South Africa

COTO

Committee of Transport Officials

TMH13

AUTOMATED ROAD CONDITION ASSESSMENTS
PART E: SKID RESISTANCE AND TEXTURE

Committee Draft Final

May 2016

Committee of Transport Officials

TECHNICAL METHODS
FOR HIGHWAYS

TMH 13

AUTOMATED ROAD CONDITION ASSESSMENTS
Part E: Skid Resistance and Texture

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Compiled under auspices of the:

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Synopsis

TMH13 provides the guidelines and procedures to assist road authorities to plan, execute and control automated road conditions assessments for: roughness, skid resistance, texture, rutting, deflections and distress imaging. Automated measurement concepts as well as background to different devices are provided. TMH 13 is a companion document to TMH 22 on Road Asset Management Systems and as such includes aspects of data capturing, analysis and documentation.

Withdrawal of previous publication:

This publication is new publication.

Technical Methods for Highways:

The Technical Methods for Highways consists of a series of publications in which methods are prescribed for use on various aspects related to highway engineering. The documents are primarily aimed at ensuring the use of uniform methods throughout South Africa, and use thereof is compulsory.

Users of the documents must ensure that the latest editions or versions of the document are used. When a document is referred to in other documents, the reference should be to the latest edition or version of the document.

Any comments on the document will be welcomed and should be forwarded to coto@nra.co.za for consideration in future revisions.

Document Versions

Working Draft (WD). When a COTO subcommittee identifies the need for the revision of existing, or the drafting of new Technical Recommendations for Highways (TRH) or Technical Methods for Highways (TMH) documents, a workgroup of experts is appointed by the COTO subcommittee to develop the document. This document is referred to as a Working Draft (WD). Successive working drafts may be generated, with the last being referred to as Working Draft Final (WDF). Working Drafts (WD) have no legal standing.

Committee Draft (CD). The Working Draft Final (WDF) document is converted to a Committee Draft (CD) and is submitted to the COTO subcommittee for consensus building and comments. Successive committee drafts may be generated during the process. When approved by the subcommittee, the document is submitted to the Roads Coordinating Body (RCB) members for further consensus building and comments. Additional committee drafts may be generated, with the last being referred to as Committee Draft Final (CDF). Committee Drafts (CD) have no legal standing.

Draft Standard (DS). The Committee Draft Final (CDF) document is converted to a Draft Standard (DS) and submitted by the Roads Coordinating Body (RCB) to COTO for approval as a draft standard. This Draft Standard is implemented in Industry for a period of two (2) years, during which written comments may be submitted to the COTO subcommittee. Draft Standards (DS) have full legal standing.

Final Standard (FS). After the two-year period, comments received are reviewed and where appropriate, incorporated by the COTO subcommittee. The document is converted to a Final Standard (FS) and submitted by the Roads Coordinating Body (RCB) to COTO for approval as a final standard. This Final Standard is implemented in industry for a period of five (5) years, after which it may again be reviewed. Final Standards (FS) have full legal standing.

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E.1 Introduction

E.1.1 Context and Scope

TMH 13 *Part E* is the fifth of seven parts on Automated Road Condition Assessments. Part E provides guidance and methodologies on the planning, execution and control of skid resistance and texture measurements. This part should be read in conjunction with TMH 13 Part A which includes basic concepts and key definitions of surface friction. Part A also covers general aspects related to the planning of automated road condition surveys.

TMH 13 Part E is a companion document to TMH 22 which is the official requirement for Road Asset Management of the South African Road Network. Part E complements TMH 22 on requirements for the collection of skid and texture data and addresses the relationship between the parameters as expressed by the International Friction Index (IFI) used as a condition parameter in road asset management. Whilst the document addresses aspects of data management and reporting, reference is made to TMH 22 and TMH 18, respectively, for supplemental information and detail requirements. In general, reference is made to other documents in the series along with appropriate standards.

Road geometry and function dictates skid resistance requirements and therefore interpretation of these measurements. In this context and for completeness, consideration is given to the collection of geometric data as part of the high speed survey. The geometric survey, however, remains secondary and do not have to form part of every skid or texture survey due to the relatively unchanging nature of these features.

The scope of these guidelines are primarily concerned with the needs of roads agencies or managers of road networks. Although some details of measurement procedures are discussed, the emphasis remains on the needs of the network manager, and not on the needs of the contractor in charge of the actual measurements.

E.1.2 Objective

The primary objective of TMH 13 Part E is to assist road network management personnel to plan, execute and control the measurement of road skid resistance and texture depth over a road network.

E.1.3 Layout and Structure of Part E

The document is written in concise format as far as possible to enable network managers to use it firstly as a practical guide, and only secondly as a source of general information on skid and texture measurement. Typical example reports and calculations, or complex but non-essential aspects, are relegated to appendices to ensure that the information can be helpful on the first reading.

Extensive use is made of concept summaries and checklists, which are clearly highlighted. A comprehensive reference list is provided and related but non-essential aspects are discussed in sidebars and appendices. Sidebar boxes are also used to highlight references to other related TMH documents or for useful further reading. The guidelines are structured as follows:

Section E.2 introduces the most common types of equipment used to measure skid resistance and texture. Typical equipment specifications are provided and the section concludes with an overview of current practice related to the interpretation of skid and texture measurements.

Section E.3 provides guidelines and methodologies for the validation and control of skid resistance and texture measurements. The selection of validation sections and reference surveys are discussed and validation criteria outlined.

Section E.4 includes operational procedures for different device types, and also discusses data capture, troubleshooting and documenting aspects.

References are provided in **Section E.5**, while **Section E.6** provides a glossary.

Appendix E-1 includes details on the calculation of the International Friction Index and **Appendix E-2** contains an example validation sheet for skid resistance measurement devices

E.2 Measurement of Skid Resistance and Texture

In this section, the different approaches to measurement of skid resistance aspects are discussed. Available devices for measurement of skid resistance aspects are also discussed. In keeping with the network related objectives of these guidelines, the discussion will focus on high speed devices that can be used for network level surveys. However, for completeness other devices used for localized measurement of skid resistance aspects are also briefly described.

The aspects of skid resistance that are typically measured can be broadly classified into two types. These are: (a) direct measurement of skid resistance; and (b) measurement of surface texture.

Each of these two broad classes can be further subdivided depending on the measurement concept or approach. Details are discussed in the following sections.

E.2.1 Devices that Measure Skid Resistance

These devices aim to directly quantify the skid resistance of a road surface by sliding a rubber wheel tyre over a wetted surface and measuring the frictional force in some way. Special test tyres are generally designed to be sensitive to microtexture. The parameter obtained from the test differs from one device to the next but for a well calibrated device the output parameter should provide an indication of the surface friction and relative accident risk.

The British Pendulum Tester (BPT), or often referred to as the Portable Pendulum Tester, has been widely used to derive friction coefficients in terms of a British Pendulum Number (BPN) since the 1960s. The same device is used in the Polished Stone Vale (PSV) test to assess the skid resistance of aggregates after accelerated polishing. The BPT, however, is not suitable for continuous measurement of skid resistance on a network level.

More about the British Pendulum Tester

- BPT Method: BS 7976-2: 2002
- Polished Stone Value: BS EN 1097-8: 2000

Devices that are suitable for network level measurement are discussed in the following paragraphs. These devices can be classified as follows based on the measurement approach:

- Side Force Testers;
- Locked Wheel Testers, and
- Fixed and Variable Slip devices.

E.2.1.1 Side Force Testers

These devices are designed to simulate the movement of a vehicle through a curve. In these devices, a test wheel is mounted on the testing vehicle. The test wheel runs freely and is mounted at an angle to the direction of movement (typically 20°).

Figure E.1 shows the principle of measurement in side force testers. As shown the angle between the direction of movement and the test wheel creates a continuous sideways force on the test wheel. This sideways force is measured to provide an indication of the skid resistance of the surface.

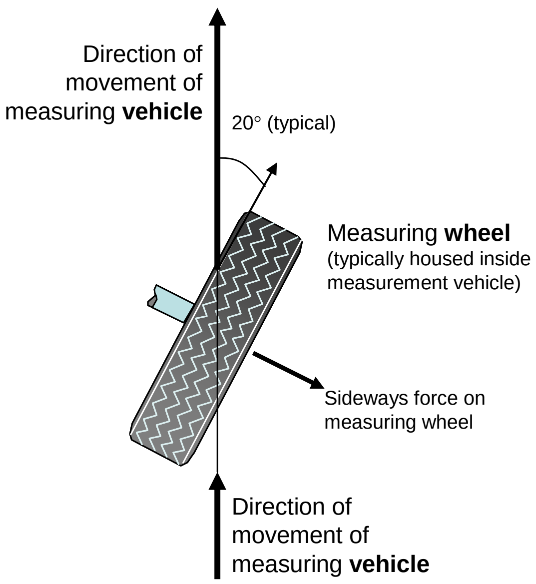

Figure E.1 Principle of Measurement in Side Force Test Devices

During side force testing, a controlled water film is applied to the pavement surface to simulate rainfall. Examples of side force measurement devices include the Mu-meter and the SCRIM (Sideway force Coefficient Routine Investigation Machine). Side-force testers such as the SCRIM typically consist of a single measurement vehicle in which the measurement wheel is a fifth wheel mounted near the middle of the vehicle chassis.

The SCRIM device (see Figure E.2) is one of the most widely used friction measuring devices and has been used for skid resistance testing in southern Africa for many years. On open roads, the testing speed with the SCRIM is typically 50 km/h, with lower speeds being used for testing on tight curves or roundabouts (Austroads 2005). Measurement is typically performed in the left wheel path.

Figure E.2 The SCRIM Device (WDM, 2008)

The SCRIM was developed in the United Kingdom, and British Standard BS7941: Part 1: 1999 (BS7941, 1999) provide details of the test method. Many road agencies have also developed mandatory or recommended procedures for testing with the SCRIM. These procedures typically prescribe aspects such as calibration, tyre condition and water flow rate. More details on some of these requirements can be found in Austroads (2005).

The SCRIM measures the sideways thrust force and normal (vertical) force on the test wheel continuously. The coefficient of these two forces is known as the Sideways Force Coefficient of friction (SFC).

Advantages of the SCRIM include the following (Austroads 2005):

- The equipment has been used for many years and there is a large knowledge base to assist in interpreting SCRIM measurements.
- The equipment has a robust construction and extended survey range (large water tanks give the vehicle a range of 50 to 100 km before water refill is needed).
- The SCRIM device can be fitted with additional sensors to allow simultaneous measurement of skid resistance and texture depth (and possibly also transverse surface profile, i.e. rut depth).

