducted with equipment calibrated as close to the testing date as possible. The time between calibration and testing should not be more than 60 days.
- All equipment calibration procedures should ensure repeatability of test results (i.e., friction measurements on test pavements at the same time under the same conditions must yield measurements with a variability of not more than 4 SN).
- Friction tests must be conducted along the inner wheelpath.
- Friction tests should not be conducted under extreme weather conditions, such as at temperatures greater than 42 °C or at freezing temperatures.

- There should be a visual inspection of the pavement surface to determine surface condition and possible contamination before testing. A report on the pavement surface condition can help explain variations in test results.

Most of the information presented above is available in FHWA Technical Advisory T 5040.17 and ASTM E-274. Testing agencies should be requested to adhere strictly to these recommendations to ensure uniformity in the testing process and to ensure reliable and accurate test results.

Feedback to Operations

In order to enhance the future usefulness of the friction data, it is strongly recommended that the following improvements in the friction data collection effort be implemented as soon as possible:

- Development of an improved guideline for friction data collection that can be used by the staff of the participating highway agencies as a training and a quality control (QC) guide.

- Improvement of the data reporting form to allow reporting of tire type and the wheelpath tested.

- A request that participating agencies perform friction testing at least every 2 years. At many sites, only a single observation is available. Single observations are not as useful as these observations do not contribute to investigations of friction change over time.

- Completion of the data tables related to surface layer material properties, construction techniques, and surface layer mixture properties. A summary of current data availability is presented in tables 20 and 21.

- Collection of macrotexture information as per ASTM E-965, Test Method for Measuring Macrotexture Depth (MTD) Using a Volumetric Technique, or as per ASTM E-1845, Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth (MPD). The collection of macrotexture data will allow the determination of IFI, which can be considered as a universal index for friction testing in the future. The use of IFI will allow the use of friction data collected using different procedures/equipment within the LTPP program. The significant benefits of the IFI procedure have been noted previously in this report.

Potential for Future Data Analysis

The LTPP friction data can be used to analyze why some surfaces retain good friction characteristics (higher SN values) over time and why some surfaces show rapid deterioration in friction over time. Such analysis can be performed globally, regionally, or for individual test sections. Participating highway agencies may find data from their own pavement sections most

Table 20. AC performance-related data.*

Data Element	Data Availability (%)
Coarse aggregate geological class	36
Coarse aggregate specific gravity	36
Fine aggregate specific gravity	36
Hardness	Not available
Polish value	3
Pavement surface moisture condition at time of testing	Not available
Aggregate shape and size	Not available
Aggregate gradation	Negligible
Average annual temperature	85
Air temperature during testing	88
Annual precipitation	85
Freeze-thaw cycles	85

* Considering all 723 pavement sections with or without time-series data.

Table 21. PCC performance-related data.

Data Element	Data Availability (%)
Coarse aggregate geological class	70
Coarse aggregate specific gravity	67
Fine aggregate specific gravity	67
Hardness	Not available
Soundness	Not available
Coarse aggregate content	85
Fine aggregate content	85
Pavement surface moisture condition at the time of testing	Not available
Aggregate shape and size	Not available
Aggregate gradation	Negligible
Texture method	82
Curing method	82

useful as these agencies can directly relate the loss in friction over time to site-specific materials, construction techniques, traffic levels, and climatic conditions.

Because time-series data are necessary to perform any type of analysis of friction data, the participating highway agencies that do not regularly perform friction testing should be requested to do so if availability of testing equipment and staffing permit this.

Summary

As with other pavement performance monitoring data, the LTPP database will provide a one-stop source of friction data collected in a systematic manner from a wide range of pavements subjected to a wide range of traffic loading and environmental conditions. Although many participating agencies collect friction data on a regular basis, there is not much work being performed to further our understanding of how friction properties change over time for different pavement surface types.

The friction data in the LTPP database are generally considered to be of acceptable quality (based on the assessment reported here). The time-series data will be useful to analysts. However, one-point data for many sections may not be of much use. As such, participating agencies should be encouraged to perform friction testing on a regular basis. Friction test data from Specific Pavement Study (SPS) test sections will further provide a wealth of additional data that will contribute to a rich database for the study of pavement friction.

APPENDIX A – PRACTICES FOR LTPP FRICTION DATA COLLECTION

FRICTION TESTING PROCEDURE

Test Method and Equipment Used at LTPP Test Sites

The LTPP database contains the necessary information related to the friction testing equipment, the procedures used, and the equipment calibration date for friction testing at LTPP test sections.

Quality Control and Calibration of Equipment

1. Is a quality control (QC) or calibration done on a regular basis? (If No, skip to question 8) ☐ Yes ☐ No

2. What is your calibration procedure?

   A. Internal ____________________

   B. External ____________________

3. How often are calibration checks performed?

   ☐ Weekly ☐ Monthly

   ■ Yearly ☐ Other (specify)

Climate-Related Data

4. Does your agency currently collect any additional climate-related data for use in friction data normalization or otherwise? (If No, skip to question 6)

   ☐ Yes ☐ No

5. Are the following included in the list of additional data collected?

Air temperature at the time of testing	☐ Yes ☐ No
Pavement temperature at the time of testing	☐ Yes ☐ No
Number of wet days in the previous consecutive 7 (or specify ______) days prior to testing	☐ Yes ☐ No
Average daily precipitation for the previous consecutive 7 (or specify ______) days prior to testing	☐ Yes ☐ No
Others ____________________	☐ Yes ☐ No

Others ____
____ ☐ Yes ☐ No

Others ____
____ ☒ Yes ☐ No

Pavement Design and Construction Characteristics

6. Please supply information regarding the pavement design and construction properties determined by your agency to be relevant to friction and collected as part of the friction testing process:

Number of lanes		☐ Yes	☐ No
Presence of lane separators		☐ Yes	☐ No
Grade and alignment		☐ Yes	☐ No
Pavement type		☒ Yes	☐ No
Mix design of surface course		☒ Yes	☐ No
Aggregate type		☒ Yes	☐ No
Others ____________________	(Specify)	☒ Yes	☐ No
Others ____________________	(Specify)	☐ Yes	☐ No
Others ____________________	(Specify)	☐ Yes	☐ No
Others ____________________	(Specify)	☐ Yes	☐ No

7. Does your agency have specific design guidelines to address skid resistance?
(If No, skip to question 21) ☒ Yes ☐ No

8. List the test(s) (e.g., L.A. Abrasion) and specifications used by your agency to address skid resistance. Please give detailed references for the test standards (e.g., ASTM No. XXX). Please attach copies of your requirements.

1. ____

2. ____

3. ____

4. ____

5. ____

Equations and Models for Determining Friction and Skid Number

9. Summarize all equations and models used by your agency for determining friction from the field test data (and, hence, skid number).

10. Is your agency involved in research related to friction currently or in the immediate past?

☐ Yes ☐ No

11. If the answer to question 10 is yes, please provide copies of the work plans, interim reports, and/or final reports. Also, include the name(s), address, and telephone and fax numbers of the person(s) involved.

Name 1: ______________________________

Title: ______________________________

Telephone No. ( ) Fax No. ( )

Name 2: ______________________________

Title: ______________________________

Telephone No. ( ) Fax No. ( )

Name 3: ______________________________

Title: ______________________________

Telephone No. ( ) Fax No. ( )

Possibly there are questions where there was not adequate space to provide a complete answer. If so, you are invited to furnish supplemental information below at your discretion. Also, we would appreciate it if you could furnish the name(s) and telephone number(s) of:

Name of Preparer 1:
Title:
Telephone No. ( )
Fax No. ( )

Name of Preparer 2:
Title:
Telephone No. ( )
Fax No. ( )

Thank you very much for your assistance.

Table 22. Summary of information request respondents and number of responses.

State/Province	Questions										
	1	2	3	4	5	6	7	8	9	10	11
Alabama	x	x	x	x	x	x	x	x		x	
Alaska	x	x	x	x			x		x	x	
Arkansas	x	x	x	x		x	x				
California	x	x	x	x		x	x	x	x	x	
Colorado	x			x			x			x	x
Connecticut	x	x	x	x		x	x	x	x	x	x
Florida	x	x	x	x		x	x	x	x	x	
Georgia	x		x	x	x	x	x	x		x	
Hawaii	x			x			x			x	
Idaho	x	x	x	x	x	x	x	x	x	x	
Illinois	x	x	x	x		x	x	x	x	x	x
Iowa	x	x		x	x	x	x	x		x	
Kansas	x	x	x	x		x	x		x	x	
Kentucky	x	x	x	x		x	x	x	x	x	
Louisiana	x	x	x	x		x	x			x	
Maine	x	x	x	x			x			x	
Maryland	x	x	x	x		x	x			x	
Michigan	x	x	x	x	x	x	x	x	x	x	
Mississippi	x	x	x	x		x	x	x		x	
Missouri	x	x	x	x	x	x	x	x	x	x	
Montana	x	x	x	x							
Nebraska	x	x	x	x	x	x	x		x	x	
Nevada	x	x	x	x		x		x	x	x	
New Hampshire	x	x	x	x	x		x		x	x	
New Mexico	x	x	x	x	x	x	x	x		x	
North Carolina	x	x	x	x	x	x	x	x	x	x	x
North Dakota	x	x	x	x	x		x	x		x	
Oklahoma	x	x	x	x	x	x	x		x	x	

Table 22. Summary of information request respondents and number of responses (continued).

State/Province	Questions										
	1	2	3	4	5	6	7	8	9	10	11
Oregon	x	x	x	x	x	x	x	x	x	x	
South Carolina	x	x	x	x	x	x	x			x	
South Dakota	x	x	x	x	x		x			x	
Tennessee	x	x	x	x	x	x	x			x	
Texas	x	x	x	x	x	x	x	x		x	
Washington	x	x	x	x	x	x	x			x	x
Wisconsin	x	x	x	x	x	x	x		x	x	
Wyoming	x	x	x	x	x		x	x	x	x	
Puerto Rico	x	x	x	x	x	x	x	x	x	x	
British Columbia	x	x	x	x	x	x	x		x	x	
Manitoba				x	x		x				
New Brunswick	x	x	x	x	x		x			x	
Newfoundland	x		x	x	x	x	x			x	
Quebec	x	x	x	x	x	x	x	x		x	
Percent Respondents	95	88	93	100	62	74	95	50	48	95	12

FOLLOW-UP CLARIFICATIONS

As part of the ongoing LTPP data analysis study, an attempt is being made to assess the LTPP friction data quality and availability. A comprehensive data clarification survey was carried out in September 1997 to clarify and rectify suspected anomalies within the LTPP data.

To further clarify the data, some follow-up information is required. Your help and cooperation are greatly appreciated. Please fax your reply to Leslie Titus-Glover at (217) 356-3088 as soon as possible. Thank you.

a. Which type of test tire do you use for LTPP testing?

AC Pavements

Smooth	☐ Yes	☐ No
Ribbed	☐ Yes	☐ No
Others	☐ Yes	☐ No

PCC Pavements

Smooth	☐ Yes	☐ No
Ribbed	☐ Yes	☐ No
Others	☐ Yes	☐ No

b. Standards for specifying test tire (e.g., ASTM X, AASHTO X) ___________

c. Within the last 10 years, have you changed the type of test tire (e.g., from smooth to ribbed) used in friction testing? ☐ Yes ☐ No

d. If so, when was it changed? ___________

e. Please state reasons for changing type of test tire ___________

Table 23. Summary of information request respondents and number of responses.

State/Province	Questions				
	a	b	c	d	e
Alabama	x	x	x	x	x
Alaska	x	x	x		
Arkansas	x	x	x		
California					
Colorado	x	x	x		
Connecticut	x	x	x	x	x
Florida					
Georgia	x	x	x		
Hawaii					
Idaho					
Illinois	x	x	x	x	x
Iowa	x	x	x		
Kansas	x	x	x		
Kentucky	x	x	x		
Louisiana	x	x	x	x	
Maine	x	x	x		
Maryland					
Michigan					
Mississippi	x	x	x		
Missouri	x	x	x		
Montana					
Nebraska	x	x	x		
Nevada					
New Hampshire					
New Mexico	x	x	x	x	x
North Carolina	x	x	x		
North Dakota					
Oklahoma	x	x	x		

Table 23. Summary of information request respondents and number of responses (continued).

State/Province	Questions				
	a	b	c	d	e
Oregon					
Pennsylvania	x	x	x	x	x
South Carolina	x	x	x		
South Dakota	x	x	x		
Tennessee					
Texas	x	x	x	x	x
Washington					
Wisconsin	x	x	x		
Wyoming	x	x	x		
Puerto Rico					
British Columbia	x	x	x	x	x
Manitoba	x	x	x		
New Brunswick					
Newfoundland					
Nova Scotia					
Ontario	x	x	x	x	x
Quebec					

Table 24. Quality control and calibration of equipment.

Respondent	Regularity of calibration/QC	What is your calibration procedure?
Alabama	Internal calibration: monthly External calibration: annually	Internal calibration using force plate and external calibration at Texas Transportation Institute (TTI)
Alaska		External calibration at test center (TTI) according to ASTM E-274
Arkansas	Internal calibration: weekly	Manufacturer's internal calibration software
California	Internal calibration: biannually External calibration: 2 to 3 years	Internal: verification/calibration External: following ASTM E-274 procedure
Colorado		
Connecticut	Internal calibration: annually External calibration: every 2 years	Internal calibration using force plate and external calibration test center (TRC of Ohio, Inc.)
Florida	Internal calibration: 30 to 45 days External calibration: annually	External calibration at TTI test center
Georgia	External calibration: 4 times a year	External calibration at DOT's test center
Hawaii		
Idaho	Internal calibration: monthly and annually External calibration: every 3 years	Internal: calibration of platform, water gauge, speed gauge, distance measuring device External: following ASTM procedures at TRC of Ohio
Illinois	Internal calibration: monthly (during test season) or as needed	Internal: calibrate torque arm, water flow system, compare test results with historical data
Iowa		
Kansas	Internal calibration: daily External calibration: annually	Internal: self-calibration by computer system External: ASTM E-274 procedure using load and traction force plate
Kentucky	Internal calibration: weekly (during test season)	Internal: use of load cell with air bearing platform if weekly routine checks indicate a problem
Louisiana	Internal calibration: each time a test is performed External calibration: annually	Calibrated annually at TTI test center Calibrated externally annually at TTI test center
Maine	Annually	By using force plates
Maryland	Internal calibration: monthly	Internal calibration every 4 to 6 weeks; speed, distance, force, traction, and water calibration done annually

Table 24. Quality control and calibration of equipment (continued).

Respondent	Regularity of calibration/QC	What is your calibration procedure?
Michigan	Internal calibration: every 3 months External calibration: annually	Internal calibration: checked against National Bureau of Standards (NBS) load cell and monthly visits to test sites External calibration: yearly trip to regional calibration centers
Mississippi	Internal calibration: weekly External calibration: annually	Internal: collecting data from designated pavement External: calibration at TTI test center
Missouri	Internal calibration: monthly External calibration: 3 to 4 years	Internal: by following AASHTO T242 External: at regional calibration center (TTI)
Montana++		
Nebraska	Internal: annually External: every 2 to 3 years	Internal: using force plate and load cell External: at central/western field test and evaluation center
Nevada	Internal: annually (or as needed) Externally: every other year	External: calibration at TTI test center
New Hampshire		
New Mexico	Internal calibration: every 2 months External calibration: every 2 years	Internal: consists basically of checking variability in test measurements External: calibration at TTI test center
North Carolina	External calibration: every 2 years	External: calibrated at test center
North Dakota	Every other year	In accordance with ASTM E-274
Oklahoma	Bi-annually	ASTM E-556 standard test method for calibrating a wheel load or torque transducer using a calibration platform
Oregon	Internal: daily External: annually	Internal: system calibration on the ground External: platform calibration (traction load)
South Carolina	Internal: every 3 to 6 months External: every $1^1/_2$ to 2 years	Internal: calibration with force plates ASTM E-556 External: calibration at the Transportation Research Center, Liberty, Ohio
South Dakota	Internal: weekly External: once every 4 years	Internal: run test strips on a weekly basis to check variability External: calibration at test center
Tennessee		Internal: run simulated test External: calibration at test center
Texas	Internal: daily External: annually	Internal: calibrated to ASTM standards External: correlated with skid rig at TTI

Table 24. Quality control and calibration of equipment (continued).

Respondent	Regularity of calibration/QC	What is your calibration procedure?
Washington	Internal: monthly External: every 2 years	Internal: static force plates and dynamic load check External: calibration and correlation checks at TTI
Wisconsin	annually	Testing control sections for variability and using force plates
Wyoming	External: biennial	Calibration at test center, Reno, Nevada
Puerto Rico	Internal: monthly, biannually, etc.	System calibration prior to running a test, monthly odometer checks, transducer calibration every 6 months, periodic calibration according to manufacturer's guidelines when more sophisticated work is required
British Columbia	Prior to every project	According to manufacturer's testing procedure
Manitoba		
New Brunswick	At every test site	By external contractor
Newfoundland	Internal calibration: weekly External calibration: annually	
Quebec	Monthly or when wheel is changed	Calibration of the force applied to wheel by applying weights up to 200 kg in 20-kg increments

++ No information provided.

Table 25. Climate-related data.

Respondent	Do you collect climate-related data?	Climate-related data collected as part of testing				
		Air temp.	Pavement temp.	Wet days in last 7 days	Precipitation in last 7 days	Others
Alabama	Yes	Yes				
Alaska	Yes	Yes	Yes			
Arkansas	Yes	Yes				Pavement moisture condition
California	Yes	Yes				
Connecticut	Yes	Yes				Freezing conditions, temperature above 4 °C
Florida	Yes	Yes				Clear or cloudy weather
Georgia	No					
Hawaii	No					
Idaho	Yes	Yes	Yes			Wind speed
Illinois	No					
Iowa	Yes	Yes				
Kansas	No					
Kentucky	No					
Louisiana	No					
Maine	No					
Maryland	No					
Michigan	Yes	Yes	Yes			
Mississippi	No					
Missouri	Yes	Yes	Yes			
Montana	No					
Nebraska	Yes	Yes	Yes			
New Hampshire	No					
New Mexico	Yes	Yes				

Table 25. Climate-related data (continued).

Respondent	Do you collect climate-related data?	Climate-related data collected as part of testing				
		Air temp.	Pavement temp.	Wet days in last 7 days	Precipitation in last 7 days	Others
North Carolina	Yes	Yes	Yes			
North Dakota	Yes	Yes	Yes			
Oklahoma	Yes	Yes				
Oregon	Yes	Yes				
South Carolina	No					
South Dakota	No					
Tennessee	Yes	Yes	Yes			
Texas	Yes	Yes				
Washington	No					
Wisconsin	Yes	Yes	Yes			
Wyoming	No					
Puerto Rico	Yes	Yes				Moisture condition (wet or dry)
British Columbia	No					
Manitoba	No					
New Brunswick	No					
Newfound-land	Yes	Yes				Wind direction, speed, weather
Quebec	Yes	Yes	Yes			

Table 26. Research, information, and test guidelines for friction.

Respondent	Specific guidelines to address skid resistance	Are you involved in friction-related research?	Information on pavement design and material properties related to friction and collected by your agency
Alabama	Yes	No	Pavement type, mix design of surface course, aggregate type
Alaska	No	No	Test speed, test location, and alignment
Arkansas	No		Number of lanes, presence of lane separators, grade and alignment, pavement type, pavement condition rating
California	Yes	No	Number of lanes, presence of lane separators, grade and alignment, pavement type, mix design of surface course, aggregate type, posted speed
Colorado	No	Yes	
Connecticut	No	Yes (1968 to 1979)	Pavement type, type of test tire (ribbed or bald)
Florida	Yes	Yes	Number of lanes, pavement type, posted speed limit, pavement location and identification, pavement classification
Georgia	Yes	No	Number of lanes, presence of lane separators, grade and alignment, pavement type, mix design of surface course, aggregate type, distress such as bleeding and flushing, surface texture, posted speed limits
Hawaii	No	No	
Idaho	No	No	Number of lanes, pavement type, location (curves, bridge deck, etc.), distress (patching, bleeding, etc.), contaminants such as dirt or others
Illinois	Yes	Yes	Number of lane separators, pavement type, mix design of surface course, aggregate type, pavement location (rural or urban), average annual daily traffic (AADT)
Iowa	Yes	No	Number of lanes, pavement type, mix design of surface course, aggregate type
Kansas	No	No	Number of lanes, presence of lane separators, pavement type, mix design of surface course
Kentucky	Yes	No	Number of lanes, grade and alignment, pavement type, mix design of surface course, aggregate type, cumulative traffic passes
Louisiana	No	Yes	Pavement type, mix design of surface course, aggregate type, curves, superelevation, bridges

Table 26. Research, information, and test guidelines for friction (continued).

Respondent	Specific guidelines to address skid resistance	Are you involved in friction-related research?	Information on pavement design and material properties related to friction and collected by your agency
Maine	No	No	
Maryland	No	No	Number of lanes
Michigan	No	No	Number of lanes, pavement type
Mississippi	Yes	No	Number of lanes, presence of lane separators, grade and alignment, pavement type, mix design of surface course, aggregate type, posted speed limits, urban/rural, average daily traffic (ADT)
Missouri	Yes	No	Number of lanes, grade and alignment, pavement type, mix design of surface course, aggregate type, tire tread depth and air pressure
Montana++			
Nebraska	No	No	Number of lanes, presence of lane separators, pavement type
Nevada		Yes	Number of lanes, pavement type, posted speed, average 85th percentile speed
New Hampshire	No	No	
New Mexico	Yes	Yes	Number of lanes, grade and alignment, pavement type, mix design of surface course, hydroplaning, excessive wheel rutting
North Carolina	Yes	Yes	Number of lanes, presence of lane separators, pavement type
North Dakota	No	No	Vehicle speed
Oklahoma	Yes	Yes	Number of lanes
Oregon	No	Yes	Pavement type
South Carolina	No	No	Number of lanes, pavement type
South Dakota	No	Yes	
Tennessee	Yes	No	Number of lanes, pavement type, mix design of surface course, aggregate type
Texas	Yes	Yes	Pavement type
Washington	No	Yes	Number of lanes, pavement type
Wisconsin	No	No	Pavement type, mix design of surface course, aggregate type

Table 26. Research, information, and test guidelines for friction (continued).

Respondent	Specific guidelines to address skid resistance	Are you involved in friction-related research?	Information on pavement design and material properties related to friction and collected by your agency
Wyoming	No	Yes	
Puerto Rico	Yes	Yes	Number of lanes, presence of lane separators, grade and alignment, pavement type, mix design of surface course, aggregate type, excessive roughness
British Columbia	Yes	No	Pavement type
Manitoba	No	No	
New Brunswick	No	No	
Newfoundland	No	Yes	Number of lanes, presence of lane separators, grade and alignment, pavement type, mix design of surface course, aggregate type
Quebec	Yes	Yes	Number of lanes, pavement type, mix design of surface course, aggregate type

++ No information provided.

Table 27. Test procedure and specifications.

Respondent	Procedure for determining skid resistance	List tests and specifications for addressing skid resistance
Alabama		L.A. Abrasion (ref. standard AASHTO T96), allowable carbonate stone criteria (ref. standards ASTM D-3319, ASTM E-303, BMTP 382)
Alaska	Calculations in accordance with ASTM E-274	
California	Calculations in accordance with California Test 342: Method of test for surface resistance with the California portable skid tester	California Test 205: Method of determining percentage of crushed particles California Test 211: Abrasion of coarse aggregate by use of L.A. Rattler California Test 214: Soundness of aggregates by use of sodium
Connecticut	Standard calculations, model to adjust measurements to standard speed of 65 km/h	L.A. Abrasion (not specifically for skid resistance)
Florida	Calculated as part of the friction test device	Use of open-graded mix according to functional class of traffic speed
Georgia		Use only hard siliceous metamorphic aggregates in design of surface mix and use related ASTM standards
Idaho	According to ASTM E-274	
Illinois	According to ASTM E-274	TRA 15: Safety improvement construction program TRA 16: Skid-accident reduction program
Iowa		Petrographical analyses to classify aggregate sources by frictional characteristics (AC pavements), use of a minimum of 40% natural sand for PCC pavements, material type and composition based on functional class, ESAL, truck ADT, AADT
Kansas	According to ASTM E-274, E-501, using K.J. Law 1290 locked-wheel dynamic friction tester	
Kentucky	Based on equipment software	Polish resistance for coarse aggregates Kentucky Method 64-223-95: Insoluble residue in carbonate aggregates Kentucky Method 64-224-95: Chemical analysis of five aggregates
Michigan	ASTM procedures used for calculating friction; measurements adjusted to standard speed using models	
Mississippi		L.A. Abrasion and related ASTM standards

Table 27. Test procedure and specifications (continued).

