Tyre and Road Surface Optimisation for Skid Resistance and Further Effects

---

Coordination Action FP7-217920

Seventh Framework Programme

Theme 7: Transport

D05

Report on analysis and findings of previous skid resistance harmonisation research projects

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n°217920	
Main Editor(s)	Erik Vos / Jacob Groenendijk
Due Date	1st March 2009
Delivery Date	25th February 2009
Work Package	WP2 Harmonisation of skid-resistance methods and choice of reference surfaces
Dissemination Level	Public (PU)

Project Coordinator	Mr. Manfred HAIDER, arsenal research, Austria phone: +43 50550 6256, e-mail: manfred.haider@arsenal.ac.at internet: http://tyrosafe.fehrl.org
This project is part of the FEHRL Strategic Research Programme "SERRP IV" (www.fehrl.org).	

Contributor(s)

Main Contributor(s)	Erik Vos, RWS, Netherlands Phone: +31 88 79 82 243, E-Mail: erik.vos@rws.nl Jacob Groenendijk, KOAC-NPC, Netherlands Phone: +31 88 562 2528, E-Mail: groenendijk@koac-npc.com
Contributor(s) **(alphabetical order)**	Minh-Tan Do, LCPC, France Phone: +33 2 40 84 57 95, E-Mail: minh-tan.do@lcpc.fr Peter Roe, TRL, UK Phone: +44 1344 770 286, E-Mail: proe@trl.co.uk

Review

Reviewer(s)	Marco Conter, arsenal research , Austria, Email: marco.conter@arsenal.ac.at Börge Wasser, BASt, Germany, Email: wasser@bast.de Manfred Haider, arsenal research , Austria, Email: manfred.haider@arsenal.ac.at

Control Sheet

Version History			
Version	Date	Editor	Summary of Modifications
0 (partial draft)	17 Oct 2008	Erik Vos / Jacob Groenendijk	Original partial draft
0.0 (draft)	3 Dec 2008	Erik Vos / Jacob Groenendijk	First partial draft for partner comment
0.1 (draft)	08 Jan 2009	Peter Roe	Revised Introduction section and new Background chapter added, with some consequential changes to other sections.
0.2 (draft)	12 Jan 2009	Erik Vos / Jacob Groenendijk	Additions to chapters 3 to 6. Reworking chapter 7 (discussion)
0.4 (draft)	23 Jan 2009	Erik Vos / Jacob Groenendijk	Comments from M-T Do and PG Roe incorporated. Summary by PG Roe added. Additions to chapters 3 to 6. Extended discussion Ch 7. Revised conclusions Ch 8. Chapters "reference device", "quality assurance" and "transitional use of local values" moved to Annexes
0.5 (draft)	5 Feb 2009	Erik Vos / Jacob Groenendijk	Comments from Arsenal, BASt, TRL and ZAG incorporated. Annexes, "quality assurance" and "transitional use of local values" deleted (to be dealt with in D09) With track traces relative to v0.4
1.0 (peer review)	6 Feb 2009	Erik Vos / Jacob Groenendijk	All tack traces accepted
1.1	19 Feb 2009	Erik Vos	Comments from peer review incorporated
1.2	24 Feb 2009	Peter Roe	Final English check
2.0	25 Feb2009	Manfred Haider	Release version

Final Version (2.0) released by		Circulated to	
Name	Date	Recipient	Date
Manfred Haider. Project Coordinator	2009/02/25	Coordinator	2009/02/25
		Consortium	2009/02/25
		European Commission	2009/02/25