Disadvantages of the SCRIM include the following:

- The machine is large and relatively expensive;
- The size of the machine makes it unsuitable for use in small areas.

E.2.1.2 Locked Wheel Testers

These devices use a test wheel that is momentarily locked (typically for 1 second) while the measuring vehicle moves forward at a constant speed. The torque force on the measuring wheel is measured over the locking period and this provides an indication of skid resistance. Locked wheel testers are the most commonly used testing device in the United States (Noyce et al., 2007).

Figure E.3 shows an example of a locked wheel tester. As this figure shows, locked wheel devices typically consist of a towing vehicle and a skid trailer that contains the measurement wheel. The measurement wheel can be a standard smooth or standard ribbed tyre. Locked wheel testing in the United States is typically performed at 64 km/h (40 mph), according to ASTM E 274 (2006).

Figure E.3 Locked Wheel Tester (Dynatest, 2008)

In the United States the use of a ribbed tyre is most common with locked wheel testers. However, Noyce et al (2007) state that a smooth tyre is being increasingly used, and that some research shows that measurements with smooth tyres are better indicators of safety than those with ribbed tyres.

More about Locked Wheel Devices

Locked wheel devices are commonly used in the United States, and there are ASTM standards for the test procedure using locked wheel testers.

- ASTM E 501 prescribes the test method when a ribbed test tyre is used.
- ASTM E 524 prescribes the test method when a smooth tyre is used.

E.2.1.3 Fixed and Variable Slip Testers

Fixed and variable slip devices take into account the effect of brake force on friction (see sidebar on "The Influence of Braking Force" at the end of Section 1). In these devices, a brake force is applied to the test wheel, but at a braking force lower than that which would lock the wheel completely. The result is that the measuring wheel rotates at a velocity that is less than the free-rolling speed, thereby causing the wheel to slip continuously over the road surface.

In the case of **fixed slip devices**, a fixed brake force (typically 10 to 20 per cent braking slip) is applied. Thus these devices attempt to measure the friction that occurs close to critical slip (as explained in the sidebar in Section 1). Examples of fixed slip devices include the Grip Tester and SAAB Friction Tester (ACPA 2007).

The Grip Tester is a three wheeled trailer (one wheel is the smooth tyre test wheel) that can be towed by a vehicle or pushed by an operator (see Figure E.4).

Figure E.4 The Grip Tester (SRT, 2008)

The Grip Tester typically measures at 50 km/h but can measure at speeds up to 130 km/h (Austroads, 2005). The main advantages of the Grip Tester are its compactness and manoeuvrability, and the relatively inexpensive operating costs. However, experience in Australia has suggested that the Grip Tester is better suited to testing on targeted sections of road than on network surveys (Austroads, 2005).

As the name implies, **variable slip devices** do not apply a fixed braking slip, but sweep through a range of braking slip ratios. ASTM Standard E1859 prescribes a range of slip ratios to be used with variable slip devices (ACPA 2007). The Norsemeter Road Analyzer and Recorder (ROAR) is an example of a variable slip testing device.

The ROAR (see Figure E.5) is a system that can measure friction using either fixed or variable slip. The device is compact and can be mounted to a vehicle or trailer. The ROAD can also be fitted with an independent texture sensor so that skid resistance and texture measurements can be made at the same time.

Figure E.5 Norsemeter ROAR

Austroads (2005) lists the compactness and manoeuvrability of the ROAR as key advantages, but notes that the device is relatively expensive to purchase and operate. Compared to other devices it also has a limited track record.

E.2.2 Surface Texture Measurements

In the context of this document, surface texture measurements refer to the macrotexture component of skid resistance, or simply measurement of texture depth. Apart from friction, these measurements have been used to assess noise emission, tyre wear, and tyre rolling resistance. Texture depth also finds application in assessment of asphalt mix segregation and as an input to reseal design on project level.

Two generic methods for measurement of surface macrotexture are highlighted in this section, namely:

- Volumetric patch method (static/ local measurement of texture), and
- Profiler method (continuous measurement of texture).

Although the volumetric method, traditionally known as the "sand patch test", is not considered to be a network level test, it has been used throughout the world for many decades and still serves as an internationally accepted reference. For this reason, the volumetric method forms an integral part of any discussion on surface texture.

E.2.2.1 Volumetric Patch Method

The well-known sand patch method gives a single and very simple measurement of surface texture and has been used extensively in southern Africa as described in Technical Recommendations for Highways (TMH6). In this method, a known volume of standard sand is spread into a rectangular patch; from the calculated area, the average texture depth is calculated.

The volumetric patch method is standardized in ISO 10844, EN 13036-1, and ASTM E965. In these methods, the material is spread out with a rubber pad in an approximate circular patch and the average diameter used to calculate the area. Moreover, sand is no longer preferred since glass beads give better reproducibility (ISO 13473-1).

It should be noted that the measurements from the volumetric patch method represent a three-dimensional case. ISO 13473-1 therefore defines Texture Depth (TD) as the distance between an arbitrary surface and a plane through the peaks of the three highest particles within a surface area that is similar in size to the tyre-pavement interface. This concept is schematically illustrated in Figure E.6. Mean Texture Depth (MTD), expressed in millimetres (mm), is the parameter obtained from this method.

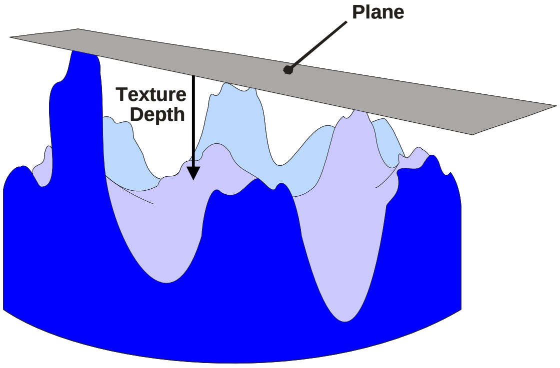

Figure E.6 Concept of Mean Texture Depth

The volumetric method remains a crude test due to its operator-dependent nature. As stated above, the use of glass beads nowadays is an attempt to improve the reproducibility of the test. Nevertheless, due to a wealth of experience and research based knowledge associated with it; the test is still used as a standard worldwide.

This method may be categorised under *static measurement devices*. Whilst only a single measurement per test is obtained, testing also poses a safety hazard since the surface needs to be partly or fully closed to traffic. Although static measurement devices are not practical for use in network level road surveys, where warranted, they may serve as texture reference devices.

E.2.2.2 Profiler Method

Surface profilers are used on routine bases to characterise pavement surfaces. The profile, which is a two-dimensional representation of the surface, is generated if a sensor continuously touches or shines on the surface when it is moved longitudinally or transversally to the direction of travel (ISO 13473-3).

Figure E.7 schematically illustrates a texture profile with related terms. The horizontal distance along the surface plane and the measure normal to the plane, i.e. the amplitude, are the two essential profile descriptors. The texture wavelength describes the horizontal dimension of surface irregularities and is defined as the minimum distance between periodically repeated parts of the curve. The inverse of texture wavelength is spatial frequency, normally expressed in reciprocal metres (m^{-1}).

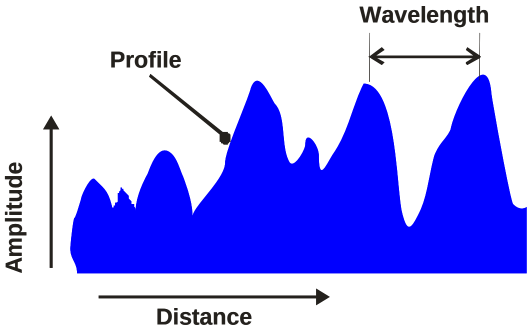

Figure E.7 Texture Profile Terms

Table E.1 provides general information on the elements used to classify profilometers with respect to their use and overall accuracy. Table E.1 shows the principles of operation, measurement, and analysis, can be very different for these devices. The table highlights device characteristics typically used for measurement of texture depth on a network level. High-speed contactless laser profilometers with a class AD wavelength range are commonly used in network level surveys worldwide. A photograph of such a device is shown in Figure E.8. The horizontal bar is fitted with numerous lasers that perform different functions, viz. roughness measurements, rut depth measurements, and texture depth measurements. This particular vehicle is equipped with two texture lasers on each side of the bar for measurement in the wheel paths.

More about Texture Profilers

TMH 13 Part D provides additional informa-tion on high speed laser profilers.

The parameter derived from measured profiles is the profile depth and relates to texture depth parameter obtained from volumetric or 3-D methods. This parameter is the vertical difference between a horizontal line through the highest profile peak, within a longitudinal distance similar to that of a tyre/pavement interface, and the corresponding profile valley. This concept is illustrated in Figure E.9.

Figure E.8 High Speed Profiler (SRT, 2008)

The figure also illustrates the calculation of mean profile depth (MPD) which is the average value of the profile depth over a predefined distance called the baseline. For texture measurements, a standard baseline of 100 mm is used.

PIARC (1995) developed an equation to relate texture depths obtained from texture profilers (MPD) and those measured using the volumetric patch method (MTD). MPD is transformed to an estimated texture depth (ETD) by applying the following equation:

$$ETD = 0.2 + 0.8 \cdot MPD \qquad (1)$$

where, ETD and MPD in mm

ISO 13473-1 states that the error in the transformation equation is estimated to be much less than the variation due to different operators and equipment of the volumetric patch method. Although ISO prefers the use of MPD in future, the transformation provides a nominal comparison between the two methods where no other reference is available during validation exercises (see Section E.3).

More about Texture Profiles and Analysis

ISO 13473-2 is a valuable reference to terminology and basic requirements related to pavement texture profile analysis.