Respondent	Procedure for determining skid resistance	List tests and specifications for addressing skid resistance
Missouri	FN = (F/W) * 100	L.A. Abrasion
Nebraska	According to K.J. Law equipment	
Nevada	By using International Cybernetics Corporation (ICC) friction device	AASHTO T96: Resistance to degradation of small-size coarse aggregate by abrasion and impact in the L.A. Machine Nevada Test Method T230C: Method of tests for determining the percentage of fractured faces
New Hampshire	Calculations in accordance with ASTM E-274	
New Mexico		L.A. Abrasion, soundness loss, fractured faces (AASHTO T96, AASHTO T104)
North Carolina	Regression models used to calibrate measurements	AASHTO T96 for aggregate and stone screening
North Dakota		L.A. Abrasion
Oklahoma	According to ASTM E-274	
Oregon	Calibration equations obtained from calibration test center	L.A. Abrasion (not directly related to skid resistance)
Texas		Polish value according to TEX 438A
Wisconsin	According to ASTM E-274 using a Cox & Sons CS 9000 friction tester	
Wyoming	Calculations in accordance with ASTM E-274	Test for carbonate content of coarse aggregates, use of 100% crushed rock, only non-limestone aggregates used
Puerto Rico	Calculations in accordance with ASTM E-274	ASTM D-3319, PSV (min) = 48%, AASHTO T96 maximum wear = 40%, the use of manufactured sand is prohibited in PCC mixes
British Columbia	Calculations in accordance with ASTM E-274	
Quebec		Surface macrotexture depth using volumetric technique, British portable tester, SCTIM sideways coefficient resistance machine, L.A. Abrasion (reference standards ASTM E-965, ASTM E-303, NQ-2560-400, NQ-2560-050, NQ-2560-070, LC-21-101, LC-21-102)

Table 28. Test tire type and specification.

Respondent	Test tire type used in LTPP testing	Standards for specifying test tire	Have you changed test tire type?	If so, when was it changed in the last 10 years?	Reasons/Others
Alabama	AC/PCC - ribbed	ASTM E-274 ASTM E-501	No		
Alaska	AC - ribbed (no PCC)	ASTM E-501	No		
Arkansas	AC/PCC - smooth	ASTM	No		
California					
Colorado	AC - ribbed PCC - smooth	ASTM E-501 (ribbed) ASTM E-524 (smooth)	No		
Connecticut	AC/PCC - ribbed	ASTM E-501 AASHTO M261	No		
Georgia	AC/PCC - ribbed	ASTM E-501	No		
Hawaii					
Idaho					
Illinois	AC - ribbed PCC - smooth	ASTM E-501 ASTM E-524	No		On heavy test years they go through two sets of tires
Iowa	AC/PCC - ribbed	ASTM E-501	No		
Kansas	AC/PCC - ribbed	ASTM E-501	No		
Kentucky	AC/PCC - ribbed	ASTM E-501	No		
Louisiana	AC/PCC - smooth and ribbed	ASTM E-501 ASTM E-524			Have been using both tires since 1991
Maine	AC/PCC - ribbed	ASTM E-501	No		
Manitoba	N/A	N/A	N/A		Hire SK to do friction testing
Maryland					
Michigan					

Table 28. Test tire type and specification (continued).

Respondent	Test tire type used in LTPP testing	Standards for specifying test tire	Have you changed test tire type?	If so, when was it changed in the last 10 years?	Reasons/Others
Mississippi	AC/PCC - ribbed	ASTM E-274			
Missouri	AC/PCC - ribbed	AASHTO M261 ASTM E-501	No		
Montana					
Nebraska	AC/PCC - ribbed	ASTM E-501			
Nevada					
New Hampshire					
New Mexico	AC/PCC - ribbed	ASTM E-501	No		
New York					
North Carolina	AC/PCC - ribbed	ASTM E-501	No		
North Dakota					
Oklahoma	AC/PCC - ribbed	ASTM E-501	No		
Oregon					
Pennsyl-vania	AC/PCC - ribbed	ASTM E-501	No		
South Carolina	AC/PCC - ribbed	ASTM E-501	No		
South Dakota	N/A	N/A	N/A		Discontinued friction testing in 1993
Tennessee					
Texas	AC/PCC - ribbed	ASTM E-501	No		
Vermont					
Washington					
Wisconsin	AC/PCC - ribbed	ASTM E-501	No		

Table 28. Test tire type and specification (continued).

Respondent	Test tire type used in LTPP testing	Standards for specifying test tire	Have you changed test tire type?	If so, when was it changed in the last 10 years?	Reasons/Others
Wyoming	AC/PCC - ribbed	ASTM E-501	No		
Puerto Rico					
British Columbia	N/A	N/A	N/A		Use British Pendulum Tester
Manitoba	N/A	N/A	N/A		Hire Saskatchewan to do friction testing
New Brunswick					
Newfound-land					
Nova Scotia	AC - smooth (no PCC)	ASTM E-94-3 (1989-1994) ASTM E-SM-99 (1996)	No		In 1996, changed from SAAB Friction Tester to Grip Tester
Ontario	AC/PCC - smooth	ASTM E-551 (ASTM Grip Tester)	Yes	1995	Switched to ASTM Grip Tester
Quebec					

APPENDIX B – SUMMARY OF FRICTION DATA QUALITY

Table 29. Summary of friction data for Alabama.

State	Section ID	No. of time-series data	Data quality	Comments
Alabama	1011	2	as expected	
	1019	3	as expected	
	1021	2	as expected	
	3028	2	as expected	
	3998	3	as expected	
	4007	2	as expected	
	4073	2	as expected	
	4084	2	as expected	
	4126	2	as expected	
	4129	2	as expected	
	5008	2	as expected	
	6012	2	as expected	
	6019	2	as expected	
	1001	1	not classified	Construction event 1
	1001	1	not classified	Construction event 2
	4125	3	questionable	Increase in SN with age, all other related variables seem reasonable.
	4127	2	questionable	
	4155	4	questionable	

Table 30. Summary of friction data for Arizona.

State	Section ID	No. of time-series data	Data quality	Comments
Arizona	1001	2	as expected	This is based on test results using ribbed tires, ignoring 1992 test results using smooth tires.
	1003	2	as expected	
	1006	2	as expected	
	1007	2	as expected	
	1015	2	as expected	
	1016	2	as expected	
	1017	2	as expected	
	1018	2	as expected	
	1022	2	as expected	
	1024	2	as expected	
	1025	2	as expected	
	1034	2	as expected	
	1036	2	as expected	
	1037	2	as expected	
	1065	2	as expected	
	6053	2	as expected	
	6054	2	as expected	
	6060	2	as expected	
	7079	2	as expected	
	7614	2	as expected	
	1002	2	questionable	Increasing SN values with age.
	1062	2	questionable	End SN values as expected; beginning SN values increasing with age.
	6055	2	questionable	Increasing SN values with age.
	7613	2	questionable	Increasing SN values with age.

Table 31. Summary of friction data for Arkansas.

State	Section ID	No. of time-series data	Data quality	Comments
Arkansas	2042	1	not classified	No time-series data available.
	3011	1	not classified	
	3048	1	not classified	
	3058	1	not classified	
	3059	1	not classified	
	3071	1	not classified	
	3073	1	not classified	
	3074	1	not classified	
	4019	1	not classified	
	4021	1	not classified	
	4023	1	not classified	
	4046	1	not classified	
	5803	1	not classified	
	5805	1	not classified	

Table 32. Summary of friction data for California.

State	Section ID	No. of time-series data	Data quality	Comments
California	2038	2	as expected	
	2040	2	as expected	
	2041	2	as expected	
	2051	2	as expected	
	2053	2	as expected	
	2647	2	as expected	
	3005	2	as expected	
	3010	2	as expected	
	3017	2	as expected	
	6044	2	as expected	
	7452	2	as expected	
	7454	2	as expected	
	7491	2	as expected	
	8150	2	as expected	
	8153	2	as expected	
	8201	2	as expected	
	8202	2	as expected	
	8534	2	as expected	
	9107	2	as expected	
	1253	1	not classified	Data quality not determined because of single data entry.
	3021	1	not classified	
	3030	1	not classified	
	8151	1	not classified	
	9049	1	not classified	
	2002	2	questionable	Increasing SN values with age may be due to the use of different test equipment.
	2004	3	questionable	
	3013	3	questionable	
	3019	3	questionable	
	3024	3	questionable	
	3042	2	questionable	
	7455	2	questionable	
	7456	2	questionable	
	7493	3	questionable	
	8156	2	questionable	
	8535	2	questionable	
	9048	2	questionable	

Table 33. Summary of friction data for Colorado and Connecticut.

State	Section ID	No. of time-series data	Data quality	Comments
Colorado	1029	1	not classified	Data quality not determined because of single data entry.
	1049	1	not classified	
	1053	1	not classified	
	1057	1	not classified	
	2008	1	not classified	
	3032	1	not classified	
	6002	1	not classified	
	6013	1	not classified	
	7035	1	not classified	
	7036	1	not classified	
	7776	1	not classified	
	7780	1	not classified	
	7781	1	not classified	
	7783	1	not classified	
	9019	1	not classified	
	9020	1	not classified	
Connecticut	1803	6	as expected	This is without SN measured on 8/27/91; it appears measurements for that day are wrong for most sections.
	4008	6	as expected	
	4020	3	as expected	Construction event 1
	4020	4	as expected	Construction event 2
	5001	7	as expected	Includes SN measured on 8/27/91.

Table 34. Summary of friction data for Delaware, District of Columbia, and Florida.

State	Section ID	No. of time-series data	Data quality	Comments
Delaware	1201	3	as expected	
	1450	3	as expected	
	4020	3	as expected	
	5001	3	as expected	
	5005	3	as expected	
District of Columbia	1400	1	not classified	No time-series data available.
Florida	1060	4	as expected	
	1370	4	as expected	
	3811	4	as expected	
	3995	4	as expected	
	4000	4	as expected	
	4057	4	as expected	
	4059	4	as expected	
	4096	4	as expected	
	4099	2	as expected	
	4100	4	as expected	
	4101	2	as expected	Construction event 1
	4101	3	as expected	Construction event 2
	4103	4	as expected	
	4105	2	as expected	
	4106	5	as expected	
	4108	4	as expected	
	4138	4	as expected	
	4153	4	as expected	
	4154	5	as expected	
	4102	1	not classified	No time-series data available.
	1030	3	questionable	Increasing SN values with age.
	3804	4	questionable	Increasing SN values with age, fluctuating SN values.

Table 34. Summary of friction data for Delaware, District of Columbia, and Florida (continued).

State	Section ID	No. of time-series data	Data quality	Comments
	3996	4	questionable	
	3997	4	questionable	
	4097	4	questionable	
	4107	4	questionable	
	4109	4	questionable	
	4135	2	questionable	Construction event 1
	4135	1	not classified	Construction event 2
	4135	1	not classified	Construction event 3
	4136	2	questionable	Construction event 1
	4136	1	not classified	Construction event 2
	4136	1	not classified	Construction event 3
	4137	2	questionable	Construction event 1
	4137	1	not classified	Construction event 2
	4137	1	not classified	Construction event 3
	9054	4	questionable	

Table 35. Summary of friction data for Georgia.

State	Section ID	No. of time-series data	Data quality	Comments
Georgia	1001	7	as expected	
	1004	7	as expected	
	1005	7	as expected	
	1031	7	as expected	
	3007	7	as expected	
	3011	7	as expected	
	3015	7	as expected	
	3016	7	as expected	
	3017	7	as expected	
	3018	7	as expected	
	3019	7	as expected	
	3020	7	as expected	
	4092	7	as expected	
	4093	7	as expected	
	4096	7	as expected	
	4111	4	as expected	
	4112	7	as expected	
	4118	7	as expected	
	4113	7	as expected	
	4119	7	as expected	
	4420	3	as expected	Construction event 1
	4420	4	as expected	Construction event 2
	7028	7	as expected	
	5023	7	questionable	

Table 36. Summary of friction data for Idaho.

State	Section ID	No. of time-series data	Data quality	Comments
Idaho	1001	1	not classified	No time-series data available.
	1005	1	not classified	
	1007	1	not classified	
	1009	1	not classified	
	1010	1	not classified	
	1020	1	not classified	
	1021	1	not classified	
	3017	1	not classified	
	3023	1	not classified	
	5025	1	not classified	
	6027	1	not classified	
	9032	1	not classified	
	9034	1	not classified	

Table 37. Summary of friction data for Illinois.

State	Section ID	No. of time-series data	Data quality	Comments
Illinois	1003	2	as expected	
	4074	2	as expected	
	4082	2	as expected	
	5020	2	as expected	
	5453	2	as expected	
	5843	2	as expected	
	5849	2	as expected	
	5854	2	as expected	
	5869	2	as expected	
	5908	2	as expected	
	6050	2	as expected	
	7937	2	as expected	
	9267	2	as expected	
	5151	1	not classified	Construction event 1
	5151	1	not classified	Construction event 2
	5217	1	not classified	Construction event 1
	5217	1	not classified	Construction event 2
	9327	2	not classified	Construction event 1
	9327	1	not classified	Construction event 2
	1002	2	questionable	Increasing SN values with age, fluctuating SN values.

Table 38. Summary of friction data for Indiana.

State	Section ID	No. of time-series data	Data quality	Comments
Indiana	1028	6	as expected	
	1037	6	as expected	
	3003	2	as expected	Construction event 2
	3030	5	as expected	
	3031	5	as expected	
	4021	5	as expected	
	4042	6	as expected	
	5022	2	as expected	Construction event 1
	5518	2	as expected	Construction event 1
	5528	4	as expected	Construction event 2
	9020	5	as expected	
	5518	1	not classified	Construction event 2
	5528	1	not classified	Construction event 1
	2008	5	questionable	Increasing SN values with age, fluctuating SN values.
	3008	5	questionable	
	3002	5	questionable	
	3003	3	questionable	Construction event 1
	5022	2	questionable	Construction event 2
	5043	6	questionable	
	5538	5	questionable	

Table 39. Summary of friction data for Iowa.

State	Section ID	No. of time-series data	Data quality	***Comments***
Iowa	3009	4	as expected	
	6049	6	as expected	
	9126	6	as expected	
	3006	6	questionable	Increasing SN values with age, fluctuating SN values.
	3028	6	questionable	
	3033	6	questionable	
	3055	6	questionable	
	5042	6	questionable	
	5046	6	questionable	
	9116	6	questionable	

Table 40. Summary of friction data for Kansas and Kentucky.

State	Section ID	No. of time-series data	Data quality	Comments
Kansas	1009	5	as expected	
	3013	5	as expected	
	3015	5	as expected	
	4053	5	as expected	
	4054	4	as expected	
	4063	5	as expected	
	4067	2	as expected	Construction event 1
	6026	3	as expected	Construction event 1
	6026	2	as expected	Construction event 2
	9037	4	as expected	
	4067	1	not classified	Construction event 2
	7085	1	not classified	Construction event 2
	1005	6	questionable	Increasing and fluctuating SN values with increasing age (ESAL's), use of different test equipment.
	1010	5	questionable	
	4016	5	questionable	
	4052	4	questionable	
	7073	5	questionable	
	7085	3	questionable	Construction event 1
Kentucky	1010	2	as expected	
	1014	5	as expected	
	1034	2	as expected	
	1034	1	not classified	
	3016	5	as expected	
	4025	4	as expected	
	6040	3	as expected	
	6043	5	as expected	

Table 41. Summary of friction data for Louisiana, Maine, Maryland, and Massachusetts.

State	Section ID	No. of time-series data	Data quality	Comments
Louisiana	3056	2	as expected	
	4001	2	as expected	
Maine	1001	4	as expected	
	1001	1	not classified	No time-series data available.
	1009	1	not classified	Construction event 2
	1028	1	not classified	Construction event 2
	1012	4	questionable	SN measurements made in October 1988 are out of trend for all pavement sections evaluated. This may be due to conditions at the time of the test. Removing all October 1988 test results will elevate status of data to as expected.
	1009	4	questionable	
	1026	4	questionable	
	1028	4	questionable	
	3013	4	questionable	
	3014	4	questionable	
	7023	4	questionable	
Maryland	2401	4	as expected	
	2805	2	as expected	Before-construction event.
	2805	2	as expected	After-construction event.
	5807	2	as expected	
	1632	3	questionable	Fluctuating SN values with increase in age and traffic.
	1634	4	questionable	Fluctuating SN values with increase in age and traffic.
Massachusetts	1003	2	as expected	
	1002	2	questionable	Increasing SN values. Indications of repair activities.
	1004	2	questionable	

Table 42. Summary of friction data for Michigan.

State	Section ID	No. of time-series data	Data quality	Comments
Michigan	1001	3	as expected	
	1010	4	as expected	
	3068	2	as expected	
	3069	2	as expected	
	5363	3	as expected	
	9029	3	as expected	
	9030	3	as expected	
	1004	1	not classified	No time-series data available.
	1012	3	questionable	
	1013	4	questionable	
	4015	3	questionable	

Table 43. Summary of friction data for Minnesota.

State	Section ID	No. of time-series data	Data quality	Comments
Minnesota	1016	1	not classified	No time-series data available.
	1018	1	not classified	
	1019	1	not classified	
	1023	1	not classified	
	1028	1	not classified	
	1029	1	not classified	
	1085	1	not classified	
	1087	1	not classified	
	3003	1	not classified	
	3013	1	not classified	
	4033	1	not classified	
	4034	1	not classified	
	4037	1	not classified	
	4040	1	not classified	
	4050	1	not classified	
	4055	1	not classified	
	4082	1	not classified	
	5076	1	not classified	
	6064	1	not classified	
	6251	1	not classified	
	7090	1	not classified	
	9075	1	not classified	

Table 44. Summary of friction data for Mississippi.

State	Section ID	No. of time-series data	Data quality	Comments
Mississippi	1016	2	as expected	
	2807	2	as expected	
	3018	2	as expected	
	3019	2	as expected	
	5025	2	as expected	
	7012	2	as expected	
	1001	1	not classified	Data quality not determined because of single data entry.
	1802	1	not classified	
	3081	1	not classified	
	3082	1	not classified	
	3083	1	not classified	
	3085	1	not classified	
	3087	1	not classified	
	3099	1	not classified	
	3090	1	not classified	
	3091	1	not classified	
	3093	1	not classified	
	3094	1	not classified	
	3099	1	not classified	
	4024	1	not classified	
	5006	1	not classified	
	5803	1	not classified	
	5805	1	not classified	
	9030	1	not classified	

Table 45. Summary of friction data for Missouri.

State	Section ID	No. of time-series data	Data quality	Comments
Missouri	1005	4	as expected	
	1008	6	as expected	
	1010	6	as expected	
	5047	6	as expected	
	5058	6	as expected	
	5081	6	as expected	
	5091	3	as expected	
	5403	6	as expected	Construction event 2
	5413	6	as expected	Construction event 2
	5473	5	as expected	
	5483	3	as expected	Construction event 1
	5483	3	as expected	Construction event 2
	5503	3	as expected	
	6067	6	as expected	
	7054	4	as expected	Construction event 1
	7054	2	as expected	Construction event 2
	5393	1	not classified	Construction event 1, no time-series data available.
	5403	1	not classified	Construction event 1, no time-series data available.
	5413	1	not classified	Construction event 1, no time-series data available.
	1002	3	questionable	Increasing SN values w/increase in age and traffic.
	4036	6	questionable	
	5000	6	questionable	
	5393	5	questionable	Construction event 2
	7073	6	questionable	
	1002	7	questionable	Increasing SN values w/increase in age and traffic.

Table 46. Summary of friction data for Montana, Nevada, and Nebraska.

State	Section ID	No. of time-series data	Data quality	Comments
Montana	6004	2	as expected	
	7075	2	as expected	
	7076	2	as expected	
	7088	2	as expected	
	8129	2	as expected	
	1001	1	not classified	Data quality not determined because of single data entry.
	7066	2	questionable	Increasing SN values with increase in age and traffic.
Nebraska	3018	3	as expected	
	3028	2	as expected	
	3033	3	as expected	
	5052	3	as expected	
	6702	2	as expected	
	7017	3	as expected	
	1030	3	questionable	Fluctuating SN values w/increase in age and traffic.
	3023	2	questionable	
	4019	2	questionable	
	6700	3	questionable	
	6701	3	questionable	
Nevada	1030	2	as expected	
	3010	3	as expected	
	3013	3	as expected	
	1021	1	not classified	Data quality not determined because of single data entry.
	7084	1	not classified	Data quality not determined because of single data entry.
	2027	4	questionable	Fluctuating SN values w/increase in age and traffic.
	7000	4	questionable	

Table 47. Summary of friction data for New Hampshire, New Jersey, and New Mexico.

State	Section ID	No. of time-series data	Data quality	Comments
New Hampshire	1001	5	questionable	Fluctuating SN values with increase in age and traffic.
New Jersey	1034	6	as expected	
	1638	6	as expected	
	4042	6	as expected	
	1003	6	questionable	Fluctuating SN values with increase in age and traffic. Use of different equipment. Measurement made in 1994 abnormally high.
	1011	6	questionable	
	1030	6	questionable	
	1031	6	questionable	
	1033	6	questionable	
	6057	6	questionable	
New Mexico	1003	2	as expected	
	1005	3	as expected	
	1112	2	as expected	
	2007	3	as expected	
	6035	3	as expected	
	6401	3	as expected	
	1002	3	questionable	Fluctuating SN values with increase in age and traffic. 1992 measurement out of trend for pavement sections 2007, 2118, and 6033.
	1022	3	questionable	
	2006	3	questionable	
	2118	3	questionable	
	3010	3	questionable	
	6033	3	questionable	

Table 48. Summary of friction data for New York.

State	Section ID	No. of time-series data	Data quality	Comments
New York	1011	2	as expected	Construction event 1
	1011	3	as expected	Construction event 2
	1008	4	questionable	Fluctuating SN values with increase in age and traffic. All other variables seem to be reasonable.
	1643	9	questionable	
	1644	8	questionable	
	4017	5	questionable	
	4018	4	questionable	

Table 49. Summary of friction data for North Carolina.

State	Section ID	No. of time-series data	Data quality	Comments
North Carolina	1006	6	as expected	
	1024	6	as expected	
	1028	7	as expected	
	1030	7	as expected	
	1645	8	as expected	
	1801	8	as expected	
	1803	2	as expected	Construction event 1
	1803	6	as expected	Construction event 2
	1992	5	as expected	
	2819	6	as expected	Construction event 1
	2819	2	as expected	Construction event 2
	2824	4	as expected	Construction event 1
	2824	4	as expected	Construction event 2
	2825	8	as expected	
	3008	8	as expected	
	3044	7	as expected	
	5826	8	as expected	
	1024	1	not classified	Construction event 2
	1040	7	questionable	Fluctuating SN values with increase in age and traffic. Using different test equipment may contribute to fluct-uations.
	1352	7	questionable	
	1802	7	questionable	
	1814	7	questionable	
	1817	7	questionable	
	3011	8	questionable	
	3807	7	questionable	
	3816	7	questionable	
	5037	8	questionable	
	5827	8	questionable	

Table 50. Summary of friction data for North Dakota and Ohio.

State	Section ID	No. of time-series data	Data quality	Comments
North Dakota	2001	1	not classified	Data quality not determined because of single data entry.
	3005	1	not classified	
	3006	1	not classified	
	5002	1	not classified	
	5569	1	not classified	
Ohio	3013	2	as expected	Construction event 1
	4018	4	as expected	
	4031	3	as expected	
	5003	3	as expected	
	7021	4	as expected	
	9006	4	as expected	
	3013	1	not classified	Construction event 2, no time-series data available.
	5569	1	not classified	No time-series data available.
	3801	4	questionable	
	5010	4	questionable	

Table 51. Summary of friction data for Oklahoma.

State	Section ID	No. of time-series data	Data quality	Comments
Oklahoma	1017	4	as expected	
	4086	4	as expected	
	4154	4	as expected	
	4160	4	as expected	
	4161	4	as expected	
	4162	4	as expected	
	4164	3	as expected	Construction event 1
	5021	4	as expected	
	4164	1	not classified	Construction event 2
	1015	4	questionable	Fluctuating SN values with increase in age and traffic.
	3018	4	questionable	
	4087	4	questionable	
	4088	4	questionable	
	4155	4	questionable	
	4157	4	questionable	
	4158	4	questionable	
	4163	4	questionable	
	4165	4	questionable	
	4166	4	questionable	
	6010	4	questionable	

Table 52. Summary of friction data for Oregon.