Table of Contents

Abbreviations

Abbreviation	Meaning
	General
ABS	Antilock Braking System
BFC	Braking (force) Friction Coefficient (=LFC)
CV	Coefficient of Variation (see Annex G)
EFI	European Friction Index
IFI	International Friction Index (developed in the 1992 International PIARC Experiment to Compare and Harmonize Skid Resistance and Texture Measurements)
IRFI	International Runway Friction Index (developed in the American Joint Winter Runway Friction Measurement Program, described in ASTM E2100)
LFC	Longitudinal (force) Friction Coefficient (also known as BFC)
MPD	Mean Profile Depth (as defined in ISO 13473-1 and ISO 13473-2)
MTD	Mean Texture Depth (as measured by a volumetric method, such as EN 13036-1)
RMS	Root-Mean Square
SD	Standard Deviation (see Annex G)
SE	Standard Error (see Annex G)
SFC	Sideway (force) Friction Coefficient
SMTD	Sensor Measured Texture Depth
SRI	Skid Resistance Index (=EFI)
WP	(TYROSAFE) Work Package
	Organisations
ASTM	American Society for Testing and Materials
BASt	Bundesanstalt für Strassenwesen (DE)
BRITE	Basic Research in Industrial Technologies for Europe
CEN	European Committee for Standardization
COST	European Cooperation in Science and Technical research
DRI	Danish Road Institute
ESDU	Engineering Sciences Data Unit International plc (UK)

FAA	Federal Aviation Administration (USA)
FEHRL	Forum of European National Highway Research Laboratories
ICAO	International Civil Aviation Organisation
ISO	International Standards Organisation
LCPC	Laboratoire Central de Ponts et Chaussées (FR)
NASA	National Aeronautics and Space Administration (USA)
PIARC	Permanent International Association of Road Congresses
RWS	Rijkswaterstaat = Department of public works and infrastructure of Ministry of transport (NL)
TC	(CEN) Technical Committee
TRL	Transport Research Laboratory (UK)
WG	(CEN) Working Group
	Projects
HERMES	Harmonisation of European Routine and Research Measurement Equipment for Skid Resistance of Roads and Runways (FEHRL project)
JWRFMP	Joint Winter Runway Friction Measurement Program (led by Transport Canada and NASA)
SPENS	Sustainable Pavements for European New member States (FEHRL project)
VERT	Vehicle-road-tyre interaction: fully integrated physical model for handling behaviour in potentially dangerous situations (BRITE EURAM project)
	Friction measurement devices
ASFT	Airport Surface Friction Tester
BPT	British Pendulum Tester (BS 7976 or EN 13036-4), sometimes (but not in this report) also known as Skid Resistance Tester SRT
CTM	Circular Track Meter (USA, ASTM E2157) sometimes also called Circular Texture Meter
DFT	Dynamic Friction Tester (USA, ASTM E1911, originally from Japan)
IMAG	Instrument de Mesure Automatique de Glissance (FR)
IRV	International IRFI Reference Vehicle
PFT	Pavement Friction Tester (UK, TRL)
RoadSTAR	Road Surface Tester of Arsenal Research (AU)
ROAR	Road Analyser and Recorder of Norsemeter

SCRIM	Sideway-force Coefficient Routine Investigation Machine (UK)
SFT	Surface Friction Tester (also Saab Friction Tester, Sarsys Friction Tester, or Safegate Friction Tester, each possibly indicating different devices)
SKM	Seitenkraft-Messverfahren (DE)
SRM	Stuttgarter Reibungsmesser (DE)
SRT	Skid Resistance Tester, in this report referring to a Polish locked wheel tester, otherwise often referring to British Pendulum Tester BPT
TWO	Traction Watcher One (NO)
TRT	Tatra Runway Tester