Table E.1 Classification of Texture Profilers (ISO 13273-3: 2002)

<table>
<tr><td rowspan="2">Mobility</td><td colspan="6">Mobile</td><td colspan="6">Stationary</td></tr>
<tr><td colspan="3">Fast (≥ 60 km/h)</td><td colspan="3">Slow (< 60 km/h)</td><td colspan="3">Fast (< 1 min)</td><td colspan="3">Slow (≥ 1 min)</td></tr>
<tr><td>Pavement contact</td><td colspan="6">Contactless</td><td colspan="6">Contact</td></tr>
<tr><td>Principle of operation</td><td colspan="3">Laser</td><td colspan="3">Light-sectioning</td><td colspan="3">Stylus (needle tracer)</td><td colspan="3">Ultrasonic</td></tr>
<tr><td>Wavelength Range (mm)</td><td colspan="2">A
0.05 to 0.16</td><td colspan="2">B
0.2 to 0.5</td><td colspan="2">C
0.63 to 2.0</td><td colspan="2">D
2.5 to 50</td><td colspan="2">E
63 to 200</td><td colspan="2">F
250 to 500</td></tr>
</table>

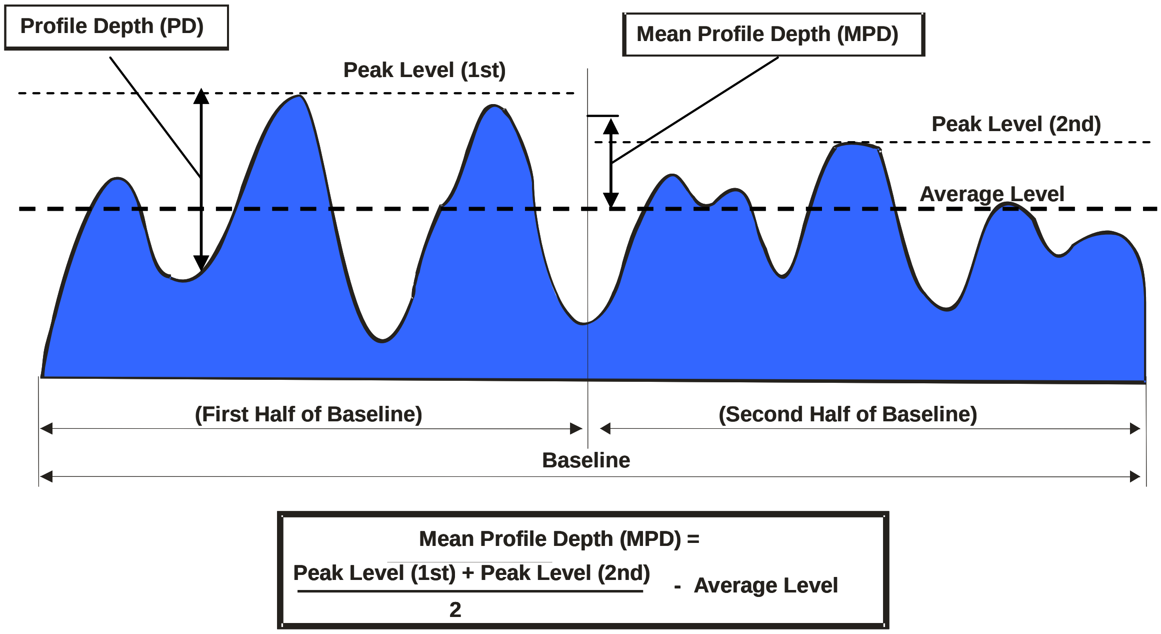

Figure E.9 Definition of Mean Profile Depth (ISO 13473-1: 1997)

E.2.3 Equipment Specifications

The equipment specification should define the minimum requirements, and should cover aspects such as instrument type, precision, and recording intervals. Equipment for measurements of skid resistance, surface texture and road geometry should be specified.

Different types of skid resistance measurement devices with their respective advantages and disadvantages were discussed in the first part of this section. These include side force testers, locked wheel testers, and fixed and variable slip devices. These devices can collect data continuously or at user defined intervals. For skid testers especially, the measurements provided by different devices are significantly different and the results are not interchangeable. This is because the measurements are influenced by many factors that are directly related to the specific device used. These aspects therefore need to be considered carefully and application of any corrections to compensate for these effects validated. For example, speed and temperature dependence need to be defined by the manufacturer and confirmed during the validation exercise (see Sections E.3 and E.4). Minimum requirements for skid testers are included in Table E.2.

Table E.2 also provides minimum requirements for vehicle mounted laser profilers suitable to measure pavement surface texture. Equipment must be compatible with ISO 13473-1 Characterization of Pavement Texture Utilising Surface Profiles – Part 1 – Determination of Mean Profile Depth.

Road geometry and function dictates skid resistance requirements and therefore interpretation of these measurements. This data is therefore essential for site description and classification purposes. The geometric survey, however, remains secondary and do not have to form part of every skid or texture survey due to the relatively unchanging nature of these features.

GPS or differential GPS equipment included as part of the surveillance systems (see Part A) can be used to extract geometric data, i.e. road centreline, horizontal curvature and vertical grade. An offset of the coordinate data ensure that the road centreline data is obtained.

For collection of high accuracy horizontal curvature and vertical grade data, an accelerometer/gyro combination should be used. Minimum equipment requirements for the collection of road geometry data is provided in Table E.3.

Table E.2 Skid and Texture Equipment Specifications

Parameter	Minimum Requirements for		
	Skid Resistance[1]	Texture [2]	Data Acquisition System
Sensor	Strain Gauged Load Cell	Laser	Not Applicable
Minimum No. of Sensors	vertical and horizontal (drag) force measurement in one wheel path	texture depth measurement in both wheel paths and between as reference	Not Applicable
Sensor Measuring Range	FS (device dependant)	0 to 200 mm	> Sensor Output
Sensor Accuracy	< 0.05% FS	0.1 mm	> Sensor Output
Sensor Repeatability	0.1% FS	0.02 mm	±1 LSB
Frequency Response	DC to 10 kHz	DC to 32 kHz	> Sensor Output
Resolution	0.1% of scale appropriate to device	0.05 mm	16 Bit
Operating Temperature Range	0°C to 50°C	0°C to 50°C	0°C to 50°C
Thermometer Accuracy	0.5 °C	Not Applicable	> Sensor Output

Note: [1] Also refer to Section E.4.3; [2] Refer to ISO13473-3 for Specification of Profilometers
Legend: FS = Full Scale (e.g. 2 kN for SCRIM, 1.2 kN for Grip Tester); LSB = Least Significant Bit

Table E.3 Equipment Specification Considerations for Road Geometry Surveys

Parameter	Minimum Requirements for	
	Road Geometry	Road Centreline
Instrument Type	Inertial Navigation System (accelerometers and gyros)	Differential GPS (Inertial Navigation System for areas with no or lost GPS coverage)
Resolution	0.2% Gradient 0.2% Cross fall 1m Curvature	Data to be provided with a minimum of 12 significant digits in decimal degrees
Accuracy	Gradient and Cross fall: ±1% (absolute error) Horizontal Radius of Curvature: ±5% (relative error)	98% of readings within 1 m
Minimum Sampling Interval/ frequency	10 m	10 Hz
Filtering/ Smoothing	30 m moving average on gradient, cross fall and curvature	Not Applicable
Operating Temperature Range	0°C – 50°C	0°C – 50°C
Repeatability	1% Slope 5 m Curvature	5 m

E.2.4 Relative Interpretation of Friction Measurements

Most modern pavement friction measuring devices are capable of providing an accurate assessment of skid resistance. However, differences in underlying principles and methods of measurement provide different output parameters and the results obtained are not interchangeable. In this subsection, harmonization between different devices through the use of common indices, and specifically the International Friction Index, is introduced. In addition, relative interpretation of friction data is illustrated by introducing the concepts of site categories and investigatory levels.

E.2.4.1 The International Friction Index

In the early 1990s, the Permanent International Association of Road Congress (PIARC) conducted an international experiment to compare and harmonize texture and skid resistance measurements. The experiment was designed to create a common scale for the reporting of pavement friction measurements for the devices that participated in the experiment. This involved 47 different devices from 16 countries and 54 sites around Belgium and Spain. The common scale developed from this data was named the International Friction Index (IFI), by analogy with the International Roughness Index (IRI). (PIARC, 1995)

In Part A it is illustrated that skid resistance at low speeds is controlled by microtexture, whilst the macrotexture (texture depth) determines the rate at which skid resistance is lost as speed increases. Texture depth is often referred to as the friction-speed gradient parameter. These principles were incorporated into the IFI model. Calculation of the IFI is described in ASTM-1960. IFI consists of two parameters, namely:

- The calibrated wet friction at 60 km/h (F60), and
- The speed constant or speed number of wet pavement friction (Sp)

Further Reading: Friction Indices

Appendix E-1 contains details on the calculation of IFI.

A number of studies have been conducted to compare and harmonize friction measurements and a number of other indices also exist.

- The Penn State Model was used as the basis for the development of IFI (Leu & Henry, 1983; Henry, 2000);
- The Rado Model (Henry, 2000)
- The European Friction Index (EFI) developed during the Belgian RRC (Road Research Centre) study and "Harmonization of European Routine and Research Measuring Equipment for Skid Resistance (HERMES) follow-up study (FEHRL, 2008)

F60 represents the average wet coefficient of friction experienced by a passenger car with four smooth tyres in a 60 km/h locked-wheel slide. Sp provides a measure of how strongly the wet friction depends on the sliding speed of the vehicle. A low Sp indicates higher sensitivity of friction to slip speed (Cenek et al, 2000). F60 and Sp is reported as IFI (F60, Sp).

E.2.4.2 Interpretation of Friction Measurements

Although relationships between skid resistance and crash rates exist (see Part A), incidents on roads can rarely be ascribed to a single contributory factor. For this reason, no simple method or a single skid resistance value exist for defining a 'safe' or 'hazardous' surface in terms of skid resistance.

A common objective in managing skid resistance is the equalization of crash risk across a road network by maintaining appropriate levels of skid resistance that is dictated by specific site characteristics. This approach optimizes utilization of resources and is therefore more sustainable than a strategy that aims to maintain a uniformly high level of skid resistance across the entire road network (Austroads, 2005).

To implement the approach described above, road authorities typically implement the following three concepts:

- Site Categories: these are categories of road use based on aspects such as section geometry, location, and crash rate data. Examples of site categories adopted in the UK and published in the HD28 Design Manual for Roads and Bridges are shown in Table E.4 to follow.
- Investigatory Levels of skid resistance: If skid measured skid resistance falls below this limits, then further investigations should typically be performed to determine if a surface treatment is justified or if some other form of action is required, and if the investigatory level is appropriate.
- Intervention Levels: if measured skid resistance falls below this level, then some form of intervention to improve skid resistance or road safety is typically required.

Appropriate skid resistance requirements are determined and assigned to each site category. In practice these requirements may vary significantly for individual sites within site categories. For this reason, investigatory levels, rather than intervention levels are specified. The HD28/04 standard introduced ranges of investigatory levels and emphasizes the importance of local engineering judgement in maximizing the effectiveness of these standards.

The HD28 standard has served as a reference for the development of skid resistance specifications in many countries and contains typical requirements associated with different facilities. Table E.4 includes example skid resistance investigatory levels for selected site categories. These values were originally developed from SCRIM measurements and are therefore in terms of Side Force Coefficient (SFC) at 50 km/h.

When authorities using this standard decide to use a different device, such as the Grip Tester, they have to either convert the Grip Tester survey results to equivalent SCRIM values, or convert investigatory levels from SFC to Grip Number (GN).