State	Section ID	No. of time-series data	Data quality	Comments
Oregon	5005	2	as expected	
	5006	2	as expected	
	5021	2	as expected	
	5022	2	as expected	
	7018	2	as expected	
	7025	2	as expected	
	7081	2	as expected	
	6011	1	not classified	No time-series data available.
	6012	1	not classified	
	7019	1	not classified	
	2002	2	questionable	Increasing SN values with increase in age and traffic.
	5008	2	questionable	

Table 53. Summary of friction data for Pennsylvania.

State	Section ID	No. of time-series data	Data quality	Comments
Pennsylvania	1605	4	as expected	
	1606	2	as expected	
	1690	2	as expected	
	1597	1	not classified	Data quality not determined because of single data entry.
	1598	1	not classified	
	1599	1	not classified	
	1608	1	not classified	
	1610	1	not classified	
	1613	1	not classified	
	1614	1	not classified	
	1617	1	not classified	
	1618	1	not classified	
	1623	1	not classified	
	1627	1	not classified	
	3044	1	not classified	
	5020	1	not classified	
	7037	1	not classified	
	9027	1	not classified	

Table 54. Summary of friction data for Rhode Island and South Carolina.

State	Section ID	No. of time-series data	Data quality	Comments
Rhode Island	7401	2	as expected	
South Carolina	1008	1	not classified	No time-series data available.
	1011	1	not classified	
	1024	1	not classified	
	1025	1	not classified	
	3012	1	not classified	
	5017	1	not classified	
	5034	1	not classified	
	5035	1	not classified	
	7019	1	not classified	

Table 55. Summary of friction data for South Dakota.

State	Section ID	No. of time-series data	Data quality	Comments
South Dakota	3009	2	as expected	
	3010	2	as expected	
	3053	2	as expected	
	5040	2	as expected	
	9187	2	as expected	
	3012	1	not classified	Data quality not determined because of single data entry.
	3013	1	not classified	
	5020	1	not classified	
	5025	1	not classified	
	9106	1	not classified	
	9197	1	not classified	
	3052	2	questionable	Increasing SN values with increase in age and traffic.
	7049	2	questionable	

Table 56. Summary of friction data for Tennessee.

State	Section ID	No. of time-series data	Data quality	Comments
Tennessee	1023	3	as expected	Construction event 1
	1023	2	as expected	Construction event 2
	1028	5	as expected	
	1029	5	as expected	
	2001	5	as expected	
	2008	5	as expected	
	3075	5	as expected	
	3101	4	as expected	Construction event 1
	3108	5	as expected	
	3110	5	as expected	
	6015	6	as expected	
	6022	4	as expected	
	9024	4	as expected	Construction event 1
	9025	4	as expected	Construction event 2
	3101	1	not classified	Construction event 2
	9024	1	not classified	
	9025	1	not classified	
	3109	5	questionable	

Table 57. Summary of friction data for Texas.

State	Section ID	No. of time-series data	Data quality	Comments
Texas	1	4	as expected	
	1056	5	as expected	
	1093	5	as expected	
	1109	3	as expected	
	1113	2	as expected	Construction event 1
	1116	3	as expected	Construction event 1
	1119	4	as expected	
	1123	4	as expected	
	1130	3	as expected	Construction event 1
	3003	3	as expected	
	3569	4	as expected	
	3579	6	as expected	
	3679	4	as expected	
	3689	4	as expected	
	3719	4	as expected	
	3729	5	as expected	
	3835	3	as expected	
	4143	3	as expected	
	5035	3	as expected	
	5301	3	as expected	
	5336	5	as expected	
	9355	2	as expected	
	1116	1	not classified	Construction event 2
	1130	1	not classified	Construction event 2
	3739	1	not classified	Construction event 1
	3875	1	not classified	Construction event 1
	1039	3	questionable	Increasing SN values with increase in age and traffic, different equipment used in measurements.
	1046	5	questionable	
	1047	5	questionable	
	1048	3	questionable	
	1049	4	questionable	

Table 57. Summary of friction data for Texas (continued).

State	Section ID	No. of time-series data	Data quality	Comments
	1050	5	questionable	Increasing SN values with increase in age and traffic, different equipment used in measurements.
	1060	5	questionable	
	1065	5	questionable	
	1068	5	questionable	
	1069	5	questionable	
	1070	4	questionable	
	1076	3	questionable	
	1077	5	questionable	
	1087	4	questionable	
	1092	5	questionable	
	1094	7	questionable	
	1096	5	questionable	
	1111	5	questionable	
	1113	2	questionable	Construction event 2
	1122	6	questionable	
	1168	4	questionable	
	1169	6	questionable	
	1174	5	questionable	
	1178	4	questionable	
	1181	5	questionable	
	1183	6	questionable	
	2108	4	questionable	
	2133	4	questionable	
	2172	6	questionable	Increasing SN values with increase in age and traffic, different equipment used in measurements.
	2176	3	questionable	
	3010	4	questionable	
	3559	4	questionable	
	3589	6	questionable	
	3609	4	questionable	
	3629	5	questionable	
	3669	4	questionable	
	3699	4	questionable	

Table 57. Summary of friction data for Texas (continued).

State	Section ID	No. of time-series data	Data quality	Comments
	3739	6	questionable	Construction event 2
	3749	6	questionable	
	3769	7	questionable	
	3779	4	questionable	
	3845	4	questionable	
	3855	5	questionable	
	3865	6	questionable	
	3875	4	questionable	Construction event 2
	4142	5	questionable	
	4146	4	questionable	
	4152	4	questionable	
	5024	5	questionable	
	5026	4	questionable	
	5154	5	questionable	
	5274	3	questionable	
	5278	2	questionable	Increasing SN values with increase in age and traffic, different equipment used in measurements.
	5283	5	questionable	
	5284	4	questionable	
	5287	3	questionable	
	5310	3	questionable	
	5317	4	questionable	
	5323	5	questionable	
	5328	4	questionable	
	5334	5	questionable	
	5335	5	questionable	
	6079	5	questionable	
	6086	5	questionable	
	6160	4	questionable	
	6179	5	questionable	
	7165	2	questionable	
	9005	3	questionable	
	9167	3	questionable	

Table 58. Summary of friction data for Utah and Vermont.

<table>
<tr><th>State</th><th>Section ID</th><th>No. of time-series data</th><th>Data quality</th><th>Comments</th></tr>
<tr><td>Utah</td><td>1001</td><td>2</td><td>as expected</td><td></td></tr>
<tr><td></td><td>1004</td><td>2</td><td>as expected</td><td></td></tr>
<tr><td></td><td>1006</td><td>2</td><td>as expected</td><td></td></tr>
<tr><td></td><td>1007</td><td>2</td><td>as expected</td><td></td></tr>
<tr><td></td><td>1008</td><td>2</td><td>as expected</td><td></td></tr>
<tr><td></td><td>1017</td><td>2</td><td>as expected</td><td></td></tr>
<tr><td></td><td>3010</td><td>2</td><td>as expected</td><td></td></tr>
<tr><td></td><td>3011</td><td>2</td><td>as expected</td><td></td></tr>
<tr><td></td><td>1005</td><td>1</td><td>not classified</td><td>No time-series data available.</td></tr>
<tr><td></td><td>7082</td><td>1</td><td>not classified</td><td></td></tr>
<tr><td></td><td>7083</td><td>1</td><td>not classified</td><td></td></tr>
<tr><td></td><td>3015</td><td>2</td><td>questionable</td><td>Increasing SN values with increase in age and traffic.</td></tr>
<tr><td>Vermont</td><td>1004</td><td>3</td><td>as expected</td><td></td></tr>
<tr><td></td><td>1682</td><td>1</td><td>not classified</td><td>Construction event 1</td></tr>
<tr><td></td><td>1682</td><td>1</td><td>not classified</td><td>Construction event 2</td></tr>
<tr><td></td><td>1683</td><td>1</td><td>not classified</td><td>Construction event 1</td></tr>
<tr><td></td><td>1683</td><td>1</td><td>not classified</td><td>Construction event 2</td></tr>
<tr><td></td><td>1002</td><td>3</td><td>questionable</td><td rowspan="2">Increasing SN values with increase in age and traffic, abnormally high 1992 SN values.</td></tr>
<tr><td></td><td>1681</td><td>2</td><td>questionable</td></tr>
</table>

Table 59. Summary of friction data for Virginia.

State	Section ID	No. of time-series data	Data quality	Comments
Virginia	1023	6	as expected	
	1417	5	as expected	Construction event 1
	1423	6	as expected	
	1464	6	as expected	
	2004	6	as expected	
	2021	6	as expected	
	5009	5	as expected	
	5010	6	as expected	
	1417	1	not classified	Construction event 2
	1002	6	questionable	Increasing SN values with increase in age and traffic, different equipment types used for measurements.
	1419	6	questionable	
	2564	6	questionable	
	5008	6	questionable	

Table 60. Summary of friction data for Washington.

State	Section ID	No of time-series data	Data quality	Comments
Washington	1002	2	as expected	
	1007	2	as expected	
	3011	2	as expected	
	3014	2	as expected	
	3019	2	as expected	
	3813	3	as expected	
	6048	2	as expected	
	7409	2	as expected	
	3812	1	not classified	No time-series data available.
	6049	1	not classified	
	1005	3	questionable	Increasing SN values with increase in age and traffic, abnormally high SN values for 1995.
	1006	3	questionable	
	1008	3	questionable	
	1501	3	questionable	
	1801	3	questionable	
	3013	3	questionable	
	6020	3	questionable	
	6056	3	questionable	
	7322	3	questionable	

Table 61. Summary of friction data for Wisconsin.

State	Section ID	No. of time-series data	Data quality	Comments
Wisconsin	3008	5	as expected	
	3012	5	as expected	
	3015	5	as expected	
	3016	4	as expected	
	5037	5	as expected	
	6351	5	as expected	
	6352	5	as expected	
	6355	5	as expected	
	3009	4	questionable	Fluctuating SN values with increase in age and traffic.
	3010	6	questionable	
	3014	3	questionable	
	3019	4	questionable	
	5040	5	questionable	
	6354	5	questionable	

Table 62. Summary of friction data for Puerto Rico.

State	Section ID	No of time-series data	Data quality	Comments
Puerto Rico	1003	4	as expected	
	3008	9	as expected	
	4121	4	as expected	
	4122	4	questionable	Repeated measurements with fluctuating trend.

Table 63. Summary of friction data for Alberta and British Columbia.

State	Section ID	No. of time-series data	Data quality	Comments
Alberta	1803	1	not classified	Data quality not determined because of single data entry.
	1804	1	not classified	
	1805	1	not classified	
	2812	1	not classified	
	8529	1	not classified	
British Columbia	1005	3	as expected	
	6006	3	as expected	
	9017	2	as expected	
	6007	1	not classified	No time-series data available.

Table 64. Summary of friction data for Manitoba, New Brunswick, Newfoundland, Nova Scotia, Ontario, and Prince Edward Island.

State	Section ID	No. of time-series data	Data quality	Comments
Manitoba	1801	3	as expected	
	3802	3	as expected	
	6450	3	as expected	
	6451	3	as expected	
	6452	3	as expected	
New Brunswick	3803	2	as expected	
	1684	2	questionable	Increasing SN values with increase in age and traffic.
	1802	2	questionable	
	6804	2	questionable	
Newfoundland	1808	2	as expected	
	1801	2	questionable	Increasing SN values with increase in age and traffic.
	1803	2	questionable	
Nova Scotia	6802	1	not classified	No time-series data available.
Ontario	1622	2	as expected	
	1680	2	as expected	
	1806	2	as expected	
	2811	2	as expected	
	2812	2	as expected	
	1620	1	not classified	Construction event 1
	1620	1	not classified	Construction event 2
Prince Edward Island	1646	2	as expected	
	1645	2	as expected	
	1647	2	questionable	Abnormally high increase in SN values with increase in age and traffic.

Table 65. Summary of friction data for Quebec and Saskatchewan.

State	Section ID	No. of time-series data	Data quality	Comments
Quebec	1021	1	not classified	No time-series data available.
	1125	1	not classified	
	1127	1	not classified	
	2011	1	not classified	
	3001	1	not classified	
	3002	1	not classified	
	3015	1	not classified	
	3016	1	not classified	
	9018	1	not classified	
Saskatchewan	6400	5	as expected	
	6801	5	as expected	
	6410	1	not classified	Construction event 1
	6412	1	not classified	Construction event 1
	6405	5	questionable	Increasing SN values with increase in traffic.
	6410	5	questionable	Construction event 2, increasing SN values with increase in age and traffic.
	6412	5	questionable	Construction event 2, increasing SN values with increase in age and traffic.

APPENDIX C – OVERVIEW OF LTPP TEST SITES WITH FRICTION DATA

Introduction

The first task of this study was to evaluate the LTPP database to obtain information on skid resistance (measured as skid number) and other pavement characteristics related to skid resistance. This chapter not only describes how the data was processed and reduced for this project, but also provides information on the characteristics of the LTPP pavement sections. Because the LTPP pavement sections are distributed across the United States and Canada, certain regional differences in the characteristics of the pavements are expected. The influence of these regional differences on friction data collection and changes in the magnitude of friction as the pavement ages were investigated in this study.

LTPP Database

The data used in this analysis come from the following LTPP General Pavement Study (GPS) experiments:

- GPS-1 Asphalt concrete pavement constructed over a granular base material.
- GPS-2 Asphalt concrete pavement constructed over a bound base material.
- GPS-3 Jointed plain concrete pavement (JPCP).
- GPS-4 Jointed reinforced concrete pavement (JRCP).
- GPS-5 Continuously reinforced concrete pavement (CRCP).
- GPS-6 Asphalt concrete-overlaid asphalt concrete pavement.
- GPS-7 Asphalt concrete-overlaid portland cement concrete pavement.
- GPS-9 Portland cement concrete-overlaid portland cement concrete pavement.

The data used in the study reported here were obtained from Release 7.0 of the LTPP data (released Fall 1996). The data consisted of pavement characteristics for the 454 AC-surfaced and 269 PCC-surfaced pavement sections located throughout the United States and Canada. These are 150-m pavement sections, typically with 3.5-m-wide traffic lanes and either AC or tied PCC shoulders. For this study, data from the following specific data modules of the LTPP database were downloaded from the National Information Management System (NIMS) for all the GPS-1, GPS-2, GPS-3, GPS-4, GPS-5, GPS-6, GPS-7, and GPS-9 pavement sections with friction data:

- Inventory.
- Materials testing.
- Climatic.
- Traffic.
- Pavement monitoring.

LTPP Friction Test Sites

The LTPP database contains friction test data for most of the GPS experiment types. The total number of sections with friction data was 723. A breakdown of the number of test sections for each GPS experimental data type is as follows:

- AC over granular base: 183 sections
- AC over stabilized base: 108 sections
- Jointed plain concrete pavement: 117 sections
- Jointed reinforced concrete pavement: 53 sections
- Continuous reinforced concrete pavement: 77 sections
- AC-overlaid AC pavement: 114 sections
- AC-overlaid PCC pavement: 49 sections
- PCC-overlaid PCC pavement: 22 sections

Pavement Age and Traffic

The pavement sections analyzed as part of this study ranged in age from 1 to 42 years, with a mean of 15 years and a standard deviation of 7.8 years. A histogram of section age is provided in figure 32.

Traffic data were available for only 590 of the 723 test sections. These sections showed a wide range of cumulative traffic loading. A plot of KESAL's for all the LTPP GPS sections with friction data is shown in figure 33. A complete summary of the traffic statistics by climatic region is presented in table 66.

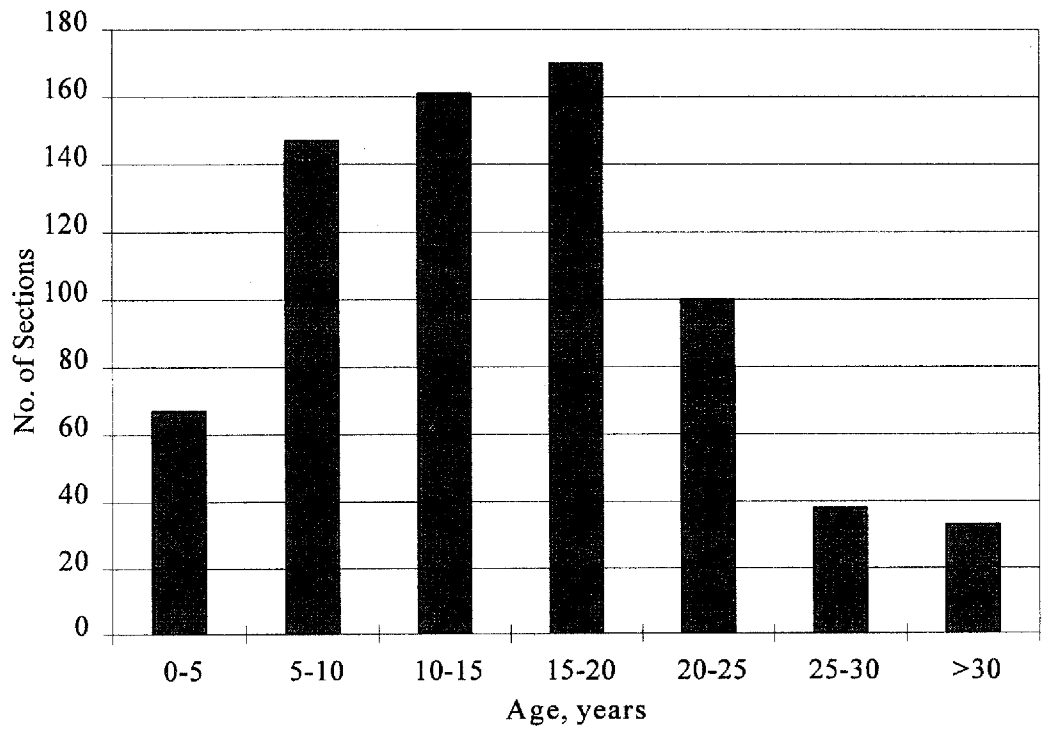

Figure 32. Age distribution for LTPP friction data sections (all experiment types).

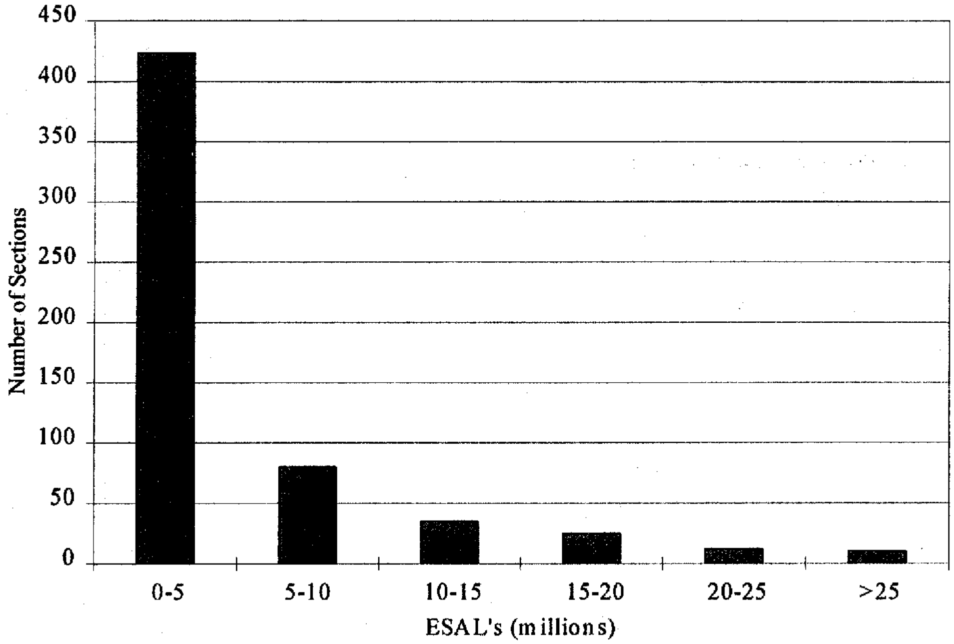

Figure 33. Histogram of cumulative ESAL's for all friction study sections.

Table 66. Traffic statistics by climatic region (KESAL's).

Statistic	Climatic Region			
	Dry-freeze	**Dry-nonfreeze**	**Wet-freeze**	**Wet-nonfreeze**
Mean	2873	7415	4696	4525
Std. deviation	3947	8335	5685	6274
Minimum value	46	212	100	48
Maximum value	17550	33490	36471	37341
Median	1429	3913	2512	1932

Friction Test Practices

Information on friction testing available in the LTPP database includes test equipment, test standard or guidelines, and test speed. Figure 34 presents a histogram of the test equipment used by the DOT's responsible for collecting LTPP friction data. Figure 34 shows the most common test equipment used to collect data for the LTPP program. Also, some of the LTPP friction data were collected with equipment manufactured in-house, such as the TxDOT equipment. A summary of the equipment used by the various transportation departments and highway agencies across the United States is presented in table 67. Table 68 is a summary of the test equipment used for friction data collection in Canada. With respect to test speed, about 90 percent of the testing was conducted at 65 km/h (ASTM E-274 specified speed).

Characterization of the LTPP AC-Surfaced Sections

The material types, material properties, and construction practices are different for AC and PCC surfaces. Therefore, detailed characterizations of the data relevant to friction for the two pavement types were done separately and are presented in the remaining sections of this chapter.

AC Pavement Types

The LTPP data sections used for the friction study consisted of 454 AC-surfaced sections from the different LTPP experiments. Forty percent (181 of 454 sections) of the AC sections were AC pavement constructed over a granular base material; 24 percent (109 of 454 sections) were AC pavements constructed over a bound (stabilized) base material. The remaining AC-surfaced sections were overlaid pavements. Twenty-five percent (114 of 454 sections) were AC-overlaid AC pavements, and the remaining 11 percent (50 of 454 sections) were AC-overlaid PCC pavements.

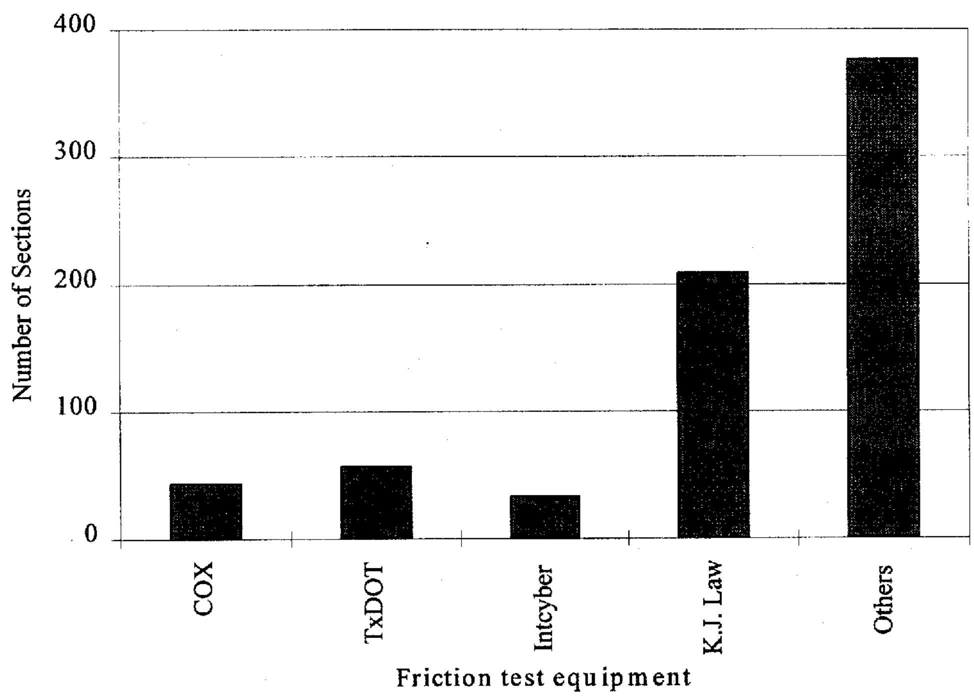

Figure 34. Friction test equipment type used for LTPP data collection.

Table 67. Summary of friction test equipment used in the United States.