Definitions

Term	**Definition**
Accuracy (of a measurement method)	A measure of the deviations of the measured values from the "true" value or any agreed reference value. These deviations are composed of a combination of random error (precision component) and a systematic error (trueness component). See ISO 3534-1, and "precision" and "trueness" in these definitions. Note: In the common British Language, accuracy often is considered to be the amount of decimal places (otherwise called "resolution") of a measurement result.
Adhesion	The transmission of forces by friction against tyre contact surfaces. Resulting from the interaction between tyres and pavement surface, adhesion is influenced by surface roughness, tyre characteristics, the nature and thickness of any intermediate medium such as water or mud, and speed.
Airfield operational testing	Measurement of the skid resistance of a surface on an airfield in response to an operational need and in whatever conditions exist at the time of the test, which may include contamination by ice, snow, slush or water.
Bound surface	Top layer or surface course of a road with the aggregates secured permanently in place
Braking force coefficient	Ratio between the longitudinal frictional force and the load on the test tyre, the test tyre mass and the rim mass. This coefficient is without dimension.
Calibration	Periodic adjustment of the offset, the gain and the linearity of the output of a measurement method so that all the calibrated devices of a particular type deliver the same value within a known and accepted range of uncertainty, when measuring under identical conditions within given boundaries or parameters.
Contact area	Overall area of the road surface instantaneously in contact with a tyre.
Device configuration	The combination of a friction measurement device (this need not be a particular specimen, but may be one of a group of nominally identical devices, possibly even from different manufacturers) with a type of test tyre, under specified conditions (at least covering yaw angle or slip ratio, test wheel load, inflation pressure, tyre tread depth where applicable, theoretical water film thickness). Test speed is not included in the device configuration.
Fixed slip	Condition in which a braking system forces the test wheel to roll at a fixed reduction of its operating speed.

Fixed-slip friction	Friction between a test tyre and a road surface when the wheel is controlled to move at a fixed proportion of its natural speed.
Friction	Resistance to relative motion between two bodies in contact. The frictional force is the force which acts tangentially in the contact area.
Harmonisation	Applied to several different measurement methods, harmonisation is "the adjustment of the outputs of different devices used for the measurement of a specific phenomenon so that all devices report the same value(s) (i.e. report in a common scale), except for some inaccuracy". This sense is mostly used in this report and in the referenced literature. Applied to European standards by CEN, "harmonised" standards for measurements are standard methods, which all European countries have agreed to use. In principle, CEN aims to get "one method for one property", which is referred to as "standardisation" in this report. Applied to the scope of TYROSAFE (which exceeds the scope of this report) regarding "harmonisation of European skid resistance approach", such harmonisation can achieved both through harmonisation of measurements (as defined in the first paragraph) or through standardisation of measurements (as referred to in the second paragraph and formulated elsewhere in the definitions).
Horizontal force (drag)	Horizontal force acting tangentially on the test wheel in line with the direction of travel.
Horizontal force (side force)	Horizontal force acting perpendicular to a freely-rotating, angled test wheel.
Longitudinal friction coefficient (LFC)	Ratio between horizontal force (drag) and vertical force (load) for a braked wheel in controlled conditions. This is normally a decimal number quoted to two significant figures.
Macrotexture	Deviation of a pavement from a true planar pavement with characteristic dimensions along the pavement of 0.5 mm to 50 mm, corresponding to texture wavelengths with one-third-octave bands including the range 0.63 mm to 50 mm centre wavelengths.
Mean profile depth	Descriptor of macrotexture, obtained from a texture profile measurement as defined in EN ISO 13473-1 and EN ISO 13473-2.
Megatexture	Roughness elements with a horizontal length of 50 to 500 mm. Roughness of this magnitude can influence accumulations of water on the pavement surface (for instance, in unevenness).
Microtexture	Deviation of a pavement from a true planar pavement with characteristic dimensions along the pavement of less than 0.5 mm, corresponding to texture wavelengths with one-third-octave bands and up to 0.5 mm centre wavelengths.