Conversion using correlations provided by manufacturers or reputable studies should be used. It is, however, important to make sure that the correlation is appropriate for the device and test conditions under consideration. The correlation between the SCRIM and Grip Tester, for example, is different for the Grip Tester Mark 1 (used during the PIARC study) and the Grip tester Mark 2. Equivalent GN investigatory levels derived from the correlation between SFC and GN (Grip Tester Mark 1) is included in Table E.4 to illustrate the application of the preceding discussion.

Because the reduction in wet friction with increased vehicle speed is governed by macrotexture, minimum levels of texture depth are specified in most countries. For many national networks, specifications only aim at macrotexture levels, whilst microtexture is governed by policies on the quality of wearing course aggregate and the type of surfacing used (Dupont and Bauduin, 2005). Figure E.10 illustrates the relative

Important!

When published relationships are used to convert friction values obtained from one device to another, the appropriateness of the correlation should be carefully evaluated.

Some of the devices included in the PIARC experiment, for example, have been upgraded and the correlations do not necessarily hold for the latest devices. An example is the Grip Tester Mark 1 and Grip Tester Mark 2. In this context, the ASTM-1960 (1998) standard for calculating the IFI contained calibration coefficients derived during the PIARC experiment, whilst these coefficients were excluded from ASTM-1960 (2007). Rather, the latter describes a standard calibration procedure to determine appropriate IFI coefficients for the measuring device and survey conditions.

importance of skid resistance and macrotexture for different network types.

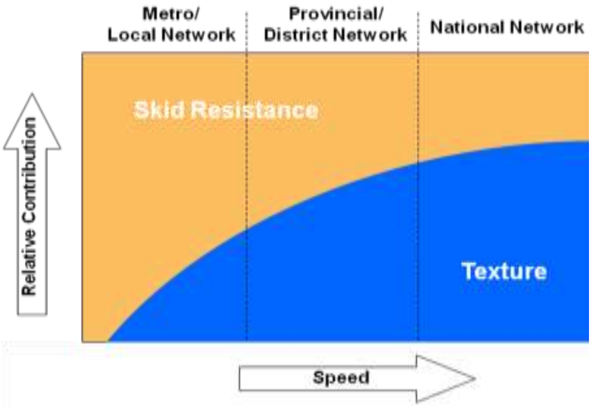

Figure E.10 Relative Importance of Friction Components for Different Network Types

Table E.4 Typical Site Categories and Investigatory Levels (UK Standard HD28/04)

Site Category	SFC50	GN (MK2)*
Dual carriageway non-event	0.35 – 0.40	0.41 – 0.47
Single carriageway non-event	0.40 – 0.45	0.47 – 0.53
Dual/ single carriageway with minor junctions & approaches to and across major junctions	0.45 – 0.55	0.53 – 0.65
Approaches to pedestrian crossings and other high risk situations	0.50 – 0.55	0.59 – 0.65
Roundabout	0.45 – 0.50	0.53 – 0.59
Gradient 5 to 10% longer than 50 m	0.45 – 0.50	0.53 – 0.59
Gradient ≥ 10% longer than 50 m	0.50 – 0.55	0.59 – 0.65
Bend radius < 500 m – dual carriageway	0.45 – 0.50	0.53 – 0.59
Bend radius < 500 m – single carriageway	0.50 – 0.55	0.59 – 0.65
*Note: for Grip Tester Mark 2, GN = SFC50 / 0.85 (Findlay Irvine, 2004)		

Typical minimum macrotexture requirements are furnished in Table E.5. In addition to macrotexture requirements for existing surfacings, provision is also made for new surfacings. Requirements for new surfacings are stricter to allow for a reduction in texture with time and a tolerance above minimum values.

Cenek et al (2000) applied IFI to skid resistance and texture depth requirements for bituminous seal surfaces on high-speed roads. Table E.6 shows the SCF and texture depth investigatory levels as well as the corresponding F60 and Sp values. In addition, F50 and F100 values were determined for comparison.

The data show that at the minimum nominal sand patch derived texture depth of 0.9 mm, there is a 50 per cent reduction in wet friction for a doubling in slip speed from 50 km/h to 100 km/h. The authors state that this result highlights the need for road authorities to pay particular attention to the condition of road surfaces in high speed zones to ensure that they provide appropriate levels of skid resistance and adequate drainage.

Table E.5 Typical Macrotexture Requirements (Cook, 2005)

Facility	Texture Depth (MPD, mm)	
	New Surfacings	Existing Surfacings
Urban; legal and operating speed equal or less than 50 km/h	0.5	0.5
Urban; legal speed less than 70 km/h	0.7	0.5
Rural; legal speed 70 km/h or higher	0.9	0.5
Note: Values represent minimum threshold levels and not investigatory levels		

Important!

The reader should note that all requirements presented in this section are purely for demonstrative purposes, for relative interpretation of friction measurements. The requirements shown in this section should therefore not be adopted "as is". Careful consideration of the authority's strategy for managing skid resistance is required to determine appropriate limits for a specific network.

Table E.6 Application of the IFI to Existing Skid Resistance and Texture Depth Requirements (Cenek et al, 2000)

Site Category	Example Requirement (Transit New Zealand)		IFI		Calculated Wet Friction Level	
	Investigatory Level (SFC50)	Sand Patch Texture, mm (MTD)	F60	Sp (km/h)	F50	F100
Intersections and crossings	0.55	0.9	0.41	91	0.46	0.27
Tight curves (< 250 m radius) and steep downgrades (< 10%)	0.50	0.9	0.38	91	0.42	0.24
Downgrades 5 to 10% and approaches to junctions	0.45	0.9	0.34	91	0.38	0.22
Undivided carriageways	0.40	0.9	0.31	91	0.34	0.20
Divided carriageways	0.35	0.9	0.27	91	0.31	0.18

E.3 Validation and Control Testing

TMH 13 Part A introduces general aspects of calibration and validation that require consideration during the survey planning process.

It should be understood that calibration of the equipment only confirms that a measurable or specified tolerance can be achieved for individual system components. Calibration does not confirm the appropriateness of the parameter measured from a moving vehicle on the network under consideration. Moreover, the objective of equipment validation is not to adjust the system outputs to match a predetermined benchmark.

Equipment is either accurate and calibrated (i.e. the equipment is "valid") or it is not. If it is not, the equipment should be fixed by the manufacturer. The validation process encompasses equipment calibration (of system components), including the effects of operational variables. Validation therefore confirms that the equipment, operator, and adopted measurement protocol, working together as a system, can provide meaningful data of sufficient accuracy while operating under normal surveying conditions.

Section E.3 provides a framework for selection of validation sections and provides validation schemes for equipment measuring skid resistance, texture and road geometry.

Important!

<u>Calibration</u> of the equipment only confirms that a measurable or specified tolerance can be achieved for individual system components. Calibration does not confirm the appropriateness of the parameter measured from a moving vehicle on the network under consideration.

<u>Validation</u> confirms that the equipment, operator, and adopted measurement protocol can provide meaningful data of sufficient accuracy while operating under normal surveying conditions.

E.3.1 General Requirements

General considerations when planning a survey and aspects to be covered in the specifications are outlined in TMH 13 Part A. This section should therefore be read in conjunction with Part A. Key aspects related to validation sections are the selection of the sections, selection of a reference device and surveying of the sections, and processing of the data. These aspects are discussed in the following paragraphs.

E.3.1.1 Validation Section Requirements

Sections should be selected for validation of skid resistance and texture measurements as well as for road geometry measurements. If appropriate, the same sections may be used for validation of different parameters. General guidelines for selection of validation sections are outlined in Part A and include considerations such as representativeness, practical lengths, closeness to centre of operations etc.

The same profilers system is often used to measure texture, roughness and rutting. To ensure efficiency and therefore compatibility of the validation processes it is recommended that consideration also be given to requirements provided in Parts C and D.

Table E.7 provides guidelines for the selection of validation sites.

E.3.1.2 Reference Surveys

In addition to selecting appropriate validation sections, these sites need to be characterized independently before the network survey starts. Normally, reference devices are used for this purpose. For texture and especially skid resistance measurements, however, validation is often impossible due to the absence of available reference equipment.

a) Skid Resistance

No direct reference device currently exists for skid resistance validation. For this reason, the validation is essentially limited to ensuring that the measurements are repeatable under various operational conditions. *Details of this process are described in Section E.3.2.* The following additional requirements may be specified:

Table E.7 Validation Requirements for Skid, Texture and Road Geometry

Parameter	Requirements		
	Minimum No of Sections/ Sites	Minimum Section Length	Parameter Ranges
Skid Resistance (GN ranges)	5	500 m	0.30 to 0.45 0.45 to 0.60 0.60 to 0.75
Texture (MPD)	5	200 m	0.5 to 1.5 mm 1.5 to 2.5 mm 2.5 to 3.5 mm
Geometry (grade, cross-fall, and curvature)	10	N/A	Vertical grade: 0 to 10% Cross-fall: -3 to +10% Horizontal curves: 50 to 300 m

- Equipment should have traceability to the *PIARC "International Experiment to Compare and Harmonize Texture and Skid Resistance Measurements"*. Both the SCRIM and Grip Tester devices are commonly used and formed part of this experiment.
- If feasible, it may be required that equipment must have completed a recognized, independent comparative trial with other equivalent skid resistance measuring equipment.

b) Surface Texture

The reference surface texture device should meet the minimum requirements of ISO 13473-1 Characterization of Pavement Texture Utilising Surface Profiles – Part 1 – Determination of Mean Profile Depth (1997). Examples of devices that conform to this specification are the Swedish Road Traffic Research Institute (VTI) Stationary Laser Profiler selected as the reference texture device for the PIARC experiment and the Transit NZ Stationary Laser profiler. Where a device meeting the ISO requirements is not available, the Sand Patch Method may be used (see Section E.2).

The following procedure is recommended for the measurement of reference texture and derivation of MPD values on validation sections:

- As a minimum, the texture along each wheel path should be recorded over the full validation length at least once. Where specified, measurements between the wheel paths should also be recorded.
- If laser profiler reference equipment is used, MPD can be derived as defined in ISO 13473-1.
- The results should be processed to give the average MPD for every 10 m segment for each wheel path.