State	Test equipment
Alabama	K.J. Law pavement friction tester
Arizona	K.J. Law pavement friction tester
Arkansas	K.J. Law pavement friction tester
California	James Cox and Sons pavement skid tester
Colorado	K.J. Law pavement friction tester
Connecticut	K.J. Law pavement friction tester
Delaware	Soil test equipment
District of Columbia	K.J. Law pavement friction tester
Florida	K.J. Law pavement friction tester and International Cybernetics
Georgia	International Cybernetics and soil test equipment
Idaho	Idaho DOT in-house equipment
Illinois	Illinois DOT in-house equipment
Indiana	Indiana DOT in-house equipment
Iowa	K.J. Law pavement friction tester
Kansas	Indiana DOT in-house equip. and K.J. Law pavement friction tester
Kentucky	K.J. Law pavement friction tester
Louisiana	K.J. Law pavement friction tester
Maine	Maine DOT in-house equipment
Maryland	K.J. Law pavement friction tester
Michigan	Michigan DOT in-house equipment
Minnesota	K.J. Law pavement friction tester
Mississippi	K.J. Law pavement friction tester
Missouri	K.J. Law pavement friction tester
Montana	K.J. Law pavement friction tester
Nebraska	K.J. Law pavement friction tester
Nevada	James Cox and Sons pavement skid tester
New York	K.J. Law pavement friction tester
New Mexico	K.J. Law pavement friction tester
New Jersey	Fabricated by Stevenson Institute of Technology

Table 67. Summary of friction test equipment used in the United States (continued).

State	Test equipment
New Hampshire	Maine DOT in-house equipment
North Dakota	K.J. Law pavement friction tester
North Carolina	K.J. Law pavement friction tester
Ohio	K.J. Law pavement friction tester
Oklahoma	K.J. Law pavement friction tester
Oregon	K.J. Law pavement friction tester
Pennsylvania	K.J. Law pavement friction tester
Rhode Island	K.J. Law pavement friction tester
South Carolina	K.J. Law pavement friction tester
South Dakota	K.J. Law pavement friction tester
Tennessee	Data not available
Texas	Texas DOT and South Dakota DOT in-house equipment
Vermont	K.J. Law pavement friction tester
Virginia	International Cybernetics
Washington	James Cox and Sons pavement skid tester
Puerto Rico	BISON test equipment

Table 68. Summary of friction test equipment used in Canada.

Province	Test equipment
Alberta	SASK Highways and Transportation tester
British Columbia	Port of Maine test equipment
Manitoba	SASK Highways and Transportation tester
New Brunswick	SAAB Runway friction tester
Newfoundland	SAAB Runway friction tester
Nova Scotia	Maine DOT in-house equipment
Ontario	K.J. Law
Prince Edward Island	SAAB Runway friction tester
Quebec	Data not available
Saskatchewan	SASK Highways and Transportation tester

AC Surface Layer Material Properties

A typical AC surface layer material consists of three main constituents, namely, asphalt cement coarse aggregate, and fine aggregate. The constituents that are designed to influence the surface texture and, hence, surface friction are the coarse and fine aggregates. Properties of the aggregates that can be used to assess the friction characteristics of the AC mixture include the aggregate geological classification, specific gravity, polish value, and the type of mineral filler used in the mixture. These properties and their availability in the LTPP database are discussed in this section.

Coarse Aggregate Geological Classification

Of the 454 AC-surfaced pavement sections studied, only 53 percent (241 of 454 sections) had data on the geological classification of the coarse aggregate used in the AC surface mixture. Figure 35 shows the distribution of the different aggregate geological classifications for the LTPP sections with data.

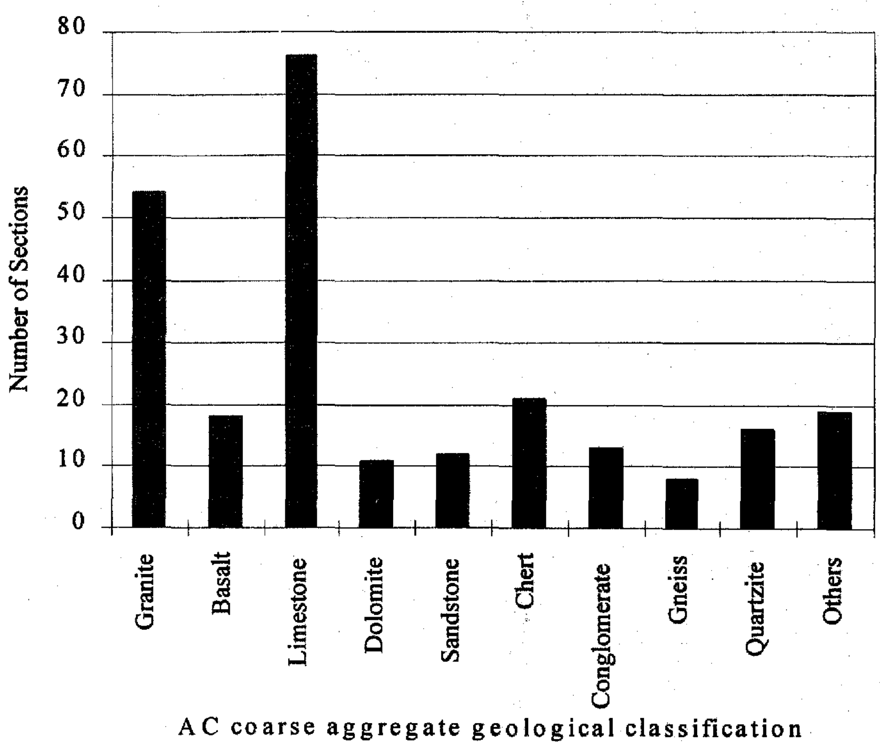

Figure 35. Histogram of coarse aggregate geological classification.

Coarse Aggregate Specific Gravity

The LTPP database contains data on the specific gravity (relative density) of coarse aggregates used in AC mixtures for only 47 percent (214 of 454 sections) of the AC-surfaced pavements. A plot of the distribution of the specific gravity of the coarse aggregate material used in the construction of AC-surfaced pavements evaluated in this study is presented in figure 36.

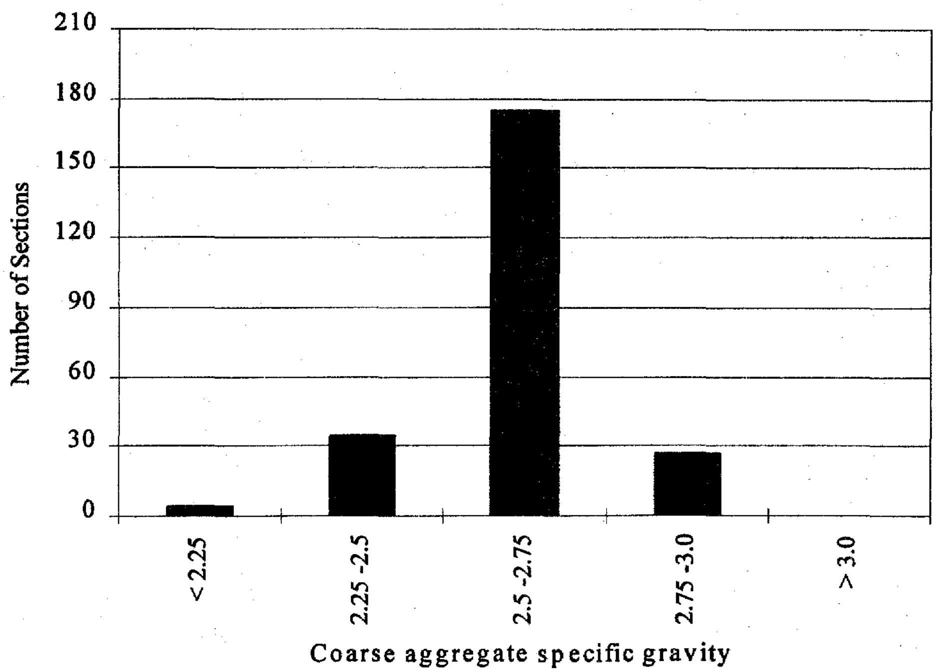

Figure 36. Histogram of available specific gravity values for coarse aggregate used in AC surface mixture.

Fine Aggregate Specific Gravity

The LTPP database had data on the specific gravity (relative density) of fine aggregates used in AC mixtures for only 48 percent (218 of 454 sections) of the AC-surfaced pavements. A plot of the distribution of the fine aggregate material specific gravity AC surface layer for pavements evaluated in this study is presented in figure 37.

Mineral Filler Material Type

Some States add additional fine material such as stone dust, fly ash, or lime to AC mixtures to ensure a stable mixture that can withstand expected traffic, moisture, and environmental damage. The LTPP database contained information on such materials for 26 percent (122 of 454 sections) of the AC-surfaced pavements. Figure 38 is a histogram of the frequencies of the material types used as mineral filler for the AC pavement mixtures evaluated in this study.

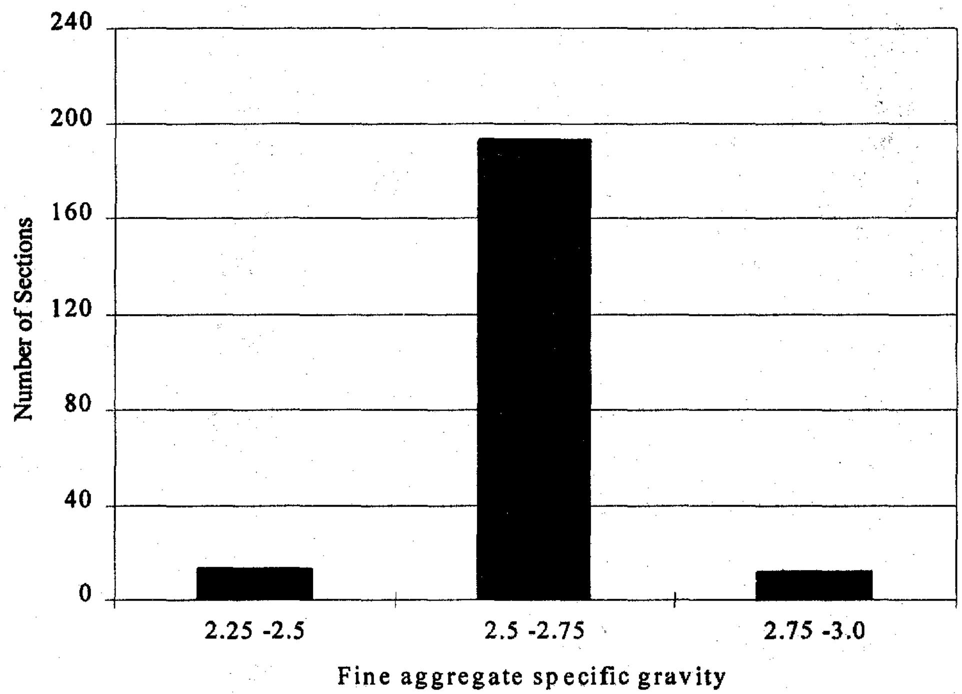

Figure 37. Histogram of available specific gravity values for fine aggregate used in AC surface mixture.

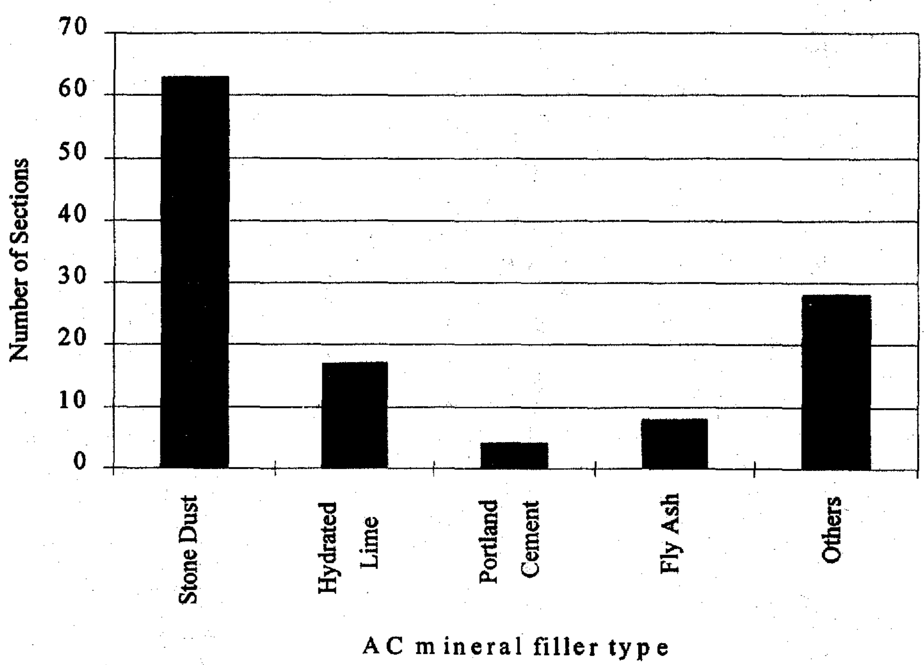

Figure 38. Histogram of mineral filler type used in AC surface mixture.

Mineral Filler Specific Gravity

Of the 122 pavement sections that included mineral filler in their AC mixtures, 60 percent (72 of 122 sections) had data on the specific gravity of the mineral filler used. A plot of the distribution of the specific gravity of the mineral fillers used in the construction of the AC-surfaced pavements evaluated in this study is presented in figure 39.

Effective Specific Gravity

For 29 percent (135 of 454 sections) of the AC-surfaced pavements evaluated in this study, the LTPP database contained data on the effective specific gravity (relative density). This is the specific gravity of the combined aggregate material (e.g., fine, coarse, mineral filler) used in the AC mixtures. A plot of the distribution of the effective specific gravity of the aggregate materials used in the construction of AC-surfaced pavements evaluated in this study is presented in figure 40.

Site Conditions

Site conditions such as temperature, precipitation, and air freeze-thaw cycles can significantly affect the rate of deterioration of AC pavement surface texture and, hence, friction. The data available in the LTPP database that characterize climate conditions are described in detail in the next few sections.

Average Annual Number of Air Freeze-Thaw Cycles

Data on average annual air freeze-thaw cycles were available for 377 of the 454 AC-surfaced pavement sections. The number of annual cycles varied from 0 to 197, with a mean of 78, a median of 78, and a standard deviation of 30. A histogram of the available average annual freeze-thaw cycle data for the AC-surfaced pavement sections evaluated is presented in figure 41.

Average Annual Total Precipitation

The LTPP database had average annual precipitation data for 378 of the 454 AC-surfaced pavements.

As expected, an analysis of the average annual precipitation within different climatic regions showed larger mean values for the regions with wet conditions. Specifically, the sections in the wet-freeze and wet-nonfreeze regions had mean values of 1.05 and 1.2 m, respectively, and the sections in the dry-freeze and dry-nonfreeze regions had mean values of 0.36 and 0.37 m, respectively. A summary of the statistics for the average annual precipitation for the four climatic zones covered by the LTPP program is summarized in table 69. A histogram showing the average annual precipitation data for the AC-surfaced sections is presented in figure 42.

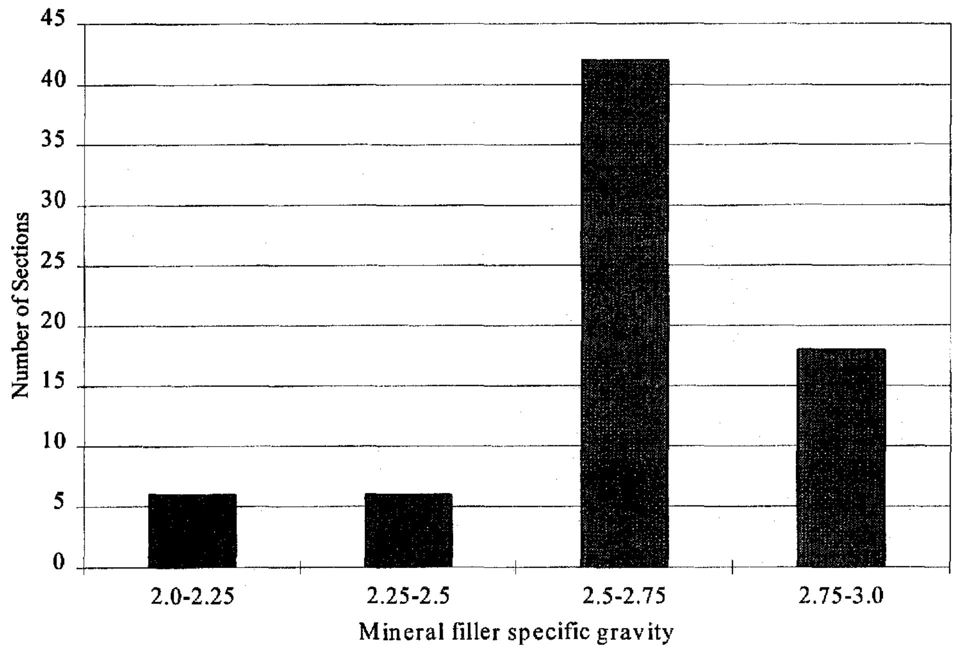

Figure 39. Histogram of mineral filler specific gravity values in AC surface mixture.

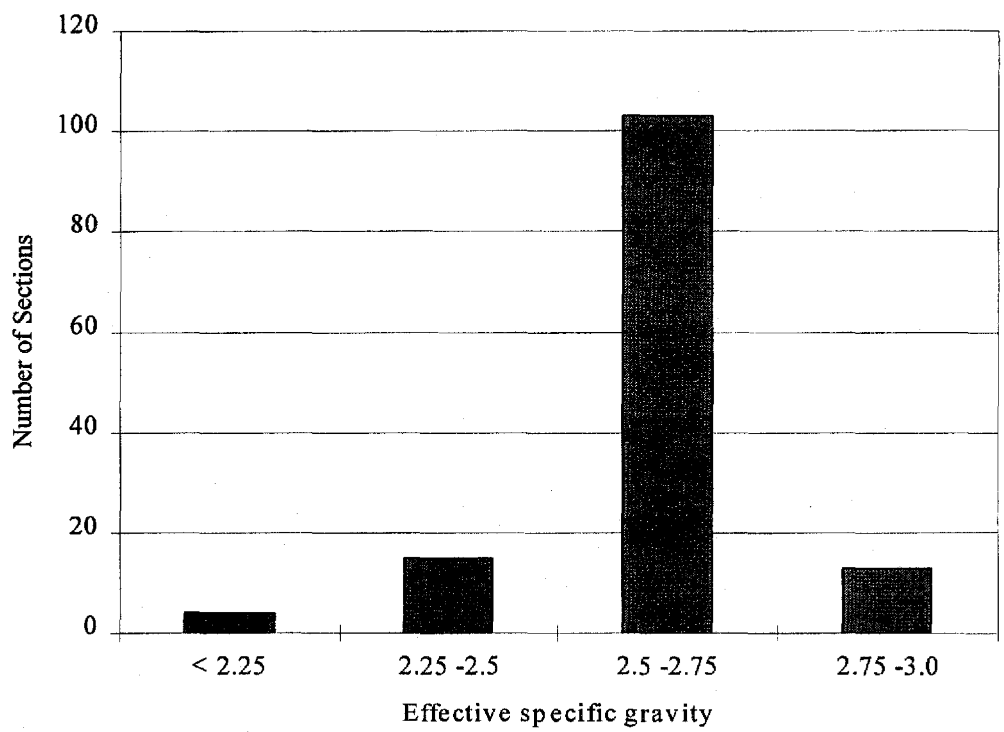

Figure 40. Histogram of effective specific gravity values for aggregate materials used in AC surface mixture.

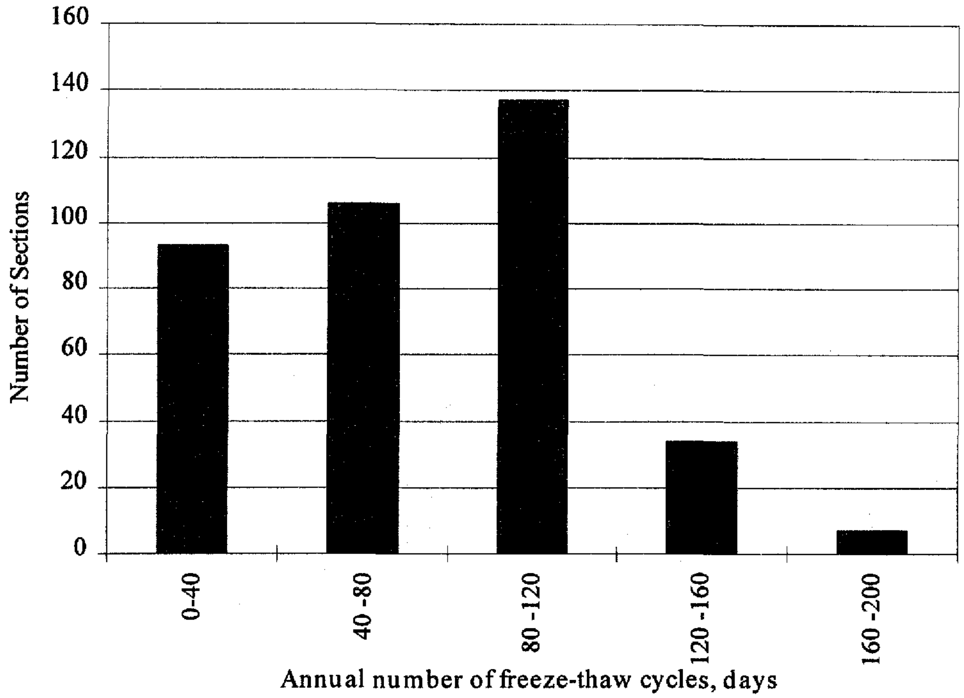

Figure 41. Bar chart of average annual number of freeze-thaw cycles for all AC-surfaced pavements evaluated.

Table 69. Summary of average annual total precipitation for AC-surfaced pavements evaluated.

Statistics	Climate region			
	Dry-freeze	**Dry-nonfreeze**	**Wet-freeze**	**Wet-nonfreeze**
Mean, m	0.36	0.37	1.05	1.2
Maximum value, m	0.60	0.60	2.135	1.78
Minimum value, m	0.18	0.076	0.635	0.365
Std. deviation, m	0.11	0.104	0.22	0.26
Median, m	0.37	0.40	1.04	1.2

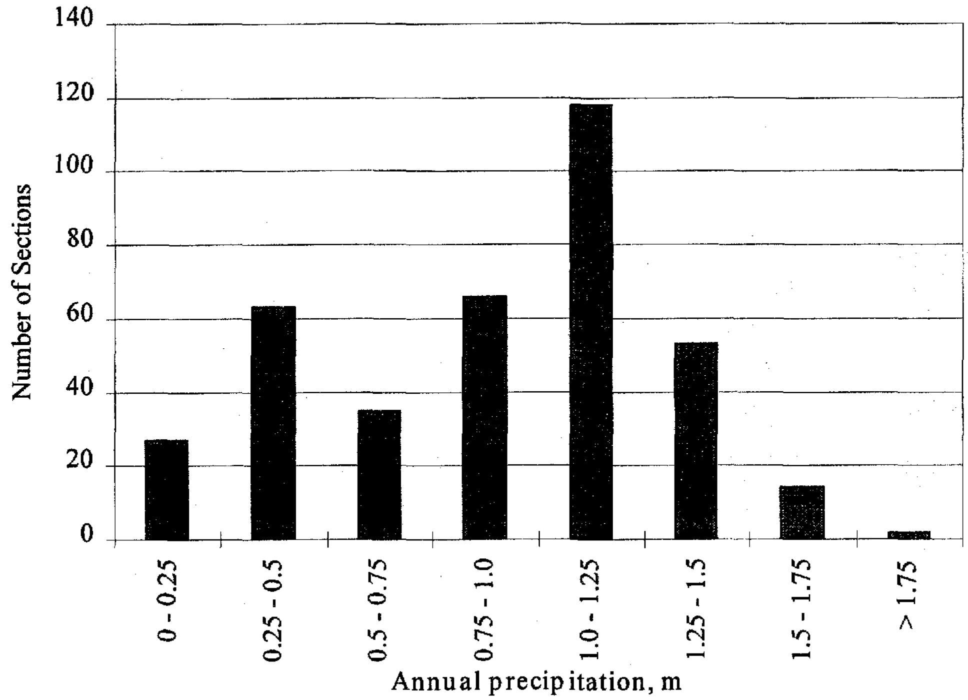

Figure 42. Bar chart of average annual total precipitation for all AC-surfaced pavements evaluated.

Average Annual Number of Wet Days

The average annual number of wet days ranged from 16 to 225, with a mean of 106, a median of 105.3, and a standard deviation of 25.25 for the 378 sections with average annual number of wet days data. As expected, an analysis of the average annual number of wet days within different climatic regions showed larger mean values for the regions with wet conditions. Specifically, the sections in the wet-freeze and wet-nonfreeze regions had mean values of 153 and 126, respectively, and the sections in the dry-freeze and dry-nonfreeze regions had mean values of 86 and 89.7, respectively. A summary of the average annual number of wet days for the four climatic zones covered by the LTPP program is summarized in table 70. A histogram of the average annual number of wet days data for the AC-surfaced sections is presented in figure 49.