Nearside wheel path	Wheel path that is closest to the edge of the road in the normal direction of travel. For countries that normally drive on the right, this is the right-hand side and for countries that normally drive on the left, this is the left-hand side.
Operating speed	Speed at which the device traverses the test surface.
Pedestrian slip resistance	The property of the trafficked surface to maintain the adhesion of a pedestrian shoe sole.
Push mode	When the device is pushed by a pedestrian
Precision (of a measurement method)	The closeness of agreement between independent measurement results under stipulated conditions, e.g. repeatability or reproducibility conditions. See ISO 3534-1
Repeatability r	The maximum difference expected between two measurements made by the same machine, with the same tyre, operated by the same crew on the same section of road in a short space of time, with a probability of 95 %. (This equals 2.77 times the repeatability standard deviation: $r = 2.77 * \sigma_r$)
Reproducibility R	The maximum difference expected between two measurements made by different machines with different tyres using different crews on the same section of road in a short space of time, with a probability of 95 %. (This equals 2.77 times the reproducibility standard deviation: $R = 2.77 * \sigma_R$)
Routine testing	Measurement of the skid resistance of a surface in standardised test conditions, which normally include a defined water flow rate.
Sampling length/interval	The distance over which responses of the sensors are sampled to determine a single measurement of the recorded variables.
Side force coefficient (SFC)	Ratio between the vertical force (load) and horizontal force (side force) in controlled conditions. This is normally a decimal number quoted to two significant figures.
Skid resistance	Characterisation of the friction of a road surface when measured in accordance with a standardised method.
Slip angle	The angle between the mid-plane of the test tyre contact surface and the direction of travel.
Slip ratio	Slip speed divided by the operating speed.
Slip speed	Relative speed between the test tyre and the travelled surface in the contact area.
Subsection	Defined length of surface for which one set of the measured variables is reported by the device.
Standard	A measure of dispersion about a mean value, calculated as the square root of the squared sum of the difference of each measured friction

deviation	value (μ_i) relative to the arithmetic mean friction value (μ_{avg}), divided by the number of measurements (n) less one. Mathematically expressed as $StdDev = \sqrt{\frac{\sum_{i=1}^{n}(\mu_i - \mu_{avg})^2}{n-1}}$
Standard error	The standard deviation divided by the square root of the number of samples. Mathematically expressed as: $StdErr = \frac{StdDev}{\sqrt{n}}$
Standardisation	In this report: Defining one single measurement method (including the measurement device, its configuration, test procedures, test conditions, and data processing) to determine a certain property for a particular purpose, with exclusion of all other measurement methods for this property for the same purpose. More generally: Describing the devices and procedures (including the device configuration, test conditions, and data processing) of a measurement method in a formal document.
Test section	Length of road between defined points (e.g. location references, specific features, or measured distances) comprising a number of subsections over which a continuous sequence of measurements is made.
Theoretical water film thickness	Theoretical thickness of a water film deposited on the surface in front of the measuring tyre, assuming the surface has zero texture depth.
Tow mode	When the device is towed by a vehicle
Trueness (of a measurement method)	The closeness of agreement between the average value obtained from a large series of test results and an accepted reference value. See ISO 3534-1. Trueness is called "bias" in ASTM E177
Vertical force	Force applied by the wheel assembly (the static and dynamic force on the test tyre, the test tyre weight and the rim weight) on the contact area.
Water delivery system	System for depositing a given amount of water in front of the test tyre so that it then passes between the tyre and the surface being measured.
Water flow rate	Rate (litres/second) at which water is deposited on the surface to be measured in front of the test tyre.
Wet road skid resistance	Property of a trafficked surface that limits relative movement between the surface and the part of a vehicle tyre in contact with the surface, when lubricated with a film of water.
Wheel paths	Parts of the pavement surface where the majority of vehicle wheel passes are concentrated.

List of Figures

List of Tables

Executive Summary

It is widely accepted that poor skid resistance on road surfaces is related to an increased risk of accidents, especially in wet conditions. If a more consistent approach to skid resistance policies is to be encouraged across Europe, then greater consistency of measurement is also needed, which might be achieved by harmonising the various techniques currently used in different countries. Also, some form of harmonisation is needed to meet the requirements of CEN for future work on test methods for assessing road surfacing materials.

There has been a considerable amount of research into the possibilities for harmonising skid resistance measurements over the years and Task 2.1 of the TYROSAFE project has included a review of the state of the art. The review has focussed on work relating to measurements on roads but similar work for measuring friction characteristics on airfields has been included so that any cross-over of ideas could be taken into account.