Guidelines for surface texture validation are provided in Section E.3.3.

c) Road Geometry

Vertical grade, cross-fall, and horizontal curvature should be established at reference locations. Geometric parameters can be determined using standard survey techniques. For grades, a reference inclinometer may be used. At least 10 reference locations are required to validate each parameter. *Guidelines for validation of geometry measurements are provided in Section E.3.4.*

d) Positioning System

At least ten reference positions should be selected and the road centreline coordinates established by a registered surveyor. These locations may also coincide with datum locations and should preferably be located in a loop section. *Guidelines for validation of geometry measurements are provided in Section E.3.5*

E.3.2 Skid Resistance Validation

Guidelines for determining validation requirements for skid resistance measurements are shown in Table E.8. It is recommended that ten runs be performed over two days for each validation section, i.e. Five runs per day. In addition, testing should be done at three or four different speeds.

As there is no direct reference device for skid resistance measurements, validation focuses on precision of the system outputs. Guidelines for setting validation criteria are shown in Table E.9.

Table E.8 Validation Requirements

Parameter	Recommendation
Number of sections for each relevant skid range[1]	Minimum 1
Section length	500 m
Segment length[2]	10 m
Repeat runs per site per day	5
Repeat series[3]	2 repeats within a day of each other
Speed dependency	3 speeds
Positions in test lane[4]	Left and right wheel paths and centre

Notes:
[1] Refer to Table E.7
[2] Data processed to mean value over 10 m;
[3] Repeat first series on second day (total 10 runs)
[4] Between wheel paths may be specified

As shown in Table E.9, the repeatability of skid resistance devices can be validated through the following checks and approaches:

- Checks should be run on the variability of measurements between different repeat runs. This can be done by evaluating the coefficient of variation of the measured skid values for each 10 m segment.
- Repeatability of the outputs within combined data sets (including all repeat runs) should be evaluated for (1) each validation section, and (2) for the total data set which includes all validation sections. The average standard deviation for the segments under consideration should be evaluated. The level of correlation between individual segment values for each run and the mean values obtained from all runs should be checked. A normal linear regression can be used and limits can be set on the coefficient of determination (R^2).
- The mean skid value for each segment, recorded over several repeat runs and on a given day, should be checked against the mean skid value for the same segment recorded on another day.
- It must be demonstrated that any speed correction is valid over the range of texture depths encountered on the network. After correction to the standard speed, the combination of any two different survey speeds should be checked for agreement.

Table E.9 Skid Resistance Validation Criteria

Check for	Parameter	Suggested Acceptance Criterion	Scope of Processing
Repeatability of skid measurements	Coefficient of variation for individual segments	≤ 5%	Check for each 10 m segment for each speed and each wheel path, for each series of runs
	Average coefficient of variation for all segments	≤ 3%	Check for combined validation data sets which includes all repeat runs at each speed in each wheel path for the segments under consideration
	R^2 of linear regression between individual segment values and mean values	≥ 0.95	
Bias error between two data series	Difference in mean 10 m skid value from repeat runs measured on different days	≤ 2%	Check for repeated measurements for individual segments at each speed and in each wheel path
Speed dependency after correction	Absolute difference between combination of any two segments	95% of values to be less than 8%	Check for each 10 m segment for combination of two survey speeds

E.3.3 Texture Validation

Guidelines for determining validation requirements for texture measurements are shown in Table E.10. It is recommended that ten runs be performed over two days for each validation section (i.e. 5 runs per day). In addition, testing should be done at three or four different speeds. The mean profile depth (MPD) should be determined for each 10 m segment in each wheel path.

Table E.10 Validation Requirements

Parameter	Recommendation
Number of sections for each relevant skid range[1]	1 (total min. of 5 sites)
Section length	200 m
Segment length[2]	10 m
Repeat runs per site per day	5
Repeat series[3]	2 repeats within a day of each other
Texture profile characteristics[4]	Minimum 1 section or 200 m
Speed dependency	3 speeds on 1 section
Positions in test lane[5]	Left and right wheel paths

Notes:
[1] Refer to Table E.7
[2] Data processed to mean value over 10 m;
[3] Repeat first series on second day (total 10 runs)
[4] Sites selected to represent range of wavelengths
[5] Between wheel paths may be specified

It may also be required to demonstrate the survey equipment's ability to measure the broad range of wavelengths that constitute the road's texture profile. Guidelines for setting validation criteria are outlined in Table E.11. As shown in Table E.11, the repeatability and bias of the texture survey equipment can be validated through the following checks and approaches:

- Checks should be run on the level of correlation between the average measured MPD and the reference MPD for each 10 m segment for the complete data set, including all repeat series and measurement speeds.
- A normal linear regression can be used and limits can be set on the confidence limits for the regression equation slope and intercept.
- Repeatability of the outputs within combined data sets (including all repeat runs and at all measurement speeds) should be evaluated for (1) each validation section, and (2) for the total data set which includes all validation sections. The average standard deviation for the segments under consideration should be evaluated. The level of correlation between individual segment values for each run and the mean values obtained from all runs should be checked.

Table E.11 Texture Validation Criteria

Check for	Parameter	Suggested Acceptance Criterion	Scope of processing
Bias from reference (all parameters are calculated from a linear regression between average 10 m MPD from repeat runs and reference 10 m MPD values)	R^2 of linear regression	≥ 0,95	Check for the complete validation data set which includes all sections and all runs, at each speed and in each wheel path
	Slope of linear regression	Between 0,9 and 1,1	
	Intercept of linear regression	Between -0,1 and +0,1	
	95% confidence interval of Slope	Should bracket 1,0	
	95% confidence interval of Intercept	Should bracket 0,0	
Repeatability of measurements	Coefficient of variation for individual segments	≤ 5%	Check for each 10 m segment for each speed and in each wheel path, for each series of runs
	Average coefficient of variation for all segments	≤ 3%	Check for combined validation data sets which includes all repeat runs and all measurement speeds for the segments under consideration and in each wheel path
	R^2 of linear regression between individual segment values and mean values	≥ 0,95	
Bias error between two data series	Difference in mean 10 m MPD value from series runs measured on different days	≤ 2%	Check for repeated series at each speed and in each wheel path for individual segments

A normal linear regression can be used and limits can be set on the coefficient of determination (R^2).

- The average MPD value for each segment, recorded over several repeat runs and on a given day, should be checked against the average MPD value for the same segment recorded on another day, i.e. the repeat series.

When a new device type or a new contractor is being used on the network for the first time, then spectral analysis of the profile wavelengths can be considered.

Such validation, however, requires specialist inputs and is not covered in detail in these guidelines. If such a validation is required, then it should be demonstrated that the equipment can measure power spectral density (PSD) of the same magnitude as the reference device over the wavelength range 2.0 mm to 100 mm. Conformance can be checked by plotting the measured PSD along with the reference PSD.

Further Reading: Validation of Texture Profiles

- ISO 13473-2 provides information on characterization of texture profiles.
- TMH 13 Part A, Appendix A-1 contains a basic outline of Spectral Analysis of Profiles.

E.3.4 Road Geometry Validation

The validation of dynamic measuring equipment should include checks for vertical grade, cross-fall, and horizontal curvature.

E.3.4.1 Vertical Grade and Cross-fall

Once the performance of the sensor used for gradient and cross-fall is accepted based on valid calibration certificates, it must be demonstrated that the zero condition is correctly defined and that there is no bias in the recorded measurements.

Data from a minimum of five runs at each of three speeds should be collected at a minimum of 10 validation sites (Table E.7) and the average grade and cross-fall for each of the sites should be reported. It is recommended that the data be reduced to 30 m moving average values. The measured gradient and cross-fall for the average of five runs at each site should be within five per cent of the reference grade and cross-fall. Repeatability of the measurements can be accepted if the coefficient of variation of the five repeat runs at each site is less than five per cent.

E.3.4.2 Horizontal Curvature

Table E.7 recommends that a minimum of 10 sites (or curves) should be selected for the validation exercise. Both left and right hand curves should be represented.

Data from a minimum of five runs at each of three speeds should be collected and the average curvature at each of the selected sites reported. It is recommended that the data be reduced to 30 m moving average values. The measured gradient and cross-fall for the average of five runs at each site should be within five per cent of the reference curve radii. Repeatability of the measurements can be accepted if the coefficient of variation of the five repeat runs at each site is less than five per cent.

E.3.5 Validation of Positioning Equipment

The validation of positioning equipment involves checking of the Global Positioning System (GPS), Inertial Navigation System (INS), and Distance Measuring Instrument (DMI). Whilst these aspects are covered in *TMH 13 Part B approaches to validation of GPS are included in Part E*.

E.3.5.1 GPS Validation

The GPS is validated by comparing coordinates at several benchmark locations set out and maintained by a registered surveyor or surveying authority. It is recommended that this check be carried out at five to ten benchmark locations.

GPS benchmark locations should roughly be one km apart, and the dynamic accuracy of the GPS should be checked by completing several survey loops through the benchmark positions.

These checks should preferably also be performed over more than one day, and at different times of the day.

The ability of the GPS inertial system to compensate for a loss in the GPS signal should preferably be demonstrated to the contractor.

The GPS coordinates should be within 5 m of the vertical and horizontal benchmark values, and for repeat dynamic measurements this accuracy should be achievable 90 per cent of the time.

E.3.6 Control Testing

Control testing should be performed from time to time during the survey to ensure that the equipment output is still valid and that the accuracy and precision of the device is still within specification.

Control testing should be performed on validation sections and the same criteria as used for validation of equipment apply. However, control testing need not be performed on all validation sections, and normally control testing on two or three sites would suffice.

Control testing should be performed on a regular basis as part of the survey process. If control testing shows that the measured values are no longer within the specified limits, then any data collected since the last successful control test should be discarded and remeasured. *Under no circumstances should control test data be used to adjust or calibrate the equipment outputs.*

It should be obvious that the cost and time implications of a failed control test are severe. For this reason, control testing should be carried out as frequently as possible within the constraints of the network and survey budget.

The frequency of testing is basically a compromise between the cost of control testing (which not only delays the survey, but requires additional time and travel), and the risk of remeasuring all data collected since the last control test.

As a rough guideline, control testing can be requested on a monthly basis or at five stages (equally spaced in terms of length surveyed) during the survey process.

E.4 Operational and Quality Control Procedures

This section of the guidelines deals with the daily checks and procedures that need to be carried out during the course of skid resistance and texture surveys. It should be noted that, while the guidelines cover the basic operational aspects and their influence on measurement, the guidelines are intended mainly for network managers, and not for contractors.

The network manager is not responsible for performing daily checks or following of proper operational procedures. However, a proper understanding of the elements that influence measurement and of the procedures that a contractor should perform each day, will allow the network manager to exercise better control over the measurement process. The guidelines in this section thus focus on how operational procedures can be controlled.

The operators of measurement devices should – in addition to the elements covered in this section – have an in-depth understanding of the influence of all operational elements on the measurement process. Relevant standards and operational manuals should be consulted for detailed operational procedures.