Air Temperature During Friction Testing

The air temperature during the time of pavement surface friction testing was available for 88 percent (401 of 454 sections) of the AC-surfaced pavement sections evaluated. The air temperature varied from 2 to 42 °C, with a mean of 22 °C, a median of 23 °C, and a standard deviation of 10.3 °C. Table 71 presents a summary of the statistics of air temperatures measured during friction testing in the vicinity of the test pavement sections.

Table 70. Summary of average annual number of wet-day cycles for AC-surfaced pavements evaluated.

Statistics	Climate region			
	Dry-freeze	**Dry-nonfreeze**	**Wet-freeze**	**Wet-nonfreeze**
Mean	86.6	59.7	153	126
Maximum value	131	102	225	204
Minimum value	32	16	86	63
Std. deviation	22.36	22.58	29.75	26.32
Median	84.5	62	151	128

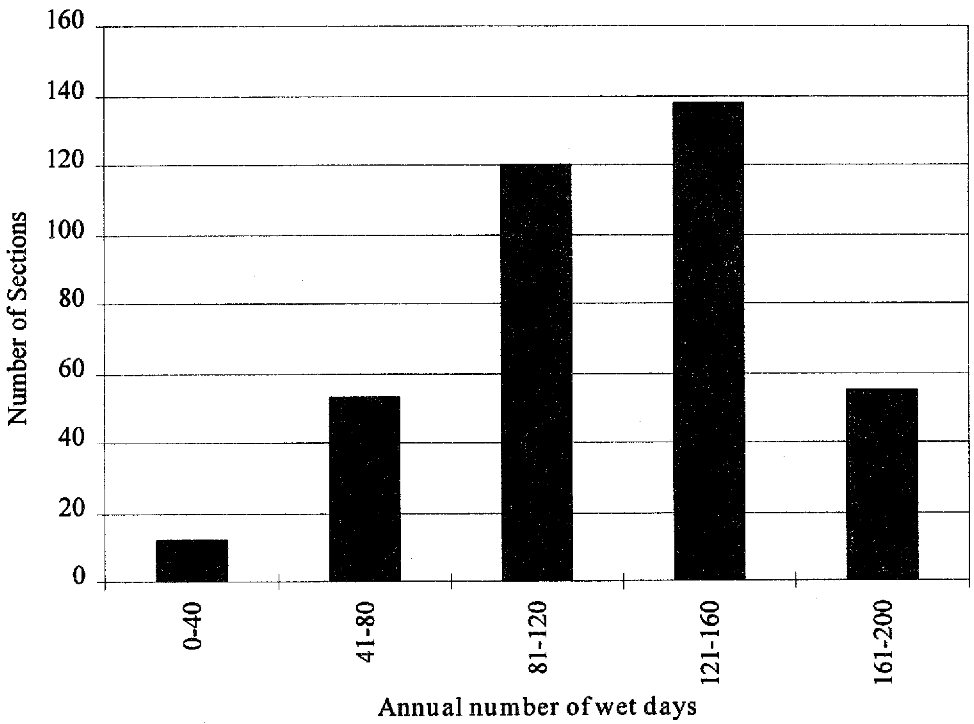

Figure 43. Bar chart of average annual number of wet days for all AC-surfaced pavements evaluated.

Table 71. Summary of measured air temperatures during friction testing.

Air temperature measured during friction testing, °C	Number of AC-surfaced sections
0 to 4.5	5
4.5 to 10	27
10 to 15.5	56
15.5 to 21	107
21 to 26	76
26 to 32	77
32 to 38	44
Greater than 38	9

Average Annual Number of Days With Temperatures Below 0 °C

The average annual number of days with temperatures below 0 °C ranged from 0 to 236 days, with a mean of 98, a median of 94.5, and a standard deviation of 35.5 for the 385 of the 454 AC-surfaced sections evaluated. As expected, an analysis of the average annual number of days with temperatures below 0 °C within different climatic regions showed larger mean values for the regions with freeze conditions. Specifically, the sections in the wet-freeze and dry-freeze regions had mean values of 138 and 160, respectively, and the sections in the wet-nonfreeze and dry-nonfreeze regions had mean values of 49.5 and 46, respectively. A summary of the average annual number of freezing days for the four climatic zones covered by the LTPP program is summarized in table 72. A histogram of the average annual number of freezing days for the AC-surfaced sections is presented in figure 44.

Average Annual Number of Days With Temperatures above 32 °C

The average annual number of days with temperatures above 32°C ranged from 0 to 180 days, with a mean of 48, a median of 24.6, and a standard deviation of 5 for the 368 out of the 454 AC-surfaced sections evaluated. As expected, an analysis of the average annual number of days with temperatures above 32 °C within different climatic regions showed larger mean values for the regions with non-freeze conditions. More specifically, the sections in the wet-nonfreeze and dry-nonfreeze regions had mean values of 58 and 101, respectively, and the sections in the wet-freeze and dry-freeze regions had mean values of 6.8 and 26, respectively. A summary of the average annual days with temperatures above 32 °C for the four climatic zones covered by the LTPP program is summarized in table 73. A histogram of the average annual precipitation data for the AC-surfaced sections evaluated is presented in figure 45.

Table 72. Summary of the average annual number of days with temperatures below 0 °C for AC-surfaced pavements evaluated.

Statistics	Climate region			
	Dry-freeze	**Dry-nonfreeze**	**Wet-freeze**	**Wet-nonfreeze**
Mean	160	46	136	49.5
Maximum value	236	128	184	123
Minimum value	18	2	6	0
Std. deviation	34.5	40.65	35.6	31.3
Median	156	36	138	48

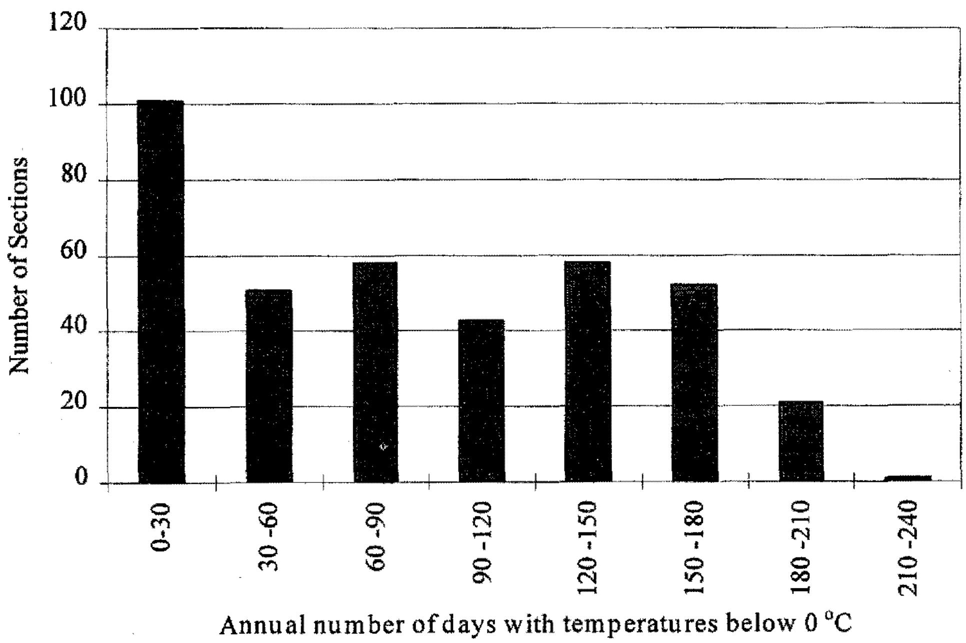

Figure 44. Bar chart of average annual number of days with temperatures below 0 °C for all AC-surfaced pavements evaluated.

Table 73. Summary of average annual number of days with temperatures above 32 °C for AC-surfaced pavements evaluated.

Statistics	Climate region			
	Dry-freeze	**Dry-nonfreeze**	**Wet-freeze**	**Wet-nonfreeze**
Mean	26.6	101.3	6.8	58.4
Maximum value	78	180	30	130
Minimum value	0	3	0	6
Std. deviation	19.8	44.75	6.2	27.4
Median	26.5	90	6	57

Characterization of the LTPP PCC-Surfaced Pavement Sections

PCC Pavement Types

The LTPP data sections evaluated as part of the friction study included a total of 269 PCC-surfaced pavements. Forty-three percent of the PCC pavements (117 of 269 sections) were jointed plain concrete pavement (JPCP), 20 percent (53 of 269 sections) were jointed reinforced concrete pavement (JRCP), 28 percent (74 of 269 sections) were continuously reinforced concrete pavement (CRCP), and the remaining 9 percent (25 of 269 sections) were PCC-overlaid PCC pavements. A histogram of the distribution of the PCC pavement type evaluated is shown in figure 46.

The pavement type characterization can be broken down further to describe the underlying pavement material types and design features, such as base type provided. Of the 117 JPCP sections evaluated, 45 sections were over non-bituminous base material, 39 sections were over unbound base, 14 sections were over bituminous base, and 19 sections were placed directly over the subgrade (treated or untreated).

Of the 53 JRCP sections, 16 sections were over non-bituminous base material, 7 sections were over bituminous base, 23 sections were over unbound base, and 7 sections were placed directly over the subgrade (treated or untreated). Of the 74 CRCP sections, 23 sections were over non-bituminous base material, 33 sections were over bituminous base, 13 sections were over unbound base, and 6 sections were placed directly over the subgrade (treated or untreated). The remaining 25 PCC pavement sections consisted of various forms of PCC-overlaid PCC pavement.

PCC Material Properties

The ultimate surface properties and material characteristics of PCC-surfaced pavements are dependent on both the properties of the constituent PCC materials and the PCC mixture composition. Availability of data on the PCC material and mixture is important in evaluating the pavement surface characteristics, and the extent of data availability is discussed in the next few sections.

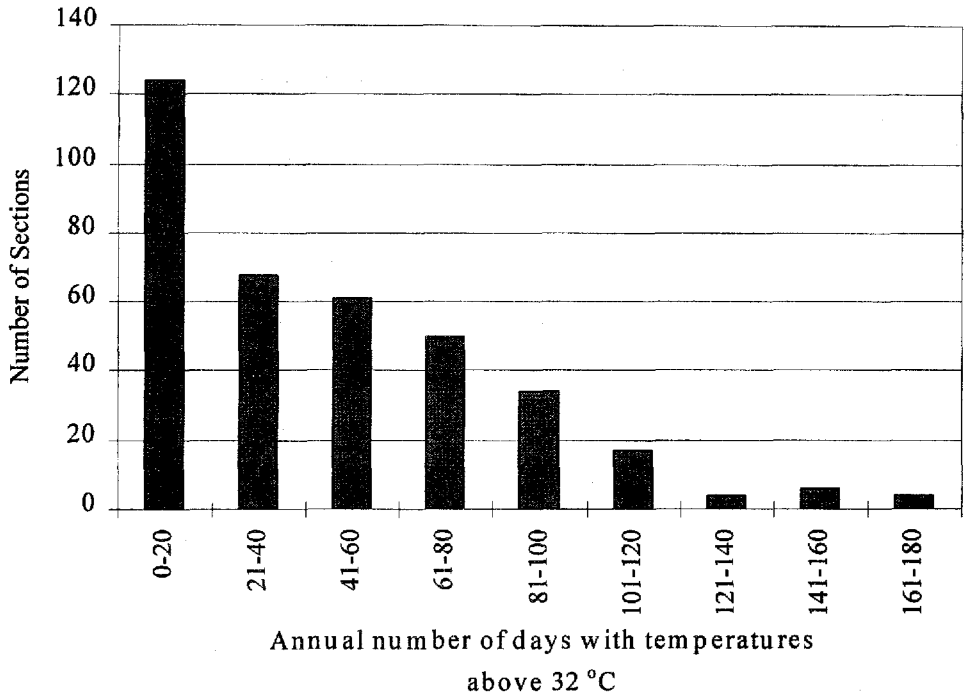

Figure 45. Bar chart of average annual number of days with temperatures above 32 °C for all AC-surfaced pavements evaluated.

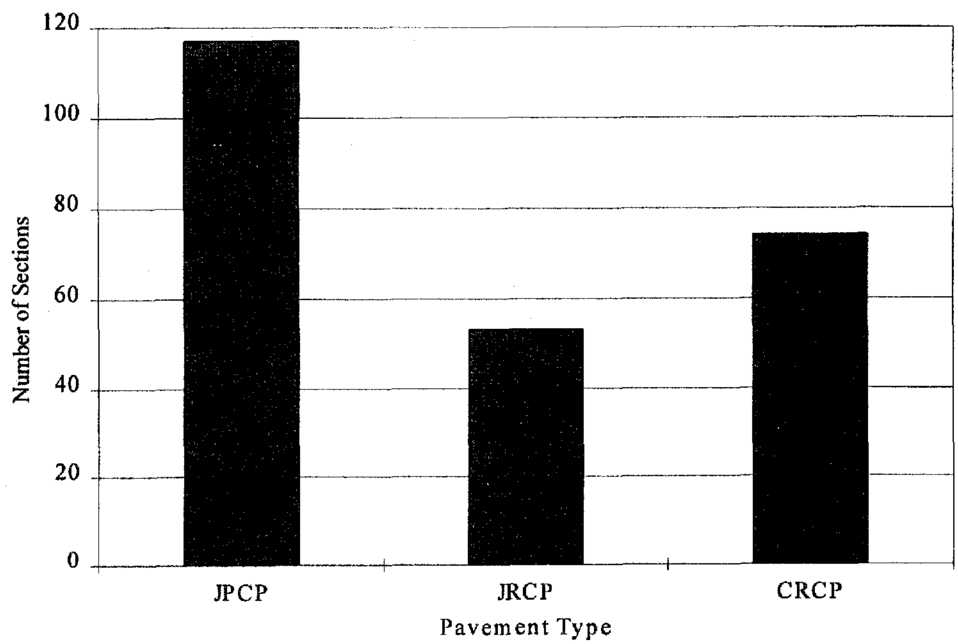

Figure 46. Distribution of PCC pavement type.

Coarse Aggregate Content of PCC Mixtures

Of the 269 PCC-surfaced sections, 87 percent (223 of 269 sections) had data on the coarse aggregate content of the PCC mixtures used. Figure 47 shows a histogram of the distribution of the coarse aggregate content of the pavements evaluated.

Fine Aggregate Content of PCC Mixtures

Of the 269 PCC-surfaced sections, 87 percent (223 of 269 sections) had data on the fine aggregate content of the PCC mixtures used. Figure 48 shows a histogram of the distribution of the fine aggregate content of the pavements evaluated.

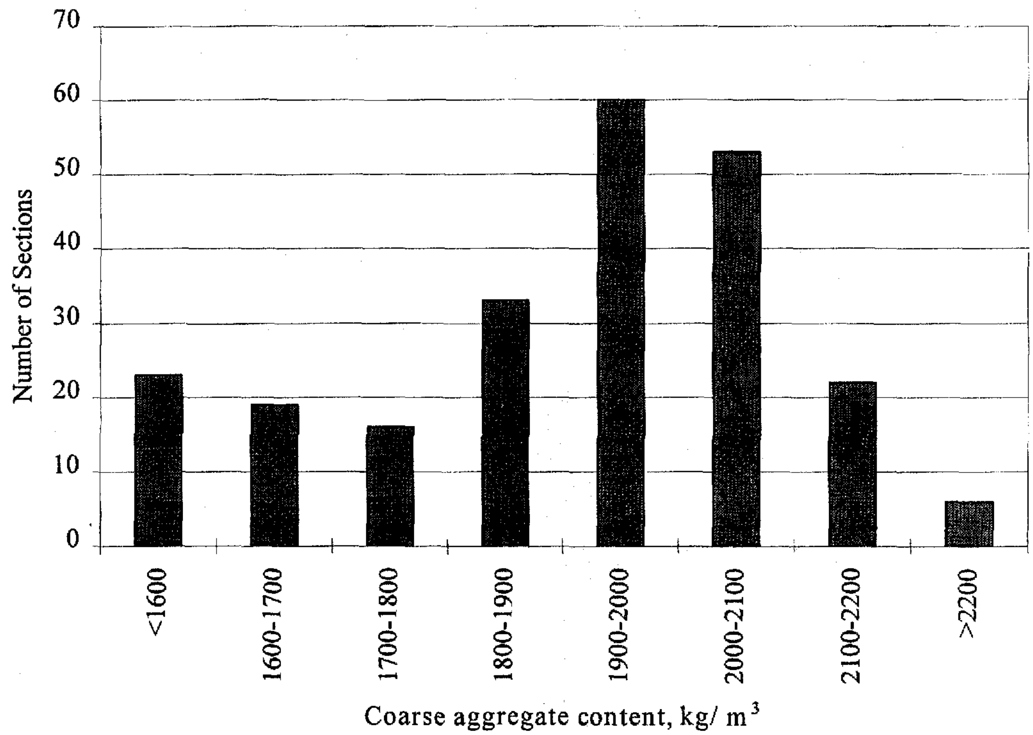

Figure 47. Distribution of PCC mixture coarse aggregate content.

Cement Content of PCC Mixtures

A total of 98 percent (263 of 269 sections) of the PCC-surfaced LTPP sections had data on the cement content of the PCC mixture used in pavement construction. Figure 49 shows the distribution of cement content by weight used for PCC mixtures for the pavements evaluated as part of this study.

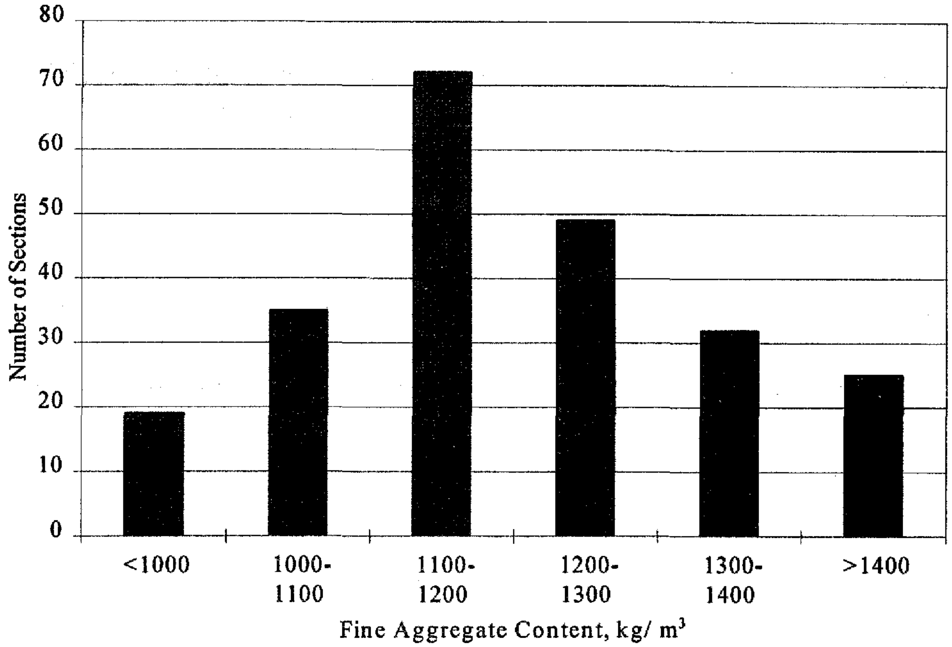

Figure 48. Distribution of PCC mixture fine aggregate content.

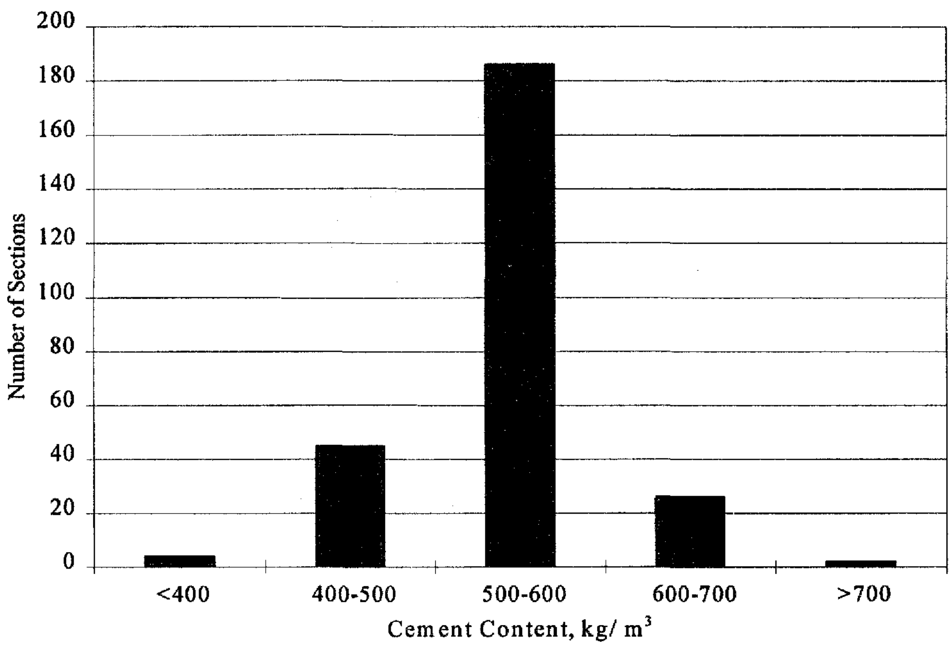

Figure 49. Distribution of PCC cement content.

Water Content of PCC Mixtures

Eighty-five percent (228 of 269 sections) had data on the water content by weight used in PCC mixtures. A histogram of the distribution of water content by weight used in the PCC concrete mixtures is shown in figure 50.

Cement Type Used for PCC Mixtures

There are several kinds of portland cement that can be used for concreting. The selection of a particular type depends on the strength expected, the type of construction, and local conditions under which the concrete is being placed. For the LTPP sections evaluated as part of the friction study, only 52 percent (138 of 268 sections) had data on the portland cement type used. A histogram showing the distribution of the portland cement types used is shown in figure 51.

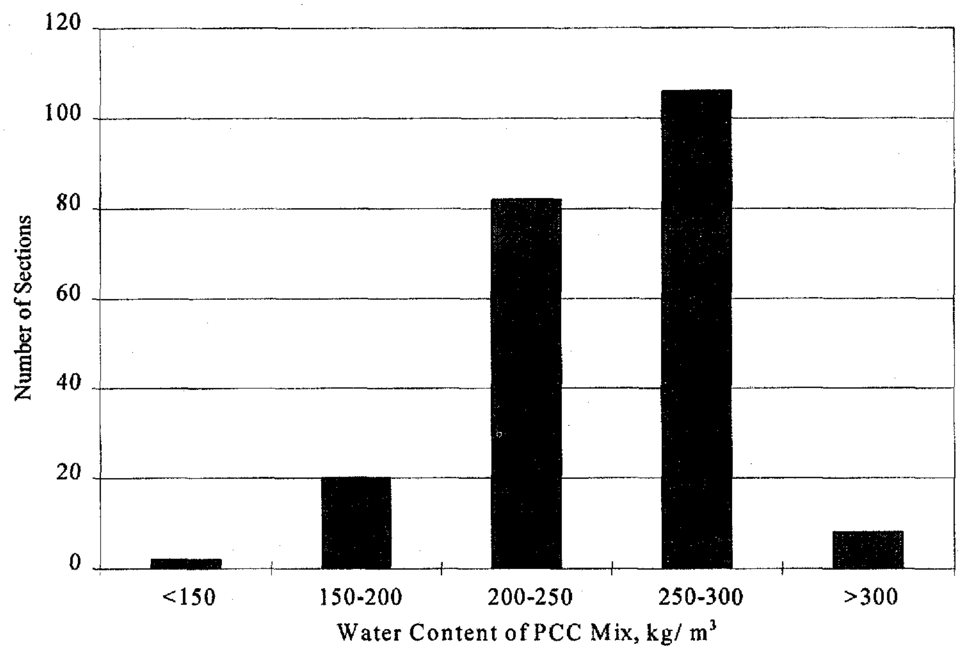

Figure 50. Distribution of PCC water content by weight.