The review has noted that there are various ways of approaching the problem. The concept of harmonisation has been described as "the definition of a common scale, against which measurements from different sources or standards based on different measurement types can be compared and understood" or "the adjustment of the outputs of different devices used for the measurement of a specific phenomenon so that all devices report the same value(s) (i.e. report in a common scale), except for some inaccuracy". However, it has also been recognised that if the inaccuracy, or imprecision, of a harmonised scale is too great for practical purposes (and what is acceptable may vary with different purposes), it may not be possible to harmonise measurements. Ultimately, standardisation might prove to be a better technical solution for a particular purpose. TYROSAFE aims at the definition of a "common scale" for skid resistance measurements, either through harmonisation or standardisation.

The main purposes for harmonised skid resistance measurements envisaged in this review have been either for acceptance of new road surfacings or for in-service network monitoring and maintenance planning. While formal harmonisation may not be necessary for measurements made for research, (including accident investigation), there is potential relevance to these fields also, since it is likely that researchers or accident investigators might wish to understand their data in the context of conditions on the wider road network. This review has concentrated on the harmonisation of measurements made in wet conditions: the frictional properties of roads affected by ice or snow or contaminants other than water are outside its scope.

The review considered a range of experimental studies into the problem of harmonisation, which has been addressed to various degrees for many years. The main effort over the last fifteen years or so has included three major studies, leading to proposals for harmonised indices: the PIARC International experiment which led to the IFI (International Friction Index); the HERMES experiment which assessed the proposed EFI (European Friction Index) and a study on airfields that led to the IRFI (International Runway Friction Index). There have also been numerous smaller exercises which have considered alternative approaches or attempted to test or validate these ideas in some specific situations.

Findings and lessons learned from IFI, EFI and IRFI

A major factor that influences skid resistance measurements is the speed at which the contact patch of the test wheel slides over the road surface during the test. The slip speed, as it is known, is influenced by both the design of the test equipment (which sets the “slip ratio” and how this is achieved) and the speed at which the device is driven over the road, the test speed. Generally, increasing the slip speed results in a reduction in the measured skid resistance but the extent to which this occurs depends not only on the slip ratio but also on characteristics of the road surface, in particular the surface texture depth, or macrotexture.

For obvious practical reasons, the test speed used to make measurements can vary in different circumstances. This leads immediately to a need to resolve differences in measurements from individual devices when they are operated at different road speeds but this is complicated further when different slip speeds that result from different operating principles are brought into consideration.

When comparing any two measurements with one another, it is important to have an independent reference or benchmark against which differences can be assessed. However, in the case of skid resistance there is no absolute measure of the property because skid resistance is the characterisation of the influence of the pavement on the complex phenomenon of pavement-tyre friction.

The main approaches to harmonisation reviewed here have therefore concentrated on resolving two issues:

- Establishing a reference value to represent the actual skid resistance of the road.
- Incorporating a method that takes account of the way in which device and road characteristics interact to bring about the changes in measured value with changing slip or test speed.

Both the PIARC and the HERMES experiments tackled these problems by:

- Using a "floating average of all devices willing to enter" to provide a reference level.
- Taking account of different slip ratios and operating speeds by adjusting the measurements to a common slip speed (60 km/h in the case of IFI, 30 km/h for EFI), using mathematical models that attempted to predict the effect of the road surface texture depth on the skid resistance measurement at different speeds for each device.

Although this worked to some extent, the harmonised skid resistance values had unsatisfactory reproducibility. Subsequent studies have suggested that, particularly when the range of variables is limited, reproducibility in practical applications may be better than was found in the original experiments (which had an extremely wide range of variables). However, the review indicates that neither the IFI nor the EFI are likely to be sufficiently reproducible for practical application as a common scale for Europe at their current state of development.