E.4.1 Operational Procedures for Skid Resistance Measuring Devices

Devices suitable for measuring skid resistance on a network level all comprise at least one measuring wheel fitted to a test vehicle or trailer. The device may be of the variable or fixed slip type and the vertically imposed and horizontal drag forces are measured by load cells. Water is introduced in front of the test wheel to wet the surface during testing. Apart from periodic calibration of system components, the following operational and quality control aspects should be checked on a daily basis.

- Tyres: Check the condition and pressure of the drive tyres. The standard test tyre should be checked for damage and ware. The cold tyre pressure should be according to specification. If a new tyre is fitted, it should be conditioned by running a test on a section of at least one km in length. Check all spare tyres.
- Batteries/ Power Supply/ Cabling: Where applicable, ensure that batteries are fully charged for both computers and the device. Check that power supplies and all cabling are on board and that all connections are good.
- Water Supply: Make sure there is sufficient water in the tank for each test run. Plan and arrange for daily water needs to complete the survey.
- Mechanical and Hydraulic Components: Check that mechanical and hydraulic parts are in good working order, e.g. for Grip Tester, check chain tension and lubrication. Check suspension: the device should bounce back and there should be no side play.
- Contamination: The tyres and all other components should be clean; free from mud, snow, or ice.
- Warm-up Time: The measuring and data acquisition systems should be subjected to sufficient warm-up time according to the manufacturer's recommendations.
- Quick Calibration: The vertical and horizontal forces measured by the load cells should be checked and necessary adjustments made and recorded.
- Water Flow: Check that the system is calibrated to produce the specified water flow at the specified travelling speed.
- Test Conditions: Strong winds may cause turbulence under the vehicle which can affect consistent water flow. The water film thickness cannot be controlled during heavy rainfall or when testing in standing water. Testing under these conditions should be avoided. In general, care should be taken to ensure measurement conditions approximate those of the validation.

Speed Control: To ensure that the survey vehicle maintains a constant speed throughout, it must be fitted with a cruise control. Situations where the speed cannot be maintained should be flagged by the operator.

E.4.2 Operational Procedures for Texture Profilers

Dynamic measurement of texture depth using profilers is similar to that used to measure road roughness and in many cases the same system is used. Reference should be made to *TMH 13 Part C, Section C.5.2 Operational Procedures for Profilers*. The checklist from operational control, Table E.13 is reproduced for convenience.

Table E.12 Checklist for Operation control Checks on Skid Resistance Measuring Devices

Control or Decision Aspect
1. Check the vehicle and measuring equipment and ensure it is the same as used in the validation exercise.
2. Ensure that the driver is the same as the one who conducted the validation exercise.
3. Request and inspect the daily checklist. Ensure it meets the Quality Control Plan format.
4. Inspect the test vehicle and skid measuring equipment for cleanliness and to ensure that mechanical and hydraulic components are in good condition.
5. Confirm that the test tyre is of the correct type and ensure there is no excessive ware or damage.
6. Request the operator(s) to conduct a quick calibration. Check to ensure that the measured vertical and horizontal forces are within limits and ensure that the operator is capable of performing the test consistently.
7. Request the operator(s) to perform a water flow calibration test. Check that the specified flow can be produced at the required measurement speed and that the operator is capable of performing the test consistently.
8. Confirm the correct operation of the GPS

Table E.13 Checklist for Operation Control Checks on Profilers

Control or Decision Aspect
1. Check the vehicle and ensure it is the same as used in the validation exercise.
2. Ensure that the driver is the same as the one who conducted the validation exercise.
3. Request and inspect the daily checklist. Ensure it meets the Quality Control Plan format.
4. Inspect the vehicle and ensure that the height sensors are free of excess dirt, mud, etc.
5. Request the operator(s) to conduct a height test using a height calibration block. Check to ensure that the measured heights are within limits and ensure that the operator is capable of performing the test consistently.
6. Request the operator (s) to perform the bounce check. Check the output to ensure the measured profile is flat, and ensure that the operator is capable of performing the check consistently.
7. Confirm the correct operation of the GPS

E.4.3 Data Capture and Documentation

The contract specifications should provide details on the format required for the captured data. As a minimum, the specifications should state the format of the required files (e.g. Comma Delimited ASCII file, Spreadsheet format) and the required columns (or fields). For skid resistance and texture data, the required columns would typically include at least the following:

- Operator name;
- Date of record;
- Section details (separate columns for Section, name, lane, direction, region);
- Surface type;
- Site category (especially for urban networks);
- Start and end km position of record;
- GPS coordinates (longitude, latitude and height);
- Measurement speed;
- Skid resistance (left and right wheel paths);
- Texture (left and right wheel paths).
- Road geometry (separate columns for grade, cross-fall, and curvature);

The contractor should also provide a definition sheet to define any codes or abbreviations used in the file and column naming. Details of the format in which the output will be provided should ideally be submitted with the contractor's quality control plan.

The specifications (see Part A) should stipulate the deadline for delivery of data files on completion of the survey. It is important to minimize delays between the time of survey and data analysis, in order for errors to be identified as soon as possible. Ideally, some data files should be given to the network manager while the survey is in progress to identify any inconsistencies at an early stage.

The contractor should flag any data files or parts thereof for which measurements are regarded as unusual because of environmental effects or significant speed changes. Operators should therefore be trained not only in vehicle operation aspects, but also in the interpretation of skid and texture values and perceived surface friction. With adequate knowledge of the impact of different conditions on the precision of surface friction measurements, files recorded under non-optimal conditions can be accurately flagged for detailed analysis.

E.4.4 Data Checking and Troubleshooting

After receiving the friction data, the network manager should perform some control checks on a few data files. The objective of these checks should be to ensure the measured friction values correspond with basic engineering judgement, and that the data are consistent with that of earlier surveys.

For these control checks, the network manager should select a few sections for which the manager is familiar with the friction characteristics. Other sources of information such as visual survey records may also be helpful to select sections with good or poor perceived friction characteristics.

The control check should look at the detailed plotted file and segment averages for skid resistance and texture measurements. If surveys were undertaken in preceding years, then the data can be graphically compared to the data collected in previous years.

If the data check reveals an inconsistency between measured surface friction and knowledge of the surface characteristics, or between the measured friction values and those reported in the previous year, then the data file should first be checked for comments from the operator regarding the pavement condition and measurement environment. These aspects are discussed in more detail in the following section.

Site visits may be warranted to clarify certain observations and to establish general confidence in the quality of data to be incorporated into the road network management system.

E.4.5 Factors that Affect Surface Friction

The components of surface friction, as defined in Part A, are intrinsically related to the surface type, the quality of materials and construction quality. Records of the surface type should be available from the agency's pavement management system, or if not, should be recorded during the survey. The quality of the materials and construction are project level considerations and will dictate the performance of the surface under different traffic and environmental conditions.

Manifestations of good or poor surface friction performance is recorded by visual or instrument measurements during periodic network surveys. It should be born in mind that it is not the objective and not always possible to explain all observations from network level data. For this reason, agencies specify investigatory levels for skid resistance and texture so that the cause of apparent low friction and proper remedial action can be determined through further more detailed investigations.

It should be remembered that the goal is to obtain data under standard, or controlled, conditions with a specific device. In this context, measurements are made at a standard speed and under normal ambient conditions.

Also, skid resistance measurements are made on artificially wetted surfaces while no water is introduced during texture measurements. As highlighted in the previous subsection on operational procedures, any deviation from standard test conditions can influence the measurements.

Part A explains concepts of micro- and macrotexture and highlighted factors related to the road, vehicle, and environment that influence friction available at the pavement surface - tyre contact interface. In this subsection, influences on surface friction measurements and factors that may be responsible for short term and longer term variations in friction data are discussed in more detail. The focus is on interpretation and processing of the measured data on a network level.

E.4.5.1 Road Site and Geometry

Sites subjected to horizontal forces tend to have relatively lower levels of skid resistance. These conditions are encountered where braking, accelerating, and turning movements occur.

Lower skid resistance may also be encountered on curves. Skid resistance levels can be 10 per cent lower at these types of sites if compared with those where straight, level and uninterrupted traffic flow occur (Kennedy et al., 1990)

E.4.5.2 New Surfacing

Skid resistance levels on newly constructed surfacing can be low when microtexture is masked by a thin binder film. Some surfacing types, such as asphalt, are more prone to this phenomenon than for example bituminous seals. Under the action of traffic, however, the binder film is worn away and the aggregate microtexture exposed with an increase in skid resistance. The degree and rate of change will depend on the type of surface material and traffic intensity. Sections with newly constructed surfacing should be flagged so that they can be excluded from certain types of analysis if necessary (HD28/04, 2004).

Surfaces with high porosity may produce a high rate of invalid texture measurements (drop-out rate). The phenomenon subsides when these surfaces becomes clogged up with time

E.4.5.3 Surface/ Pavement Condition

Bleeding (binder rises and covers the surface) can be a source of unexpected reduction in skid resistance and texture depth. Texture depth can also show erratic changes over a short time when aggregate loss and surface disintegration occur.

Pavement distresses such as cracking, potholes and patching can influence measurements significantly. Apart from data

anomalies that can be caused by potholes, variation in the travelled line from year to year may cause significant differences in the measurements. Materials used for patching are normally different from the original surface which will produce variations in the data.

Road roughness can affect skid resistance measurements. The degree of influence also depends on the type of measurement device and test speed. The Grip Tester, for example, is more

sensitive to this effect than the SCRIM.

E.4.5.4 Measurement Environment

The environment in which measurements are performed may impact on the repeatability of measurements. Operators and network managers should be able to identify conditions that may impact on measurements.

In severe cases operations should be stopped while conditions persist. In less severe cases, the operator should flag the data file to indicate that measurements were taken under non-optimal conditions, and should specify the nature of the problem. Environmental factors that may impact on measurements are:

- Wind: Heavy wind and gusts may affect skid and texture measurements. For texture profilers, this effect is more pronounced when ultrasonic height sensors are used. The effect will also be more severe if there is sand, snow, or other loose substances (e.g. leaves or grass) present.

  Wind turbulence under skid measurement devices may divert the water jet direction with incorrect water flow in front of the test tyre.

- Temperature and Humidity: In extreme temperature or humidity situations, the operator should check to ensure that the conditions are still within the operating range for components as specified by the manufacturer.

  It is generally accepted that the coefficient of friction decreases with an increase in tyre temperature (and therefore air and pavement temperature). The effect of temperature is also device dependant and although correction factors or relationships have been developed for most devices, the practical significance of such a correction is a controversial matter.