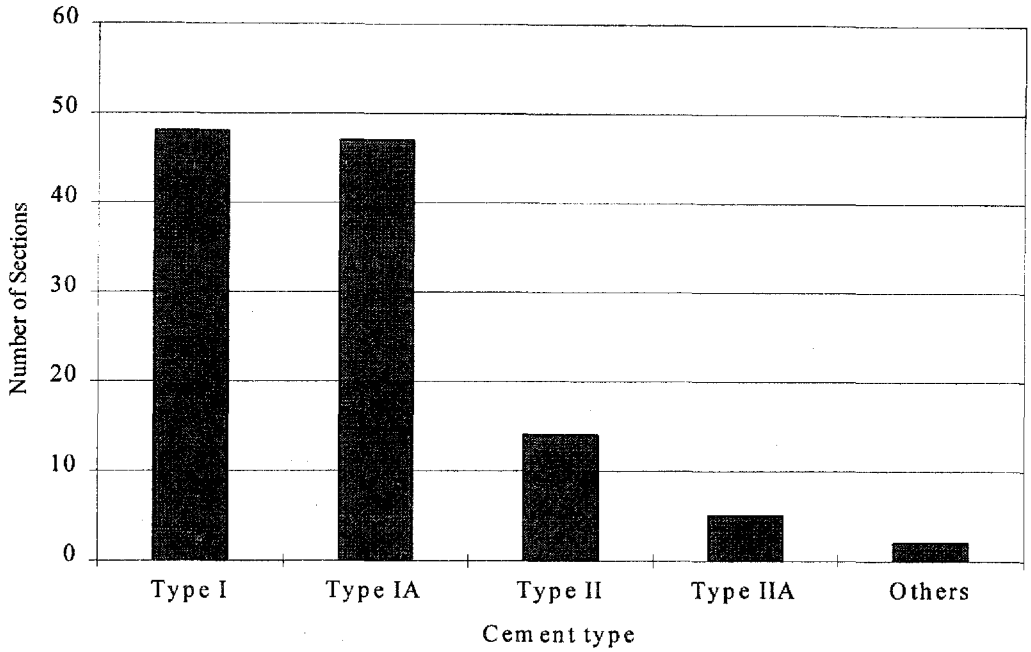

Figure 51. Distribution of PCC cement type.

Alkali Content of PCC Mixtures

A total of 38 percent (102 of 269 sections) of the LTPP PCC-surfaced sections evaluated had data on the alkali content of the PCC mixture. A distribution of the alkali content for the pavements evaluated for this study is shown in figure 52.

Entrained Air Content for PCC Mixtures

Seventy-eight percent (211 of 269 sections) of the PCC-surfaced pavements evaluated as part of this study had data on the entrained air content of the PCC mixtures. Figure 53 shows a plot of the distribution of the entrained air content of the PCC mixtures used for the pavements evaluated as part of this study.

Coarse Aggregate Geological Classification

Of the 269 PCC-surfaced pavement sections studied, only 63 percent (170 of 269 sections) had data on the geological classification of the coarse aggregate used in the PCC surface mixture. Figure 54 shows the distribution of the different aggregate geological classifications for the LTPP PCC-surfaced sections.

Coarse Aggregate Specific Gravity

The LTPP database contained data on the specific gravity (relative density) for only 30 percent (81 of 170 sections) of the PCC-surfaced pavements. A plot of the distribution of the specific gravity of the coarse aggregate material used in the construction of the PCC surface layer for pavements evaluated in this study is presented in figure 55.

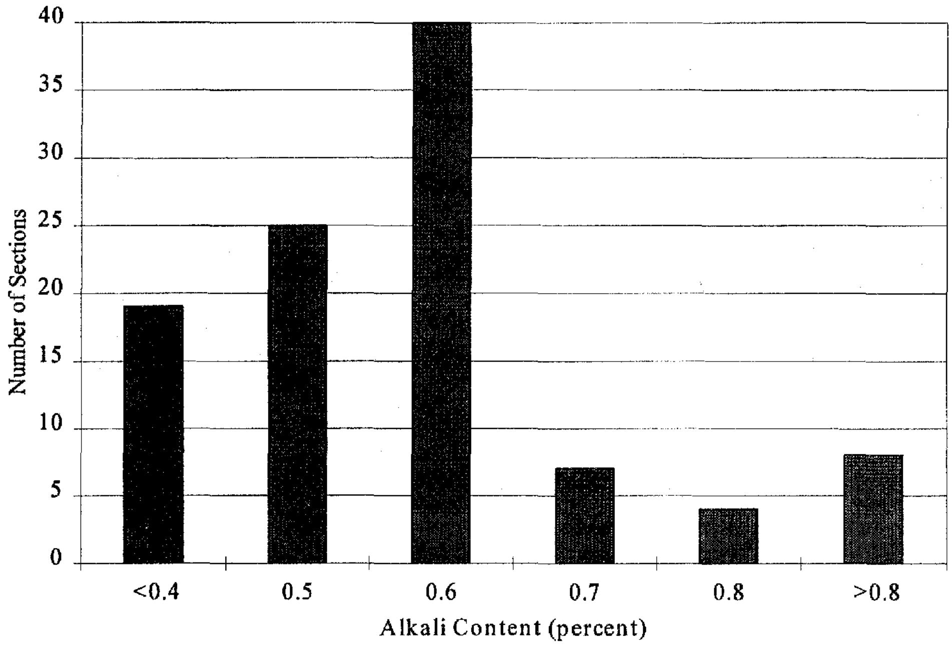

Figure 52. Distribution of PCC alkali content.

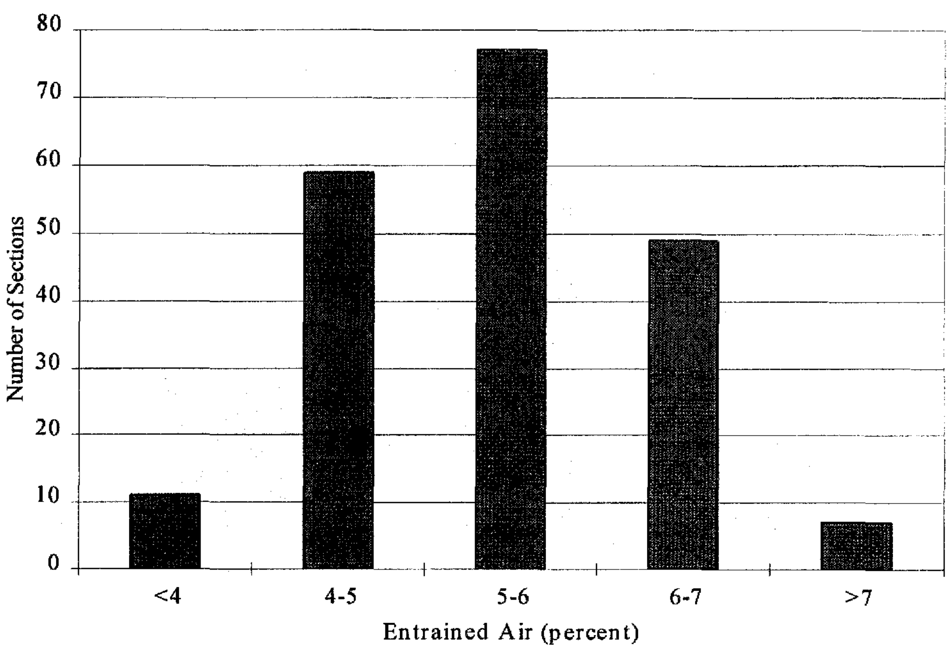

Figure 53. Distribution of PCC entrained air content.

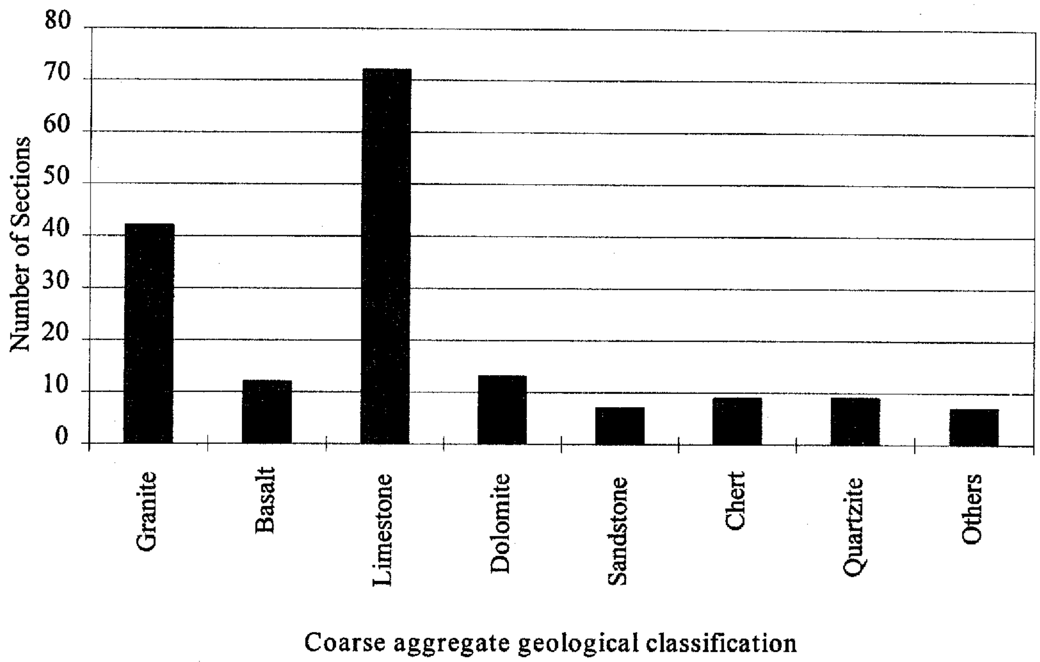

Figure 54. Histogram of coarse aggregate geological classification.

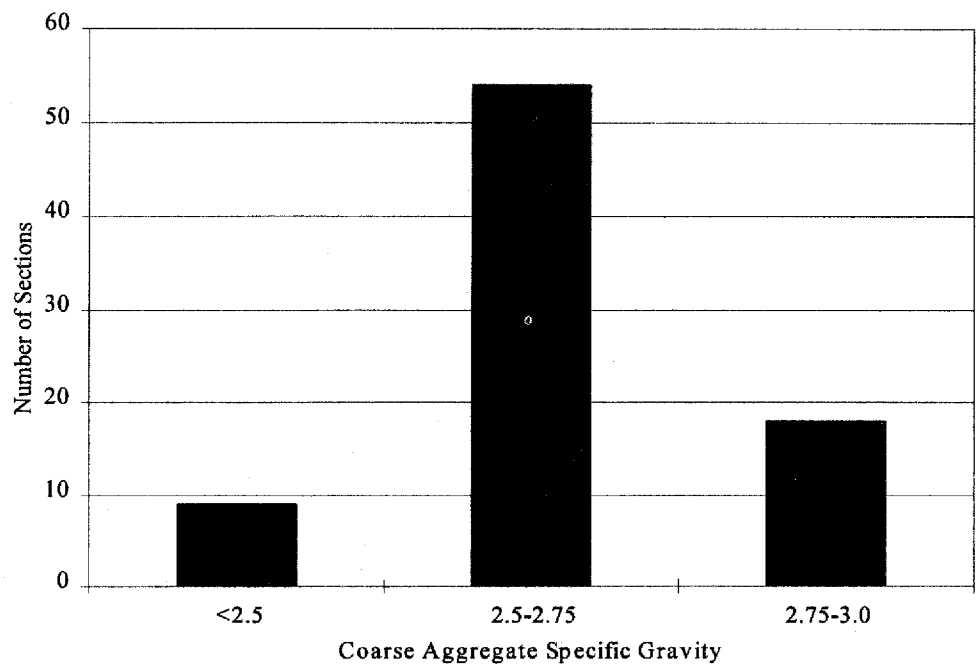

Figure 55. Distribution of PCC coarse aggregate specific gravity.

Fine Aggregate Specific Gravity

Only 24 percent of the LTPP PCC-surfaced sections evaluated as part of this study (93 of 269 sections) had data on the specific gravity of the fine aggregate used in the PCC mixture. A plot of the distribution of the specific gravity of the coarse aggregate material used in the construction of the PCC surface layer for pavements evaluated in this study is presented in figure 56.

Construction Practices

Several construction practices affect the final surface texture and, therefore, surface friction of the pavement, including the paver type used in construction, surface texturing method, and the concrete curing method. The relevant construction practices identified in the LTPP database are discussed in the next few sections.

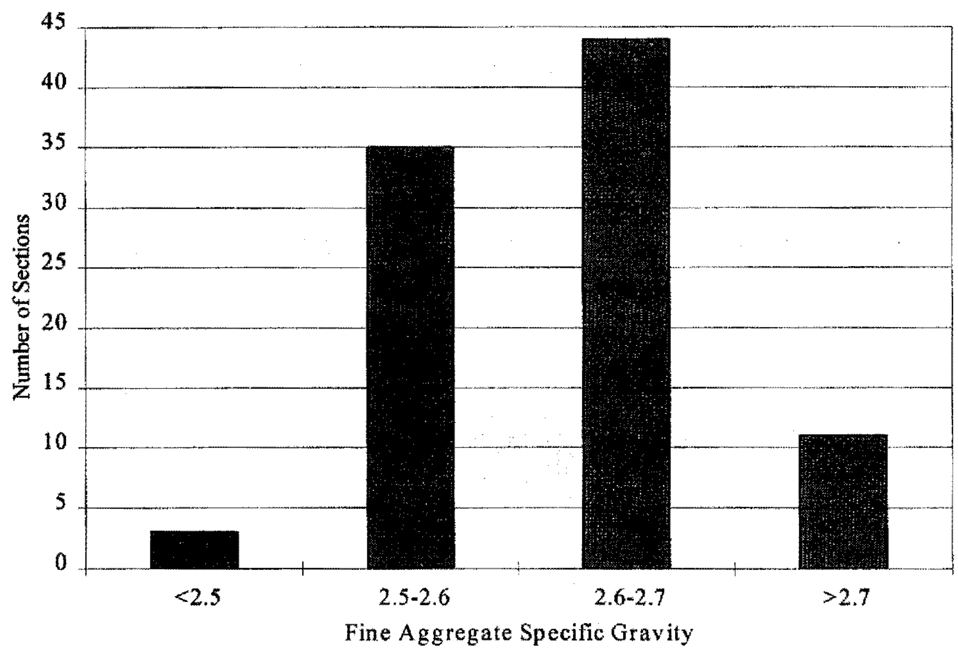

Figure 56. Distribution of PCC fine aggregate specific gravity.

PCC Surface Texturing Method

There were data available for 46 percent (126 of 269 sections) of the sections evaluated as part of this study. Figure 57 is a plot of the distribution of all the texturing methods used for the sections evaluated as part of this study.

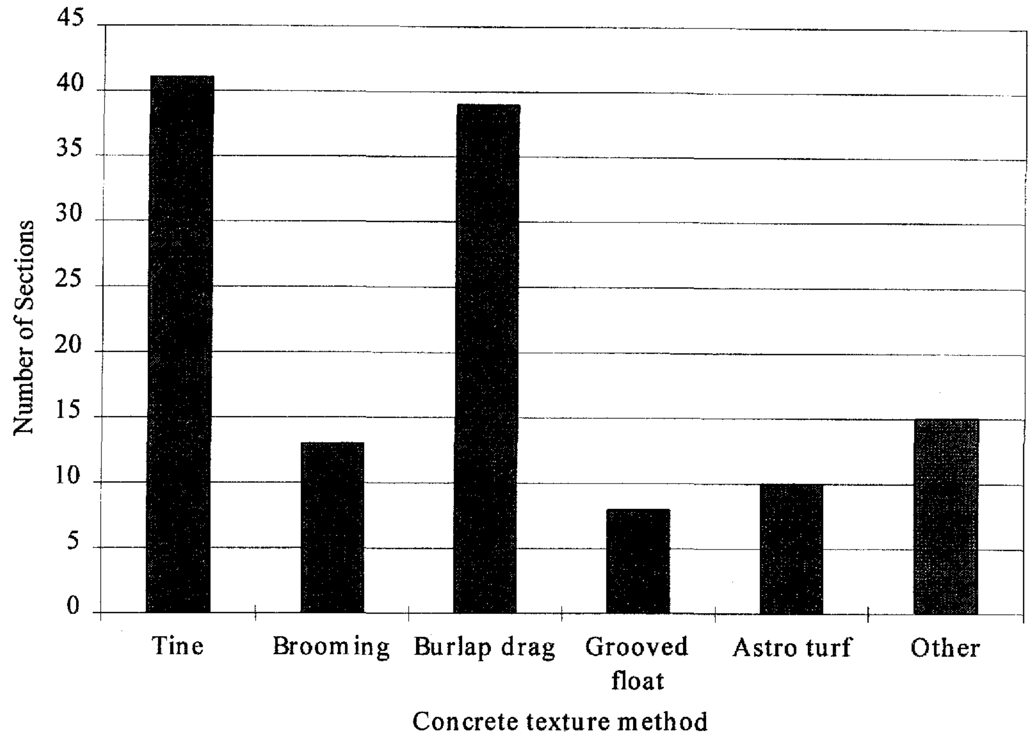

Figure 57. Concrete texturing methods for all PCC-surfaced pavements evaluated.

PCC Curing Method

The LTPP database had curing method data for 46 percent (125 of 269 sections) of the concrete pavements. Figure 58 is a plot of the distribution of curing methods used for the sections evaluated as part of this study.

PCC Paver Type

The LTPP database had paver type data for 49 percent (132 of 269 sections) of the concrete pavements evaluated. Figure 59 is a plot of the distribution of paver types used for the sections evaluated as part of this study.

Site Conditions

Site conditions such as temperature, precipitation, and air freeze-thaw cycles can significantly affect PCC pavement surface characteristics, texture, and, hence, friction. The site condition at testing could also influence friction results. As an example, friction measurements on wet pavement surfaces are usually less than on dry surfaces. It is therefore important to evaluate the effects of site-related conditions on both friction test measurements and the rate of friction loss. The following is a summary of the site conditions-related data for PCC pavements in the LTPP database.

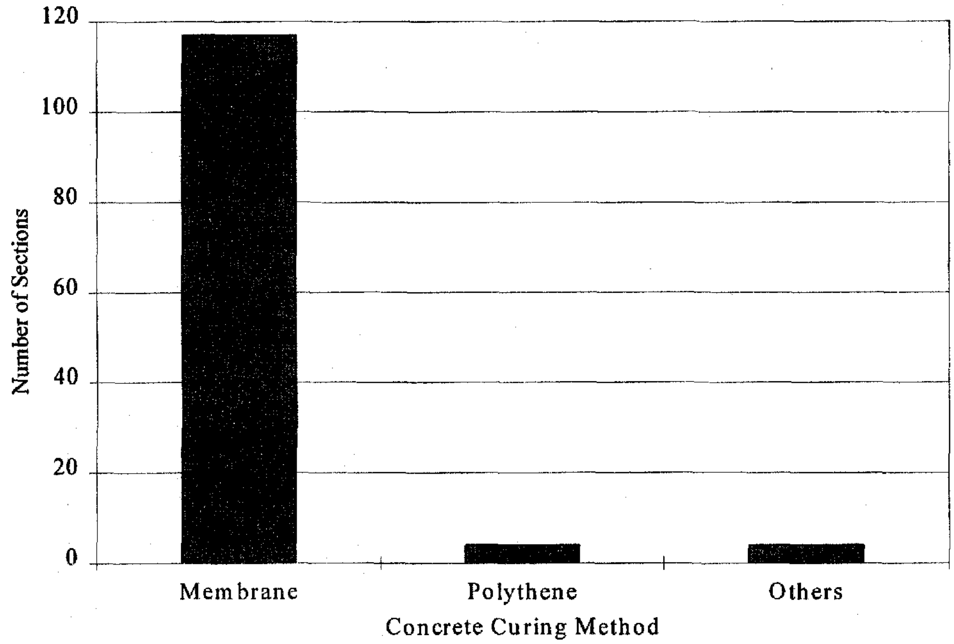

Figure 58. Concrete curing methods used for all PCC-surfaced pavements evaluated.

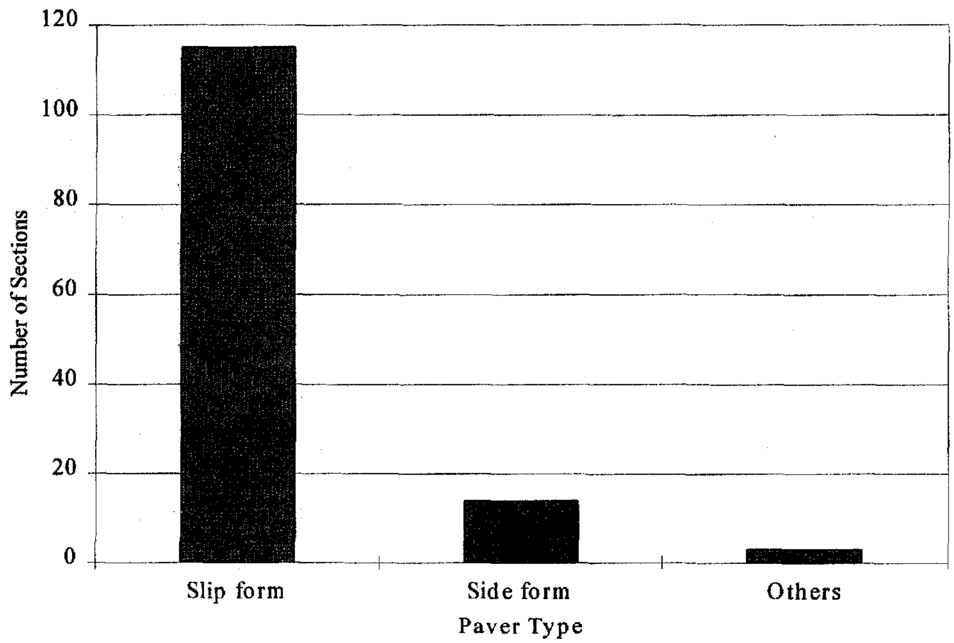

Figure 59. Paver types used for all PCC-surfaced pavements evaluated.

Average Annual Number of Air Freeze-Thaw Cycles

The average annual number of freeze-thaw cycles was available for 98 percent (263 of 269 sections) of the PCC-surfaced pavement sections, and the number of cycles varied from 0 to 165 cycles, with a mean of 73.17, a median of 69.5, and a standard deviation of 26.6. A summary of the average annual number of freeze-thaw cycles for the four climatic zones covered by the LTPP program is provided in table 74.

Average Annual Total Precipitation

The average annual precipitation ranged from 0.15 to 1.75 m, with a mean of 0.72 m, a median of 0.71 m, and a standard deviation of 0.165 m for all 269 sections evaluated. As expected, an analysis of the average annual precipitation within different climatic regions showed larger mean values for the regions with wet conditions. Specifically, the sections in the wet-freeze and wet-nonfreeze regions had mean values of 0.94 and 1.06 m, respectively, and the sections in the dry-freeze and dry-nonfreeze regions had mean values of 0.4 and 0.38 m, respectively. A summary of the average annual total precipitation for the four climatic zones covered by the LTPP program is provided in table 75, and a histogram of the average annual precipitation data for the PCC-surfaced sections is presented in figure 60.

Average Annual Number of Wet Days

The average annual number of wet days ranged from 33 to 219, with a mean of 100, a median of 100, and a standard deviation of 19.03 for all 263 sections evaluated. As expected, an analysis of the average annual number of wet days within different climatic regions showed larger mean values for the regions with wet conditions. More specifically, the sections in the wet-freeze and wet-nonfreeze regions had mean values of 134 and 125, respectively, and the sections in the dry-freeze and dry-nonfreeze regions had mean values of 87 and 55, respectively. A summary of the average annual number of wet days for the four climatic zones covered by the LTPP program is provided in table 76. A histogram of the average annual precipitation data for the PCC-surfaced sections is presented in figure 61.

Air Temperature During Friction Testing

The average air temperature measured during the time of pavement surface friction testing was available for 85 percent (230 of 269 sections) of the pavement sections, and it varied from 1.67 to 40.5 °C with a mean of 16.6 °C, a median of 16.6 °C, and a standard deviation of 8.2 °C. Table 77 presents a summary of the air temperatures measured during friction testing around the vicinity of the test pavement section.

Average Annual Number of Days With Temperatures Below 0 °C

The average annual number of days with temperatures below 0 °C ranged from 0 to 197, with a mean of 91, a median of 88, and a standard deviation of 33.1 for all 269 sections evaluated. Ninety-eight percent (263 of 269 sections) of PCC-surfaced sections evaluated had data on the annual number of days with temperatures below 0 °C. As expected, an analysis of

Table 74. Summary of average annual number of freeze-thaw cycles for PCC-surfaced pavements evaluated.