  The HD28/04 standard for SCRIM measurements states that temperature correction is not necessary when the air temperature during the survey is higher than 5°C (HD28/04, 2004). According to the developers of the Grip Tester, the coefficient of friction is insensitive to changes in ambient and surface temperature after the tyre has been adequately conditioned.

Network managers are cautioned against blind application of foreign temperature correction factors or relationships to skid resistance measurements. Applications developed in more temperate climates may not be appropriate for operating ranges typically encountered in more tropical or subtropical climates.

If correction for temperature is considered, it should be demonstrated that device specific correction is valid for the range of temperatures encountered on the survey network.

- Rainfall and Standing Water: Operations should not be undertaken if there is water standing or flowing on the pavement surface. If localised, these sections should be flagged. Rainfall can cause significant short-term variation in surface friction measurements. Variations of up to 25 per cent have been reported within the same week (Hill and Henry, 1981).

  Contamination from rubber and oil deposits may accumulate on the surface during dry conditions that cause slipperiness when water is applied during testing or after a rain shower. Sufficient rainfall induces a cleansing process, also called *scouring*, which rejuvenates surface friction. It is therefore important to record any rainfall that occurred within a week before the survey.

- Contaminants: A data file should be flagged if the operator observes obvious contamination over large parts of the measurement section. Such contaminants may include spilled sand, loose gravel, mud, or oil.

E.4.5.5 Measurement Speed

It was explained in Section 1 that the rate at which skid resistance reduces with speed is primarily a function of texture depth. It is, however, important to note that texture measurements as such are not significantly influenced by variations in speed. Skid measurements, in turn, are sensitive to speed changes. For this reason device specific speed correction factors or relationships are often used to normalize skid data to the target speed.

Most of these corrections are however generalized and do not take into account the effect of texture depth. It follows that the use of such corrections should be restricted to situations where traffic or road conditions necessitated deviation from the target speed, i.e. to normalize data. Moreover, the section should be flagged and data discarded if the measurement speed differs substantially form the target speed.

For example, the HD28/04 manual allows corrections for SFC within the speed range of 25 to 85 km/h. Alternatively, it should be demonstrated that the speed correction is valid for the texture range encountered on the survey network. Ideally, the IFI or similar relationship should be used to convert the measurements to any required speed (see Section E.2).

E.4.5.6 Traffic Intensity

The level of heavy vehicles together with the quality of the surfacing aggregate is responsible for the loss of aggregate microtexture, or polishing, with time. Also, contaminants that probably consist of a mixture of rubber and oil are mainly deposited by heavy vehicles (Croney and Croney, 1998).

It is believed that contamination, polishing, and scouring (described above) is an ongoing process which produces an “equilibrium” state of surface friction associated with the level of commercial traffic. As illustration of this phenomenon, Szatkowski and Hosking (1972) observed that the daily heavy traffic decreased from 2750 to 730 vehicles per day, during the construction of a bypass, with an increase of the SFC form 0.43 to 0.58.

E.4.5.7 Seasonal Variation

After polishing has reached a stable or nearly “equilibrium” state for the level of traffic, the coefficient of friction follows an approximately cyclic pattern with seasons of the year. As a result, available skid resistance under wet conditions will vary throughout the year with the lowest values occurring towards the end of the dry season and the highest values during the wet season.

It is customary to test in the dry season when skid resistance is low. However, even in a given season these measurements can vary significantly which complicates maintenance programming and mask trends from one year to the next. For these reasons, strategies have been developed to derive characteristic friction coefficients. The two main strategies are illustrated in Figure E.11.

- Mean Season Survey Method (MSSM): In this approach the network is surveyed three times at reasonably spaced intervals during the test season and the results are averaged. Because the cost of such a strategy is excessive, a third of the network is usually surveyed three times a year. This approach does not take account of variations between years.

  Alternatively, control sites may be established in designated climatic areas and these tested three times a year. A single annual survey can then be conducted at any time within the survey season provided that the control sections are also tested at that time. Data from control sites can also be used to assess whether the results of the current year is unusually low or high, e.g. as a result of an unusually dry or wet season.

- Single Annual Survey Method (SASM): In this approach the timing of the survey is rotated through the early, middle, and late periods of the test season in successive years. In subsequent analysis, the average value of the previous three years is used to evaluate variations between years.

The data obtained from the survey strategies discussed above is commonly reduced to a single equilibrium correction factor for each climatic area. The factor is calculated by dividing the average friction value obtained during the annual survey into the reference friction value (the average over different seasons). The seasonal correction factor is then applied to friction coefficients for each 10m segment to determine the characteristic friction coefficient.

More about Seasonal Correction

In using a single factor approach it is implicitly assumed that there is a one on one relationship for the correction factor across the range of friction values measured within or between years. By implication, measurements closer to the mean are adjusted more appropriately than those at the extremes which can lead to significant errors. A regression approach, in turn, allows for proportional correction of measurements which will reduce the amount of apparently low skid resistance values and therefore avoid triggering of unnecessary investigations or maintenance actions. This approach is described by Donbavand and Cook (2005).

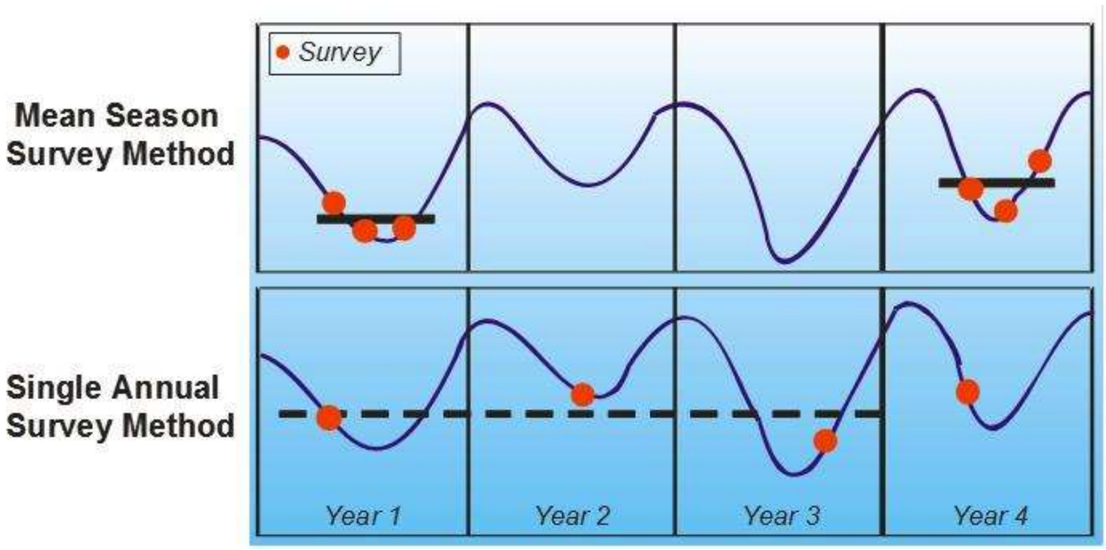

Figure E.11 Illustration of Skid Resistance Survey Strategies (adapted from Sinhal, 2005)

Table E.14 Trouble Shooting for Inconsistent Data

Possible Cause of Data inconsistency
1. Equipment: Was there any changes in the device since the last survey? 2. Equipment: Check that all equipment calibration and validation certificates have been received. 3. Check to see if the data file was flagged 4. Site location: Is the section under consideration possibly located where aggressive tyre action occurs? 5. Check if the positions of distance markers were changed since the last survey 6. Check the maintenance records: Did the road section receive a new surface since the last survey? 7. Surface age and type: If the surface is relatively new, an increase in both skid resistance and texture is possible. Texture measurements on relatively new surfaces of high porosity may not be valid based on the drop-out rate. 8. Check the pavement condition as reported in the current and previous surveys for prominent features such as excessive aggregate loss, bleeding, patching, potholes, roughness etc. 9. Environment: Check rainfall records. Was the pavement possibly flooded during measurement? Did any rainfall occur within the week before testing? 10. Measurement speed: Were there sections where the speed of measurement changed significantly? Were speed corrections applied to skid resistance data and are the corrections valid? 11. Traffic intensity: Were there any significant changes in the traffic intensity since the last survey? 12. Seasonal effects: Check the time of measurement relative to the time of measurement in the previous year(s). Check if skid resistance measurements were corrected for seasonal effects, if the method used is consistent with the method previously used, and if the method was applied correctly. 13. Environment: Were wind conditions severe at the time of measurement? Check for comments or flags in the data file. 14. Environment: Was there any activity (construction, mining etc.) in the area at the time of measurement that could have contaminated the surface. Check for comments or flags in the data file. 15. Environmental: Check the temperature and humidity records. Were these perhaps outside the operating range of the equipment?

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ASTM Standards

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ASTM E501-08. Standard Specification for Standard Rib Tire for Pavement Skid-Resistance Tests.
ASTM E524-08. Standard Specification for Standard Smooth Tire for Pavement Skid-Resistance Tests.
ASTM E965-96 (2006). Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique.
ASTM E1859-97 (2006). Standard Test Method for Friction Coefficient Measurements Between Tire and Pavement Using a Variable Slip Technique
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ISO 13473-3. 2002. Characterization of pavement texture by use of surface profiles - Part 3: Specification and classification of profilometers

European (EN) Standards

EN 13036-1: 2001. Road and airfield surface characteristics - Test methods - Part 1: Measurement of pavement surface macrotexture depth using a volumetric patch technique and classification of profilometers

E.6 Glossary

Calibration: The process of determining the relationship between the output of a measuring device and the value of the input quantity. Calibration is often regarded as including the process of adjusting the output of a measurement instrument to agree with the value of the applied standard (definition after Wikipedia, 2007).

Coefficient of Friction: Normalized friction. The frictional force divided by the normal force (the load). Term used interchangeably with 'friction coefficient'.

DGPS: Differential Global Positioning System. A system that uses a network of fixed ground based reference stations to broadcast the difference between the positions indicated by the GPS satellite systems and the known fixed positions (definition after Wikipedia, 2007).

Friction: The resistance an object encounters in moving over another object. Often the force needed to move the object, the frictional force. In this document, pavement surface friction and friction is used interchangeably, referring to the friction contributed by the surface.

Filter: A mathematical function used to process a measured profile, normally with the objective of removing certain wavelengths from the profile. The moving average is an example of a simple filter.

GPS: Global Positioning System.

International Friction Index (IFI): Friction index defined by two parameters, a calibrated friction value at 60 km/hr, F(60), and the speed gradient (or speed constant), SP.