Statistics	Climate region			
	Dry-freeze	**Dry-nonfreeze**	**Wet-freeze**	**Wet-nonfreeze**
Mean	113	37.3	92	50.4
Maximum value	165	102	143	93
Minimum value	55	1	22	0
Std. deviation	27	37.3	17.6	24.5
Median	114	19	91	54

Table 75. Summary of average precipitation for PCC-surfaced pavements evaluated.

Statistics	Climate region			
	Dry-freeze	**Dry-nonfreeze**	**Wet-freeze**	**Wet-nonfreeze**
Mean, m	0.39	0.38	0.94	1.06
Maximum value, m	0.61	0.60	1.75	7.73
Minimum value, m	0.15	0.18	0.64	0.64
Std. deviation, m	0.14	0.12	0.19	0.21
Median, m	0.40	0.40	0.91	1.17

the average annual number of days with temperatures below 0 °C within different climatic regions showed larger mean values for the regions with freeze conditions. Specifically, the sections in the wet-freeze and dry-freeze regions had mean values of 131 and 147, respectively, and the sections in the wet-nonfreeze and dry-nonfreeze regions had mean values of 51 and 35, respectively. A summary of the average annual number of days with temperatures below 0 °C for the four climatic zones covered by the LTPP program is provided in table 78. A histogram of the average annual number of days with temperatures below 0 °C data for the PCC-surfaced sections is presented in figure 62.

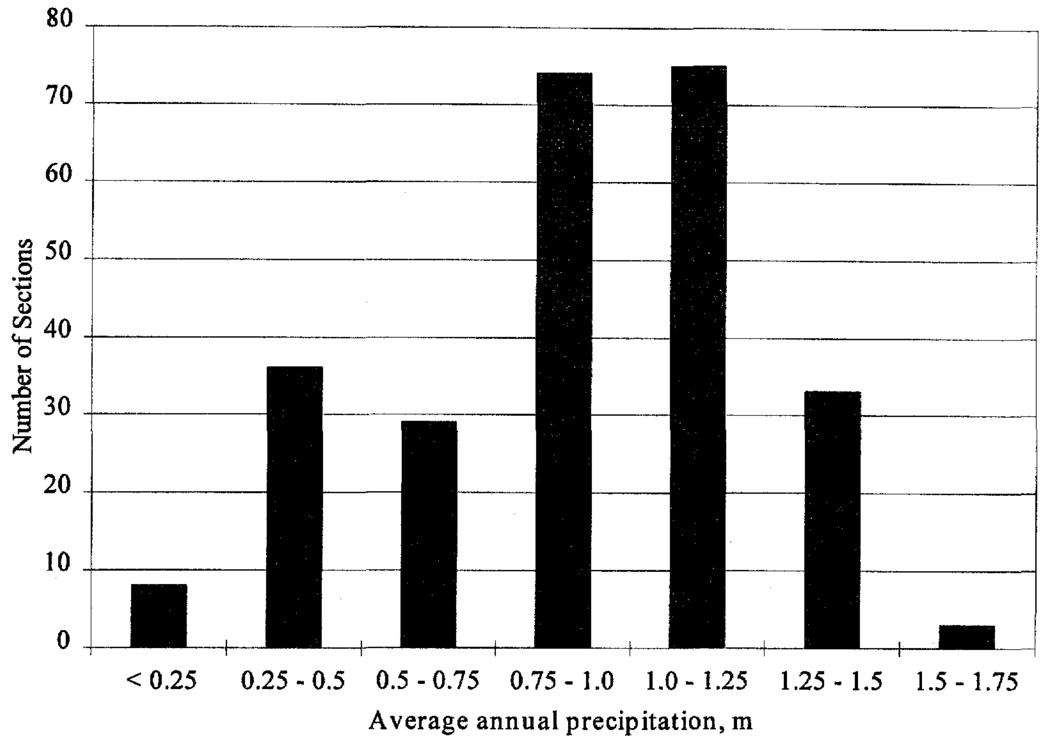

Figure 60. Average annual total precipitation for all PCC-surfaced pavements evaluated.

Table 76. Summary of average annual number of wet days for PCC-surfaced pavements evaluated.

Statistics	**Climate region**			
	Dry-freeze	**Dry-nonfreeze**	**Wet-freeze**	**Wet-nonfreeze**
Mean	87	55	134	125
Maximum value	121	94	198	219
Minimum value	49	33	91	72
Std. deviation	18.6	15.8	22	22
Median	87	54	134	125.5

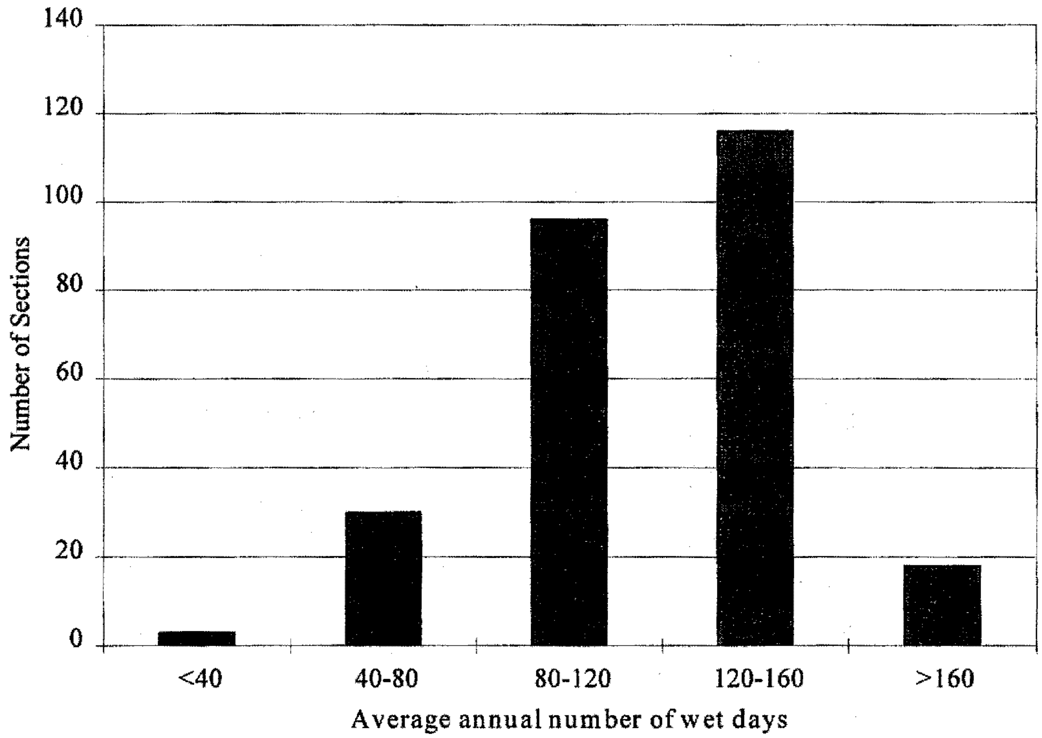

Figure 61. Average annual number of wet days for all PCC-surfaced pavements evaluated.

Table 77. Summary of measured air temperatures from friction testing.

Air temperature measured during friction testing, °C	Number of PCC-surfaced sections
0 to 4.5	5
4.5 to 10	27
10 to 15.5	56
15.5 to 21	107
21 to 26	76
26 to 32	77
32 to 38	44
Greater than 38	9

Table 78. Summary of average annual number of days with temperatures below 0 °C for PCC-surfaced pavements evaluated.

Statistics	Climate region			
	Dry-freeze	**Dry-nonfreeze**	**Wet-freeze**	**Wet-nonfreeze**
Mean	147	35.3	130.6	51
Maximum value	197	106	187	107
Minimum value	62	0	19	0
Std. deviation	32	39	32.4	27
Median	153	14.5	131	53

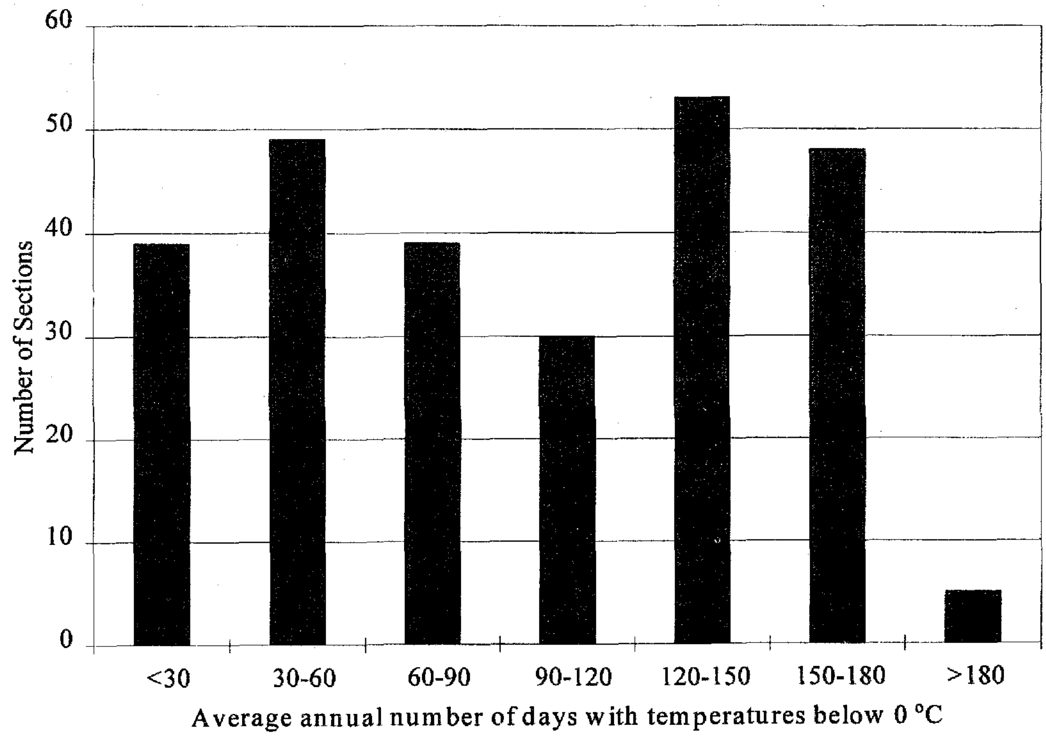

Figure 62. Average annual number of days with temperatures below 0 °C for all PCC-surfaced pavements evaluated.

Average Annual Number of Days With Temperatures Above 32 °C

The average annual number of days with temperatures above 32 °C ranged from 0 to 182, with a mean of 46.03, a median of 45.6, and a standard deviation of 23.3 for all 98 percent (263 of 269 sections) that had data available. As expected, an analysis of the average annual number of days with temperatures above 32 °C within different climatic regions showed larger mean values for the regions with non-freeze conditions. Specifically, the sections in the wet-nonfreeze and dry-nonfreeze regions had mean values of 58 and 83, respectively, and the sections in the wet-freeze and dry-freeze regions had mean values of 14 and 28, respectively. A summary of the average annual number of days with temperatures above 32 °C for the four climatic zones covered by the LTPP program is provided in table 79. A histogram of the average annual number of days with temperatures above 32 °C data for the PCC-surfaced sections is presented in figure 63.

Table 79. Summary of average annual number of days with temperatures above 32 °C for AC-surfaced pavements evaluated.

Statistics	**Climate region**			
	Dry-freeze	**Dry-nonfreeze**	**Wet-freeze**	**Wet-nonfreeze**
Mean	28	83	14	59
Maximum Value	57	182	71	111
Minimum Value	7	7	0	5
Std. Deviation	14.27	44.05	11.5	23.42
Median	28	70	12	57.5

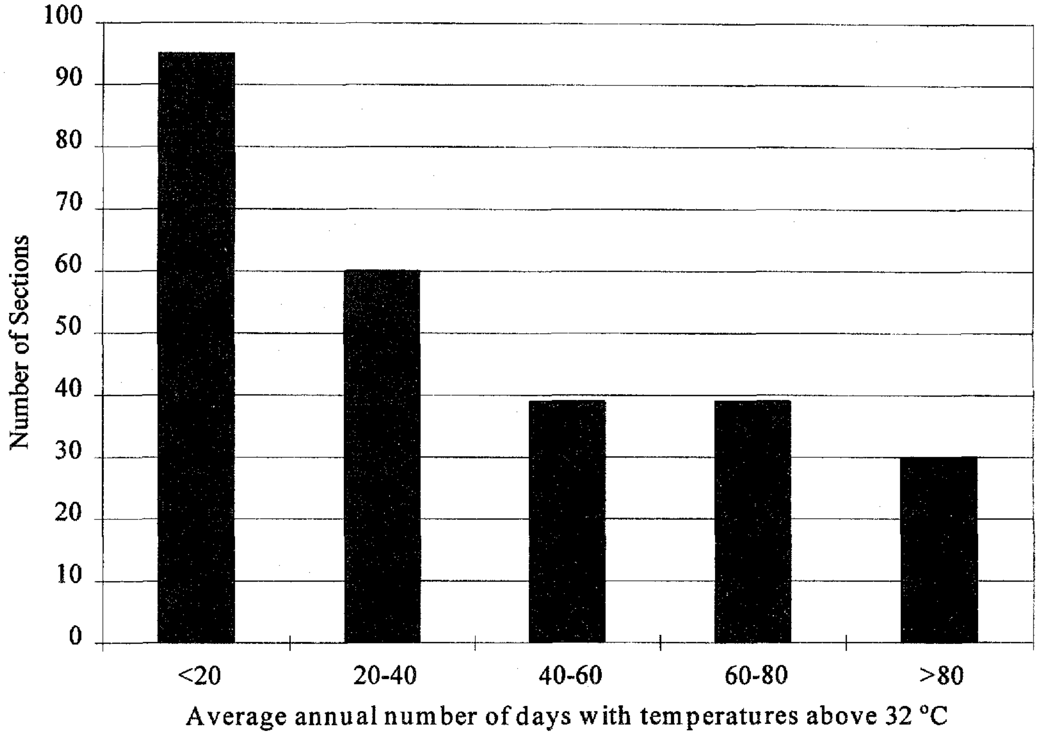

Figure 63. Average annual number of days with temperatures above 32 °C for all PCC-surfaced pavements evaluated.

APPENDIX D – SUMMARY OF RELEVANT SECTIONS OF FHWA TECHNICAL ADVISORY T 5040.17

FHWA TECHNICAL ADVISORY T 5040.17
December 23, 1980
Appendix B

SKID MEASUREMENT SYSTEM DESCRIPTION AND OPERATING PROCEDURES

B.1 DESCRIPTIONS OF SKID MEASUREMENT SYSTEM

The requirements of American Society for Testing and Materials (ASTM) E-274 states "The method utilizes a measurement representing the steady-state friction force on a locked test wheel as it is dragged over a wetted pavement surface under constant load and at constant speed while its major plane is parallel to its direction of motion and perpendicular to the pavement."

Although this specification may be met by a system involving only one wheel attached to a towing vehicle and although a few such systems are in use, the vast majority of skid measurement systems in use and expected to be in use in the near future consist of a towing vehicle and two-wheel trailer. On many systems, either wheel may be locked during testing, but most commonly, the left is used.

ASTM considers testing the left wheel track to be "normal." However, a differential in friction levels between the left and right wheel track may exist. When testing a site where a differential may exist, especially a high wet weather accident site, all lanes and wheel tracks should be tested. If a two-wheel trailer system is used, it is desirable to have the capability of testing with either wheel.

A skid measurement system must have a transducer associated with each test wheel that senses a force equal or directly related to the force developed between the sliding wheel and the pavement during testing, electronic signal conditioning equipment to receive the transducer output signal and modify it as required, and suitable analog and/or digital readout equipment to record either the magnitude of the developed force or the calculated value of the resulting skid number (SN).

The system must include a facility for the transport of a supply of water—usually 757 to 1893 L (200 to 500 gal)—and the necessary apparatus to deliver a specified amount of water—15 L (4 gal) per minute per wetted 25.4 mm (1 in) of pavement at 64 km/h (40 mi/h) within specified limits in front of the test wheel.

Finally, the system must include provisions for measuring (and preferably for recording) the speed at which the test is conducted.

B.2 FIELD OPERATING PROCEDURES

B.2.1 Field Force Verification

It is generally impractical to perform force plate calibrations at frequent intervals while the measurement system is in the field. Facilities should, however, be available to permit the operator to ascertain that significant changes have not occurred in the force measurement subsystem since the most recent force plate calibration.

If the measurement system uses a torque transducer and is adaptable to mounting a torque arm, the verification can be accomplished within a reasonable time and effort. This device, consisting of an arm capable of being bolted to the test wheel in a horizontal position and of supporting known weights located at specified distances from the center of the test wheel, may be used to test the torque transducer to predetermined values of torque. Typically, the test wheel of the inventory system is raised off the ground, the torque arm is attached to the test wheel and held in a horizontal position, the brake of the test wheel is locked, and a series of known weights are suspended on the torque arm. This procedure will induce a series of known strains on the transducer, resulting in a series of output signals through the signal conditioning equipment. The magnitude of these signals should then be compared to the magnitude of signals produced through use of the same technique immediately after the most recent force plate calibration. Adjustment of signal conditioning equipment gain setting may be made to offset small force measurement subsystem variations that could occur.

Verification should be repeated periodically.

B.2.2 Test Tire and Wheel Preparation, Control of Tire Pressure

Tire Specification

Unless otherwise specified, all tests shall be performed with tires meeting the requirements of ASTM E-501, Standard Tire for Pavement Skid Resistance Tests, and all pertinent sections of that specification, as well as ASTM E-274, should be observed in their use.

Tire Mounting and Break-In Procedure

The tire should be mounted on a Tire and Rim Association 6JJ rim. The rim should have been examined to determine that it has suffered no damage or misalignment in prior use. After mounting, and before break-in, the tire and wheel should be balanced. The tire should be subjected to a break-in of 322 km (200 mi) of use before being used for testing. This break-in may be accomplished by using the tire on the skid trailer wheel that is not used for testing. If the tire must be remounted before test use, it should be rebalanced after remounting.

Tire Warm-Up Procedure

The test tire should be inflated to 165 ± 3.4 kPa (24 ± 0.5 lb/in^2) measured at ambient temperature. After tire pressure measurement and adjustment, the tire should be subjected to a 8-km (5-mi) warm-up, traveling at conventional highway speeds, before tests are performed. The 8-km (5-mi) warm-up should be repeated on any occasion when the measurement system is parked for a period of 15 minutes or more.

Tire Wear and Replacement Procedure

The standard pavement test tire has a series of visual wear guide sipes (small circular holes) cast into each of the outer ribs of the tire. The test tire should be withdrawn from testing use when wear has progressed to a point at which the wear guide sipes are no longer visible. During routine testing, test tires should be examined at least twice daily (and more frequently as the tire nears unacceptable wear level) to determine that wear has not progressed beyond acceptable limits.

Additionally, after any series of tests on pavements having very high skid numbers (in excess of SN=70) or in the event of a deliberate or inadvertent dry skid, the test tire should be examined for the development of a flat spot. If a significant flat spot or spots develop on a test tire, it should be withdrawn from test use due to the tendency of the test wheel to seek out and return to such a flat spot in subsequent lockups.

B.2.3 Watering Subsystem Procedures

Daily Procedures

Prior to the beginning of each day's activity, the crew should perform at least the following functions with respect to the water subsystem:

1. Determine that the water nozzle (nozzles), when in the testing position, assumes the proper angle with respect to the pavement (ASTM E-274 requires an angle of 25 ± 5 degrees).

2. If the measurement system has a provision for raising and lowering the nozzle between tests, determine that the mechanism is working properly and that the nozzle assumes a fully lowered position during the test sequence.

3. Determine that the nozzle, when in the test position, will discharge water directly in front of and centered on the test wheel.

4. Examine the nozzle outlet orifice to determine that it is free from damage or distortion.

The above inspections should be repeated during a day's testing in the event of operation on very rough highways (or in the event of any off-highway travel) that may have caused damage to the nozzle or adversely affected its orientation.

Water Trace Width Check

Periodically, the crew should make a measurement of the water trace width as a gross measure of overall water subsystem performance. This may be accomplished by driving the measurement system over a pavement at a selected convenient speed (the same speed should be used on all occasions), initiating water flow without locking the test wheel brakes, and measuring the width of the resulting water trace on the pavement. The trace width measurement should be made as quickly as possible after passage of the inventory system (preferably within 30 seconds). This would require that one member of the crew drive and operate the measurement system, while the other member is positioned off the side of the pavement at the location at which the measurement is to be made. The best results are achieved if this procedure is performed on a relatively smooth pavement surface (low macrotexture).

B.2.4 Instrumentation Calibration Verification

Provision should be made to allow for verification of the signal conditioning instrumentation calibration (to account for the effects of zero and gain drifts).

General Requirements for Calibration Signal

The minimum acceptable facility for verification of conditioning instrumentation is a calibration signal subsystem. The calibration signal should be provided from such a source and in such a manner that there is little likelihood of variation in the calibration signal itself. This assurance then permits the operator to make adjustments in the measurement subsystem gain to offset the frequent small deviations that occur due to changes in ambient temperature and other operating parameters.

Force Measurement Calibration Signal

The most straightforward technique for providing a force measurement calibration signal is to make provisions for switching a high-quality shunting resistor of known value in parallel with one arm of the force transducer strain gauge bridge. This induces an imbalance in the bridge equivalent to the application of a known force to the transducer. The resultant signal is sufficient to verify, or provide a means of adjustment for, all elements of the force measurement system forward of the transducer itself.

Frequency of Use

Instrumentation calibration verification through the use of calibration signals should be accomplished at the beginning of each day's operation after equipment warm-up, at intervals of no more than 2 hours when the system is in continuous use, and upon the renewal of operation throughout the day after any period during which the signal conditioning equipment has been turned off or the unit has been allowed to stand unused for 30 minutes or more.

B.2.5 Check List

A check list should be available to the crew and should be used prior to the beginning of daily operations and on any occasion during the day when testing is suspended for 30 minutes or more, or when instrumentation has been turned off. The check list varies from system to system due to differences between the systems, but should provide for at least the following checks:

1. All power subsystems on and providing proper levels of power.

2. All signal conditioning subsystems on for an adequate time to reach stable operation (typically 10 to 30 minutes).

3. All recording systems on and functioning properly.

4. Instrument calibration (described above) performed.

5. Tire pressure checked and adjusted, if necessary.

6. Test tire checked for wear.

7. Water nozzles checked for position and condition.

8. Water tank adequately filled.

9. Fuel supply adequate.

10. Safety chains and all other connections between trailer and towing vehicle properly connected, positioned, and protected, if necessary.

11. Trailer jacks (if available) in retracted position.

12. All auxiliary equipment (air compressors, lights, etc.) functioning properly.

B.3 USE OF STATIC AND DYNAMIC CALIBRATION PROCEDURES

B.3.1 Purpose of Field Test Center

At the present time, the highest order of calibration and evaluation available for a State skid measurement system is that provided through the Field Test Center established under contract with the Federal Highway Administration (FHWA). Arrangements to receive the services of the Field Test Center may be initiated by a State through submittal of a request for such services to the local FHWA division office.

B.3.2 Criteria for When to Use the Field Test Center

Each measurement system should be submitted for calibration and evaluation at the Center as soon as possible after its introduction into service. It should be resubmitted for calibration and evaluation whenever:

1. Significant repair or modification has been accomplished by the owning agency that might reasonably be expected to affect test results, or

2. Whenever it has experienced sufficient use such that normal wear in the various subsystems might be expected to have affected their operation.

The second consideration suggests that each measurement system should be resubmitted at least every 2 years.

B.3.3 Calibration Services Provided by Field Test Center

The static and dynamic calibration services provided by the Field Test Center include the following:

1. Horizontal and Vertical Force Calibration. This provides for evaluation of the accuracy, linearity, and hysteresis of the measurement system force transducers and signal conditioning equipment through use of an air-bearing force plate maintained by the Center and periodically calibrated by the National Bureau of Standards.

2. Flow Rate Evaluation and Adjustment If Required. This includes determination that the water delivery subsystem of the measurement system provides a quantity of water (dependent upon trace width) in front of the test tire that meets ASTM E-274 requirements at speeds between 32 and 97 km/h (20 and 60 mi/h).

3. Static Evaluation of Water Distribution. This provides an evaluation of the uniformity with which the total water flow is distributed across the trace width

and adjustment, if necessary, to ensure that the water is, in fact, delivered uniformly and in line with the test tire.

4. Force Plate or Load Cells. The visitor's force plate used for routine checks of the force measurement subsystem can be calibrated while at the Center.