Intervention Level: The friction level (skid resistance, texture depth or friction index) or point on a friction deterioration curve where an agency must either take immediate corrective action, such as applying a restorative treatment, or provide proper cautionary measures, such as posting "Slippery When Wet" signs and/or reduced speed signs.

Investigatory Level: The friction level (skid resistance, texture depth or friction index) or point on a friction deterioration curve where an agency should start more carefully monitoring the friction and/or crash levels at a particular site and begin the process of planning for some sort of restorative action.

Macrotexture: Deviation of a pavement surface from true planar surface with characteristic dimensions along the surface of 0.5 mm to 50 mm (definition after ISO 13473-2:2002)

Mean Profile Depth (MPD): Average value of the profile depth over a 100 mm baseline. MPD is normally expressed in mm (definition after ISO 13473-2:2002). Also see 'Profile Depth'

Mean Texture Depth (MTD): Quotient of a given volume of standardized material and the area of that material spread in a circular patch on the surface being tested (definition after ISO 13473-2:2002). Also see 'Texture Depth'

Microtexture: Deviation of a pavement surface from a true planar surface with characteristic dimensions along the surface of less than 0.5 mm (definition after ISO 13473-2:2002)

Profile Depth: The height difference between the profile and a horizontal line through the highest peak within a distance along the surface of the same order of length as a tyre pavement interface. Profile depth represents the two-dimensional case and is normally expressed in mm (definition after ISO 13473-2:2002).

Profilometer: A mobile device used for measuring the profile of surface texture.

Repeatability: The expected standard deviation of measures obtained in repeated tests, when using the same instrument and measurement team on a single, randomly selected test section.

Reproducibility: A measure of the ability to reproduce a measured result by another measurement device or measurement team working independently (definition after Wikipedia, 2007).

Resolution: The resolution of a device specifies the smallest measurement increment that the device is capable of.

Side Force Coefficient: Friction coefficient resulting when an angle is introduced between the line the tyre is steered and the general direction of travel. This quantity represents the situation where a vehicle changes direction or compensates for pavement cross-fall and/or wind effects.

Skid Resistance: The ability of the traveled surface to prevent the loss of tyre traction. In this document skid resistance is synonymous with microtexture and is always associated with wet surface conditions.

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

Surface Profile: Two-dimensional sample of the pavement texture when a sensor, such as a laser spot, continuously touches or shines on the pavement surface while it is moved along a line on the surface (definition after ISO 13473-2:2002).

Texture Depth: Distance between the surface and a plane through the peaks of the three highest particles within a surface area in the same order of a size as that of a tyre-pavement interface. Texture depth represents the three-dimensional case and is normally expressed in mm (definition after ISO 13473-2:2002).

Validation: The process of determining if a measurement device, when operated according to a established procedure and within established operating ranges, can operate effectively and reproducibly (definition after Wikipedia, 2007).

Verification: The process of proving or disproving the correctness of a system or measurement device with respect to a certain formal specification.

APPENDIX E-1

CALCULATION OF THE INTERNATIONAL FRICTION INDEX

The International Friction Index (IFI) consists of two parameters, namely:

- The calibrated wet friction at 60 km/h (F60), and
- The speed constant or speed number of wet pavement friction (Sp)

F60 represents the average wet coefficient of friction experienced by a passenger car with four smooth tyres in a 60 km/h locked-wheel slide. Sp provides a measure of how strongly the wet friction depends on the sliding speed of the vehicle. A low Sp indicates higher sensitivity of friction to slip speed (Cenek et al, 2000). F60 and Sp is reported as IFI (F60, Sp).

Sp is determined from texture measurements as follows:

$$S_p = a + b \cdot TX \qquad (A1)$$

where a and b are constants which depends on the type of device and TX is the measured texture parameter in mm, such as MTD or MPD.

The measured friction (FRS) at some slip speed (S) is used with Sp to calculate the friction at 60 km/h (FR60) as follows:

$$FR60 = FRS \cdot EXP\left[(S - 60)/S_p\right] \qquad (A2)$$

Equation A2 can therefore be used to adjust measured friction values where a device can not maintain its normal operating speed during a survey. The calibrated wet friction number at 60 km/h (F60) is then calculated using the following relationship:

$$F60 = A + B \cdot FR60 + C \cdot TX \qquad (A3)$$

where A, B and C are calibration constants. The coefficient C is zero for devices operating with smooth test tires. Calibration constants determined during the PIARC experiment are provided in Table A-1 for selected devices. Table A-1 also includes the relevant slip speeds for these devices as an example. The wet friction (FS) at any slip speed can be calculated with:

$$FS = F60 \cdot EXP\left[(60 - S)/S_p\right] \qquad (A4)$$

Table A-1 Slip Speed and Calibration Coefficients for Selected Devices

Device	**Slip Speed**	**Calibration Coefficient (PIARC Experiment)**			
	S	**A**	**B**	**a**	**B**
SCRIM	V × 34%	0.0326	1.1176	N/A	N/A
Grip Tester Mark 1	V × 15%	0.0821	0.9104	N/A	N/A
Laser Profilometer	N/A	N/A	N/A	14.2	89.7
Sand Patch Test	N/A	N/A	N/A	-11.6	113.6
V denotes the measurement speed					

APPENDIX E-2

SKID RESISTANCE VALIDATION CALCULATION EXAMPLE

km	km/hr	Run-1	Run-2	Run-3	Run-4	Run-5	Mean	Std. Dev	Coefficient of Variation	
0.01	60	0.72	0.73	0.69	0.73	0.70	0.71	0.02	2.6%	✓
0.02	60	0.67	0.69	0.65	0.68	0.65	0.67	0.02	2.7%	✓
0.03	60	0.70	0.71	0.68	0.71	0.68	0.70	0.02	2.4%	✓
0.04	60	0.71	0.73	0.69	0.72	0.69	0.71	0.02	2.5%	✓
0.05	60	0.72	0.74	0.69	0.73	0.69	0.71	0.02	3.2%	✓
0.06	60	0.72	0.74	0.70	0.73	0.70	0.72	0.02	2.8%	✓
0.07	60	0.72	0.74	0.70	0.74	0.71	0.72	0.02	2.4%	✓
0.08	60	0.72	0.75	0.69	0.74	0.70	0.72	0.03	3.7%	✓
0.09	60	0.76	0.78	0.73	0.77	0.73	0.75	0.02	3.0%	✓
0.10	60	0.78	0.80	0.75	0.79	0.75	0.77	0.02	2.8%	✓
0.11	60	0.77	0.79	0.75	0.78	0.75	0.77	0.02	2.2%	✓
0.12	60	0.77	0.79	0.74	0.78	0.74	0.76	0.02	3.3%	✓
0.13	60	0.77	0.79	0.74	0.78	0.74	0.76	0.02	2.9%	✓
0.14	60	0.75	0.76	0.72	0.76	0.73	0.74	0.02	2.5%	✓
0.15	60	0.74	0.76	0.72	0.76	0.72	0.74	0.02	2.6%	✓
0.16	60	0.73	0.76	0.71	0.75	0.71	0.73	0.02	2.9%	✓
0.17	60	0.73	0.75	0.72	0.75	0.72	0.73	0.02	2.1%	✓
0.18	60	0.72	0.75	0.70	0.74	0.70	0.72	0.02	3.0%	✓
0.19	60	0.73	0.76	0.71	0.75	0.72	0.73	0.02	2.6%	✓
0.20	60	0.74	0.76	0.71	0.75	0.72	0.73	0.02	2.8%	✓
0.21	60	0.73	0.76	0.70	0.75	0.70	0.73	0.03	4.2%	✓
0.22	60	0.74	0.76	0.71	0.76	0.72	0.74	0.02	3.1%	✓
0.23	60	0.72	0.75	0.69	0.75	0.70	0.72	0.03	4.1%	✓
0.24	60	0.71	0.73	0.69	0.73	0.69	0.71	0.02	2.7%	✓
0.25	60	0.73	0.74	0.70	0.74	0.71	0.73	0.02	2.5%	✓
0.26	60	0.76	0.79	0.73	0.78	0.73	0.76	0.03	3.5%	✓
0.27	60	0.75	0.77	0.73	0.77	0.73	0.75	0.02	2.5%	✓
0.28	60	0.74	0.75	0.71	0.75	0.72	0.73	0.02	2.5%	✓
0.29	60	0.75	0.77	0.73	0.77	0.73	0.75	0.02	2.7%	✓
0.30	60	0.76	0.78	0.73	0.78	0.73	0.76	0.02	3.2%	✓
0.31	60	0.76	0.78	0.72	0.78	0.73	0.75	0.03	3.8%	✓
0.32	60	0.77	0.80	0.75	0.79	0.75	0.77	0.02	2.8%	✓
0.33	60	0.76	0.77	0.74	0.77	0.74	0.76	0.02	2.2%	✓
0.34	60	0.76	0.78	0.73	0.78	0.74	0.76	0.02	2.9%	✓
0.35	60	0.75	0.77	0.71	0.76	0.72	0.74	0.03	3.5%	✓
0.36	60	0.69	0.77	0.69	0.76	0.70	0.72	0.04	5.5%	×
0.37	60	0.74	0.75	0.72	0.75	0.72	0.73	0.01	2.0%	✓
0.38	60	0.73	0.74	0.70	0.74	0.70	0.72	0.02	3.0%	✓
0.39	60	0.77	0.79	0.76	0.79	0.76	0.78	0.01	1.8%	✓
0.40	60	0.80	0.80	0.74	0.79	0.73	0.77	0.03	4.3%	✓
0.41	60	0.77	0.79	0.75	0.78	0.75	0.77	0.02	2.4%	✓
0.42	60	0.75	0.77	0.72	0.76	0.73	0.75	0.02	2.9%	✓
0.43	60	0.75	0.77	0.74	0.77	0.75	0.76	0.01	1.8%	✓
0.44	60	0.77	0.79	0.75	0.79	0.75	0.77	0.02	2.6%	✓
0.45	60	0.78	0.80	0.76	0.79	0.76	0.78	0.02	2.1%	✓
0.46	60	0.76	0.78	0.74	0.78	0.74	0.76	0.02	2.9%	✓
0.47	60	0.74	0.76	0.72	0.76	0.72	0.74	0.02	3.0%	✓
0.48	60	0.73	0.75	0.71	0.75	0.71	0.73	0.02	2.8%	✓
0.49	60	0.72	0.73	0.69	0.73	0.69	0.71	0.02	2.6%	✓
0.50	60	0.73	0.75	0.71	0.75	0.71	0.73	0.02	2.6%	✓
Mean		0.74	0.76	0.72	0.76	0.72	0.74	0.02	2.9%	✓
R^2		0.93	0.94	0.96	0.96	0.95				