5. Speed Calibration. The speed measurement (and recording, if available) subsystem is evaluated, calibrated, and, where necessary and possible, adjusted to produce accurate speed measurement values over the range of 32 to 97 km/h (20 to 60 mi/h).

6. Tire Pressure Gauge Calibration. This provides assurance that tire pressures in the test wheels and in the speed-measuring fifth wheel (if used) can be accurately measured and set.

7. Dynamic Correlation. Two such correlations are conducted: The first with the measurement system in the "as arrived" condition and the second after all of the foregoing evaluations have been conducted and indicated adjustments accomplished. The first correlation results in the development of mathematical relationships between the measurement system and the Area Reference Skid Measurement System that permit data collected by the measurement system, prior to its visit to the Center, to be adjusted to a common base provided by the use of the Area Reference System. The second correlation permits the development of similar relationships that may be used to relate the results of subsequent testing to the Area Reference System base. The data from the second correlation also provide an estimate of the system measurement variance.

B.4 MAINTAINING SYSTEM INTEGRITY BETWEEN FIELD TEST CENTER CALIBRATIONS

Two basic types of procedures are available for determining that significant changes have not occurred in the measurement system since its most recent evaluation and calibration at the Center. These involve techniques for evaluating important subsystem performance and techniques for evaluating performance of the total system.

B.4.1 Techniques to Evaluate Subsystem Performance

As a minimum, the owner of each measurement system should maintain and periodically make use of facilities for evaluating the force, water, and speed measurement subsystem of the inventory system.

Evaluation of Force Subsystem

The force subsystem should be evaluated through use of a force plate. An air-bearing force plate is recommended since its action is such as to essentially eliminate the effect of friction in the plate itself. If an air-bearing force plate is not available, any of several commercial mechanical force plates may be used. If a mechanical device is used, precautions should be taken to ensure that all moving parts (particularly load application screws and spherical or roller bearings) are well lubricated and that the lubricant is periodically removed and replaced.

To conduct an evaluation, the test wheel of the measurement system should be centered on the force plate, the test wheel brake locked, and known frictional forces introduced to the tire-force plate interface through appropriate motion of the force plate. Frictional forces should be both increased and decreased in a stepwise manner to allow for detection of possible hysteresis effects. The indicated force readout values for the system should then be plotted against known force input values. The resulting plotted calibration line should be evaluated for nonlinearity and hysteresis characteristics. Also actual readout values for known force inputs should be compared with those readout values determined from tests conducted with the same equipment after the most recent Center evaluation.

Evaluation of Water Subsystem

The most effective evaluation of the water subsystem to discern variations in performance is that of flow. Flow rate may be evaluated by raising the rear wheels of the towing vehicle, running the vehicle at an indicated speed of 64 km/h (40 mi/h) (or any other desired speed), collecting the water pumped through the system and out the nozzle during a measured time period, and calculating the flow rate in gallons. This procedure should be repeated at two or more speeds to evaluate linearity of the water delivery subsystem with test speed.

The Pennsylvania State University has developed a water rate flow tank that is circular in cross section and of such size that it fits easily into a standard manhole. The tank has a threaded opening in the bottom for drainage and a stop-plug with a long handle that permits the plug to be removed and replaced from the top of the tank after it is hanging in the manhole. It also has a scale calibrated in gallons on the inside of the tank. This tank may be suspended in a standard manhole, the measurement system positioned so that the nozzle will discharge directly into the tank, the rear wheel of the towing vehicle raised, and total flow measured at any desired speed. The only additional equipment required is a stopwatch.

Evaluation of Speed Measurement Subsystem

The speed measurement subsystem should be evaluated by operating the measurement system at various test speeds over a measured-mile course. If the basic speed measurement is done through the use of the tow vehicle speedometer or through a tachometer-generator driven by the tow vehicle or by a fifth wheel, then the vehicle should be driven over the measured-mile course at a selected speed and the time of transit measured with a stopwatch. The actual speed, calculated from the distance and the elapsed time, is then compared to the indicated speed.

If speed measurement is based upon a pulse generator driven by a fifth wheel, the accuracy of the speed measurement is directly dependent upon the accuracy of the fifth wheel for distance measurement. To evaluate this subsystem, the fifth wheel tire pressure is adjusted until the distance indicated agrees with the known distance traversed (the assumption being made here is that the electronic package that converts the pulses to velocity is functioning properly).

If tapeswitch event detectors, placed 61 m (200 ft) apart, and an interval timer (+0.01-second resolution) are available to measure the time required by the inventory system to travel 61 m (200 ft), a very accurate speed measurement is obtained to check against the indicated value.

Time Between Subsystem Evaluations

The force, water, and speed measurement subsystems of the measurement system should be checked by the methods described above at intervals no greater than 3 months.

B.4.2 Techniques to Evaluate Total System Performance

Use of Measurement System Sample Variance as a Performance Measure

A portion of the information furnished, as a result of an evaluation at the Center, is the pooled sample standard deviation of the measurement system for repeated testing at three test speeds on five special test surfaces. If the sample standard deviation at the desired speed is squared, the resulting value, SD^2_t, is an estimate of the skid measurement system variance. Subsequent to the Center evaluation, the crew should periodically select a pavement location having a skid number of approximately 30 to 40, and run 20 repeat tests at the desired speed over the same location. From the results of these latter tests, a new estimate, SD^2_E, can be calculated. If the ratio SD^2_E/SD^2_t does not exceed 2.0, the chances are 19 out of 20 that the system standard deviation has not doubled over that established during its visit to the Center. (If the system has not been to a Center to obtain an estimate of SD^2_t, its crew should select a pavement location having a skid number of approximately 30 to 40, run repeat tests at each desired speed over the same location, and calculate the sample standard deviation at each such speed.)

As an alternative, the above procedure could be performed making only 10 repeat tests on the selected pavement. In this case, the ratio of SD^2_E/SD^2_t should not exceed

2.2. The chances are then four out of five that the system standard deviation has not doubled over that previously established.

The above procedure should be performed at time intervals no greater than 3 months.

Short-Term Checks of System Performance

The agency operating the measurement system should select several pavements located close to the site at which the system is normally garaged and perform repeated tests on the surfaces at quite frequent intervals, preferably weekly. Measured values of skid resistance on these surfaces will obviously change as the surfaces change from traffic wear and environmental and/or seasonal variations. However, these changes should occur in an orderly and predictable fashion and any abrupt change would be an indication of possible erratic performance of the measurement system. A continually updated record of the results of such tests should be maintained and examined after each updating for evidence of such erratic performance.

FHWA TECHNICAL ADVISORY T 5040.17
December 23, 1980
Appendix D

SPECIFIC DATA TO BE REPORTED FOR SAMPLE SITES

The following data should be collected in testing sample locations:

D.1 Skid numbers (SN) should be taken for major classes of roads stratified by traffic volume and geographical location.

D.2 Auxiliary data that should be included in order to establish distribution of skid numbers may include the following:

(a) Location of site or roadway section.

(b) Responsible jurisdictional unit and route number or other designator.

(c) Functional classification of road (e.g., two-lane, four-lane divided without full control of access, etc.).

(d) Surface type (e.g., bituminous, open-graded, concrete, tine finish, etc.).

(e) Average annual daily traffic (use traffic count data if available).

(f) Length of roadway section.

(g) Lane where skid measurements are made.

(h) Date of skid measurements.

(i) Number of tests made in section.

(j) Average SN.

(k) Range of SN measurements.

(l) Presence of a typical geometric or feature.

(m) Evidence of skidding (e.g., skid marks, scarred posts, etc.).

APPENDIX E – PROPOSED ASTM STANDARD ON INTERNATIONAL FRICTION INDEX

Proposed ASTM Standard Practice for Calculating International Friction Index of a Pavement Surface, April 1997.

February 24, 1998

Designation E XXXX - XX

ITEM 1

Standard Practice for Calculating International Friction Index[1] of a Pavement Surface

This standard is issued under the fixed designation E xxxx; The number immediately following the designation indicated the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice[1] covers the calculation of the International Friction Index (IFI) from a measurement of pavement macrotexture and wet pavement friction. The IFI was developed in the PIARC International Experiment to Compare and Harmonize Texture and Skid Resistance Measurements. The index allows for the harmonizing of friction measurements with different equipment to a common calibrated index.

1.2 The International Friction Index consists of two parameters that repot the calibrated wet friction at 60 km/h (F60) and the speed constant of wet pavement friction (S_P).

1.3 The mean profile depth (MPD) and mean texture depth (MTD) have been shown to be useful in predicting the speed constant (gradient) of wet pavement friction (1)[2].

1.3 A linear transformation of the estimated friction at 60 km/h provides the calibrated F60 value. The estimated friction at 60 km/h is obtained by using the speed constant to calculating the estimated friction at 60 km/h from a measurement made at any speed.

1.4 The values stated in SI (metric) units are to be regarded as standard. The inch-pound equivalents are rationalized, rather than exact mathematical conversions.

1.5 This standard does not purport to address all of the safety problems, if any associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM *Standards*[3]:

E-867 Terminology of Vehicle-Pavement Systems.

E-965 Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique.

E1191 Test Method for Measuring Paved Surface Frictional Properties using the Dynamic Friction Tester.

E-1845 Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth.

2.2 ISO *Standard:*

DIS 13473-1 - Acoustics - Characterization of Pavement Texture using Surface Profiles - Part 1: Determination of Mean Profile Depth[4]

3. Terminology

Terminology used in this standard conforms to the definitions included in Terminology E-867.

4. Summary of Practice

4.1 This practice uses measured data of the pavement surface on: I) macrotexture and 2) measured friction (FRS) on wet pavement. The practice accommodates these data measured with different equipment at any measuring speed.

4.2 Measurement of the pavement macrotexture is used to estimate the speed constant (S_P).

4.3 The measured friction (FRS) at some slip speed (S) is used with the speed constant of the pavement

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[1]This practice is under the jurisdiction of Committee E-17 on Vehicle-Pavement Systems and is the direct responsibility of Subcommittee E17.23 on Surface Characteristics Related to Tire-Pavement Friction.

[2]The **boldface** numbers in parentheses refer to the list of references at the end of this test method.

[3]*Annual Book of ASTM Standards, Vol. 04.03*

[4]Draft International Standard under the jurisdiction of ISO/TC43/SC1 currently under ballot.

(S_P) to calculate the friction at 60 km/h (FR60) and a linear regression is used on FR60 to find the calibrated friction value at 60 km/h (F60).

4.4 F60 and S_P are then reported as IFI (F60, S_P), the International Friction Index.

5. Significance and Use

5.1 This is the practice for calculating the International Friction Index (IFI) of the pavement. The IFI has proven useful for harmonization of the friction measuring equipment. F60 and S_p have proven to be able to predict the speed dependence of wet pavement-related measurements of the various types of friction-measuring equipment (1) The two IFI parameters (F60 and S_P) have been found to be reliable predictors of the dependence of wet pavement friction on tire slip and vehicle speed.

5.2 The IFI parameters, F60 and S_p, can be used to calculate the calibrated friction at another slip speed using a transformation equation.

5.3 The IFI model given below describes the relationship between the values of wet pavement friction (FRS) measured at a slip speed of (S) and between the friction values measured by different types of equipment.

5.3 A significance of the IFI Model is that the measurement of friction with a device does not have to be at one of the speeds run in the experiment. FRS can be measured at some S and is always adjusted to FR60. Thus, if a device can not maintain its normal operating speed and must run at some speed higher or lower because of traffic, the model still works well. In that case S is determined by the vehicle speed (V) which can be converted to S by multiplying V by the percent slip for fixed slip equipment or by multiplying V by the sine of the slip angle for side force equipment.

5.4 This practice does not address the problems associated with obtaining a measured friction or measured macrotexture.

6. Profile or Mean Texture Depth Requirements

6.1 The amount of data required to calculate the mean profile depth (MPD) ideally comprises a continuous profile made along the entire length of the test section.

6.1.1 A minimum requirement shall be 10 evenly spaced profiles of 100 mm (3.9 in) in length for each 100 m (3900 in) of the test section. However, for a uniform test section it is sufficient to obtain 16 evenly spaced profiles regardless of test section length. For surfaces having periodic texture (i.e. grooved or tined surfaces) the total profile length shall include at least ten periods of the texture.

Note 1—When characterizing a long test section with relatively short sample lengths it is important to ensure that the texture is sufficiently homogeneous to provide a representative measure. It is necessary for the user to use sound judgement to determine the minimum number of samples to characterize a non-homogeneous pavement.

Note 2—The texture of roads that have been in service varies across the pavement. In this case the transverse location of the measurements shall be determined by the intended use of the data.

6.2 Resolution

6.2.1 Vertical resolution shall be at least 0.05 mm (0.002 in). Vertical range shall be no less than 20 mm (0.75 in) and vertical non-linearity shall be no greater than 2% of the range.

Note 4—for stationary devices on smooth pavements a lesser range may be used. In this case non-linearity need not exceed the above requirement of .4 mm (0.015 in). The higher range is usually required to allow for a sensor mounted on a moving vehicle.

6.2.2 Maximum spot size for a laser or other electro-optical device shall be no greater than 1 mm (0.04 in). The stylus in a contact device shall have a tip having a major diameter no greater than 1 mm (0.04 in).

6.2.3 The sampling interval shall not be more than 1 mm (0.04 in). Variations of the sampling interval shall not be more than ±10%. This requires that the sensor speed over the surface be maintained within ±10% whether the device is stationary or mounted on a moving vehicle.

6.3 The angles between the radiating emitting device surface and between the radiation receiving device and the surface shall be no more than 30°. The angle of the stylus relative to the surface shall be no more than 30°.' Larger angles will underestimate deep textures.

6.4 Calibration shall be made using calibration surfaces having a known profile. The vertical accuracy of the calibration surface in relation to its theoretical profile shall be at least 0.05 mm (0.002 in). The calibration shall be designed to provide a maximum error of 5% or 0.1 mm (0.004 in) whichever is lower.

Note 5—One suitable calibration surface is a surface machined to obtain a triangular profile with a peak-to-peak amplitude of 5-20 mm (0.2-0.75 in). This gives an indication of not only the amplitude, but also the nonlinearity and the texture wavelength scale.

6.5 If mean texture depth (MTD) is used, 10 evenly spaced measurements should be made on every 150-meter section or every 15 meters as a minimum. MTD is not practical for survey work, but may be used in calibration of other equipment if a texture profilometer is not available

7. Friction requirements

7.1 Only friction measuring equipment that have been calibrated to measure IFI and that remain within their own calibration limits shall be used.

7.2 The equipment shall have a resolution of at least 0.005 and shall have a standard deviation less than 0.03

7.3 The equipment shall meet its own standard test method and shall be operated accordingly.

8. Data Processing

8.1 Outliers—Invalid readings should be eliminated when their value is higher or lower than the range of that surrounding their location. The invalid value for that location should be replaced or dropped according to the standard practice for that device.

8.2 Transformation equations (1):

8.2.1 The speed constant is first computed from a macrotexture measurement as follows:

$$S_p = a + b \bullet TX \quad (8.1)$$

Where a and b are constants depending upon the method used to determine the macrotexture as given in Table 1.

Table 1. Values of a and b for estimating the speed constant (S_p):

TX	a	b
MPD per E1845	14.2	89.7
MTD per E-965	-11.6	113.6

8.2.2 The next step uses the measured value of friction (FRS) at a given slip speed (S) to adjust the friction to a common slip speed of 60 km/h. This is accomplished using the speed number predicted by the texture measurement in the previous step and using the following relationship:

$$FR60 = FRS \bullet EXP\ [(S-60)/S_p \quad (8.2)$$

Where: FR60 is the adjusted value of friction from a slip speed of S to 60 km/h for the equipment,
FRS is the friction measured by the equipment at slip speed S and
S is the slip speed of the equipment as described above

8.2.3 The final step in harmonization is the calibration of the equipment, by regression of the adjusted measurement FR60, with the calibrated Friction Number (F60):

FR60

$$F60 = A + B \bullet R60 + C \bullet TX \quad (8.3)$$

A, B and C are calibration constants for a particular device and are given in appendix A for devices already calibrated. For other devices a calibration must be performed as outlined in the appendix to establish the A, B and C for that device. For many devices the value of C was found to be zero or so small it could be neglected, in particular C is not needed for smooth treaded tires.

8.2.4 Combining the results above, F60 can be expressed in terms of the friction and texture measurements (FRS and TX):

$$F60 = A + B \bullet FRS \bullet EXP\ [-(60-S)/(a + b \bullet TX)] + C \bullet TX \quad (8.4)$$

8.2.5 F60 is the prediction of the calibrated Friction Number and S_p is the prediction of the calibrated Speed Number. The values of F60 and S_p are then reported as the International Friction Index.

8.2.6 (Optional) Friction at some other slip speed S may be calculated with:

$$FS = F60 \bullet EXP\,[(60-S)/S_P] \tag{8.5}$$

9. Report

9.1 The test report for each test surface shall contain the following items:

9.1.1 Date of friction and profile measurement,
9.1.2 Location and identification of the test surface
9.1.3 Description of the surface type,
9.1.4 Description of surface contamination which could not be avoided by cleaning, including moisture,
9.1.5 Observations of surface condition such as excessive cracking, potholes, etc.,
9.1.6 The position of the friction measurement and profile on the surface, for example in relation to the wheel track, etc.,
9.1.7 Identification of the friction and profile equipment and its operators,
9.1.8 Type and date of calibration,
9.1.9 Measurement speed,
9.1.10 Percentage of invalid readings eliminated (dropouts),
9.1.11 Total length measured and the number of segments analyzed,
9.1.12 The IFI values, F60 and S_P.
9.1.13 (Optional) The friction at some other slip speed, FS.

10. Precision and Bias

10.1 Precision- The reproducibility using two different texture profile systems and test crews was found in the same experiment (1) to be 0.15 mm (0.006 in) corresponding to 10% of the average MPD values included in the experiment. The reproducibility of the friction devices varied, but was generally within 0.03 (1). However at low friction values 0.02 should be obtained.

10.2 Bias¥There is no basis for determination of the bias in F60 and S_P. With respect to the average "calibrated" value, the maximum error and average error are given for each device in tables 2 and 3 in the Appendix A. With respect to the MTD, the MPD is biased by 0.2 mm (0.008 in) which is due to the finite size of the glass spheres used in the volumetric technique.

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APPENDIX A

Table 1. List of Equipment that have been Calibrated and Their.Regression to Predict F60 using the PIARC Model

$F60 = A + B \cdot FRS \cdot EXP\,[(S-60)/S_p] + C \cdot TX$, where S_p is determined using MPD

BLANK TIRE DEVICES:		S	A	B	C	MAX[E]	AVE[E]	RMSE	R
Locked Wheel:	ASTM E274 (USA)	65	0.045	0.925	0	0.095	0.02	0.027	.97
	LCPC Skid Trailer (F)	60	0.002	1.008	0	0.06	0.016	0.024	0.98
Fixed Slip	OSCAR at 86% (N)	52	-0.03	0.864	0	0.038	0.021	0.027	0.96
	OSCAR at 20% (N)	12	0.119	0.643	0	0.089	0.031	0.041	0.92
	Komatsu Skid Trailer (J)	10	0.042	0.849	0	0.091	0.031	0.039	0.94
	DWW Trailer (NL)	43	0.019	0.868	0	0.203	0.043	0.058	0.84
	Griptester (UK)	9.4	0.082	0.91	0	0.086	0.027	0.035	0.85
Side Force	Stradograph (DK)	12.5	0.054	0.77	0	0.091	0.029	0.036	0.94
	Odoliograph Wallon (B)	12.9	0.113	0.729	0	0.081	0.024	0.030	0.96
	Odoliograph CRR (B)	20.5	0.113	0.746	0	0.085	0.025	0.031	0.96
	SCRIM Flemish (B)	20.5	0.049	0.967	0	0.074	0.023	0.03	0.96
	SCRIM CEDEX (E)	20.5	0.019	0.813	0	0.131	0.043	0.056	0.84
	SCRIM MOPT (E)	20.5	0.032	0.873	0	0.063	0.02	0.026	0.96
	SCRIM SRM (D)	20.5	0.017	0.85	0	0.067	0.018	0.026	0.97
	SCRIM GEOCISA (E)	20.5	0.021	0.928	0	0.113	0.039	0.052	0.88
	SCRIM (F)	20.5	-0.006	0.862	0	0.085	0.026	0.034	0.95
	SUMMS (I)	20.5	0.002	0.987	0	0.094	0.031	0.037	0.94
	SCRIMTEX (UK)	17.1	0.033	0.872	0	0.112	0.30	0.039	0.93
RIBBED TIRE DEVICES:									
Locked Wheel	Stuttgarter Reibungmesser (CH)	60	0.022	0.5	0.082	0.085	0.033	0.042	0.9
	Skiddometer (CH)	60	0.026	0.504	0.099	0.114	.039	0.049	0.9
	Stuttgarter Reibungmesser (A)	60	-0.072	0.767	0.086	0.124	0.038	0.049	0.9
	ASTM E274 (USA)	65	-0.023	0.607	0.098	0.115	0.033	0.043	0.92
	Friction Tester (PL)	60	-0.025	0.807	0.068	0.011	0.033	0.041	0.93
Fixed Slip	Stuttgarter Reibungmesser (CH)	12	0.141	0.323	0.074	0.126	0.05	0.062	0.83
	Skiddometer	12	0.03	0.918	-0.014	0.073	0.028	0.035	0.95
	BV-11 (S)	12	0.04	0.856	-0.016	0.084	0.029	0.037	0.94
	Stuttgarter Reibungmesser (A)	12	0.02	0.867	-0.006	0.118	0.033	0.041	0.92
SLIDER DEVICES									
DF Tester at 60 km/h (J)		60	-0.034	.0.771	0	0.086	0.027	0.048	0.9
DF Tester at 20 km/h (J)		20	0.081	0.732	0	0.069	0.026	0.031	0.96
Pendulum Tester BPT (USA)		10	0.056	0.008	0	0.109	0.043	0.053	0.87
Pendulum Tester SRT (CH)		10	0.044	0.01	0	0.173	0.03	0.045	0.91

Notes:
1. N = number of data points
2. Max|E| = maximum absolute error
3. Ave|E| = average absolute error
4. RMSE = root mean square of the residual error
5. R = correlation constant

APPENDIX B CALIBRATION OF OTHER EQUIPMENT

Using one of the methods below, estimate the calibrated values with F60 and S_P on a statistical representative number of sites encompassing a sufficiently wide range of texture and friction (a minimum of 10 is suggested). Equipment that is new and has never been calibrated, or equipment that needs to be re-calibrated would then measure the same sites and regressions using the PIARC Model would need to be run to find the constants a, b, A, and B (also C if the device uses treaded tires).

As an example, suppose it is desired to use a new texture measuring system other than the MPD. First the device would measure the test (calibration) sites with the texture device and determine F60 and S_P for each site. The measurements would then be repeated using the new texture device, called TX_{NEW}. Then a linear regression of S_P and TX_{NEW} would be performed as follows:

$$S_P = a + b \bullet TX_{NEW}$$

and the constants a and b are determined. Then, the slip speed for each run must be determined and the second regression of FRS_{NEW} and F60 needs to be performed as follows:

$$F60 = A + B \bullet .FRS_{NEW} \bullet EXP\,[(S-60)/S_P] + C \bullet TX_{NEW}$$

and the constants A, B and C are determined. Now, with a, b, A, B and C determined, N is calibrated to use FRS_{NEW} and TX_{NEW}

In all of the sections below only equipment that was calibrated in the experiment should be used to establish the calibrated values for recalibration and each must insure that their calibrations have not changed.

Using Friction Devices that were In the Experiment

On the ten or more sites with different frictional properties, one can use the equipment that participated in the experiment to measure and estimate the values (F60 and S_P) for the sites, then the new equipment can be calibrated to the estimated "true value" (called target here) as shown above. This method could be improved if several devices that participated in the experiment were used. Then each of them would calculate F60 and S_p and the values would be averaged to estimate the target values for these sites. Obviously the devices that had the better correlation in the experiment would be the better choice to use here as the secondary standard.

Using DF tester or Griptester (at walking speed)

These devices are singled out since they are small and can easily be shipped to a location where there is no equipment that participated in the experiment. Again, ten or more sites are measured with either device along with a texture measure to get F60 and S_p. Then the new equipment is calibrated in the same manner, except the estimated Target values, F60 and S_p, are determined by the DF tester and a texture measure or the Griptester at 5 km/h and a texture measure. Both the DF tester and the Griptester had excellent correlation and are similar to the BPT, but measure over a much larger area than the BPT.

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