The IRFI study, with its particular focus on establishing friction conditions on runways, took a simplified approach, choosing one specific device and defining its results as providing the "reference" level and then using simple regression between the results of individual devices and the reference device. In the context of airfields, there is less need for different operating speeds to be used and so the IRFI makes no attempt to harmonise the effects of different operating speeds.

This probably explains in part why the IRFI has good precision, but this has also been aided by the fact that most skid resistance measurement devices for airfields operate on similar principles (mostly LFC, mostly around 15% slip ratio). The HERMES team also observed that precision could be improved by confining the harmonisation to a smaller set of devices with more similar operating conditions.

Another factor that the review has identified as key to the harmonisation process is the adequacy of the mathematical models used to represent the influence of road surface texture and slip speed or slip ratio on the measured values in combination with empirically-derived coefficients. It is clear that current models do not fully describe the behaviour of all types of device across their practical operating ranges: in particular, some influence of speed remains even after harmonised values have been calculated. The HERMES team were unable to arrive at a sufficiently improved model to accommodate the data that they had available, but improved understanding of the various devices might enable better approaches to be proposed.

There is also a clear issue of maintaining consistency between devices of nominally the same type, both within and across national boundaries. A first step to try and improve this situation has been made by the CEN Working Group (TC227/WG5), which has promoted the preparation of draft Technical Specifications for each of the main devices used in Europe.

The various studies reviewed have shown that the procedures to establish common scales can be followed in practice (and some detailed processes have been proposed). However, the imprecision of the harmonised scales and the complexity of maintaining the full range of different devices correctly calibrated against them are currently major barriers to their widespread use.

Aspects requiring further consideration to improve harmonisation.

The next stage of the TYROSAFE project is to prepare a "Road Map" setting out the possible options for moving forward to providing a harmonised approach to skid resistance measurements in Europe by 2020. It is not the place of this report to consider that, which will not only need to take a broad view of the findings of the present review but will also take account of other aspects of the project, including the review of device types (Deliverable D04) and options for reference surfaces (Deliverable D07). However, some areas for further consideration can be suggested.

1. The choice of reference level is clearly an area requiring further thought. In the absence of an absolute reference scale, then the options appear to be to
   1. Persist with the "average of all devices" approach, in which case improved quality control of individual devices will probably also be needed.
   2. Pursue the concept of defining an individual device (or device configuration) as the reference level, in which case either an existing device should be selected or a new device must be developed and evaluated (as was suggested as a possibility by the HERMES team) to fulfil this role.

   However, even if a reference device is established, that, too will require verification and so the further alternative of developing some kind of "absolute" reference through specially-designed surfaces (also being reviewed in TYROSAFE) also needs consideration.

2. Unsurprisingly, it would appear that the precision of current approaches to harmonisation could be improved by reducing the number of variables in the process. Further attention should be paid to the modelling process to establish whether it is realistically possible to harmonise the diverse range of principles to a common scale.

3. If developing better models were to prove too difficult, or can only be achieved over limited ranges of conditions, it may be necessary to consider making the process of harmonisation easier by deliberately reducing either the number of device configurations or the range of conditions, in particular the test speeds, over which harmonisation is attempted. In the case of test speeds, however, account will need to be taken of the real practical issues of different target test speeds being necessary (for safety reasons at least) on different types of road and the fact that it is rarely possible to maintain a constant speed in traffic anyway.

4. If a move towards a single European device configuration (i.e. full standardisation instead of harmonisation of existing devices) were to become a preferred approach, this would require consideration of its advantages and disadvantages. Examples of the latter are the costs in replacing existing fleets and revising current standards to align with the new measurements, the commercial interests of current device manufacturers, and a possible lack of political will to adopt a single device.

Conclusion

This review has found that there have been a number of attempts to establish methodologies and common scales to harmonise measurements from different skid resistance devices. Although some progress has been made, there is not yet a scale or system that can harmonise the range of devices currently used in Europe with sufficient precision to be of practical application with widespread acceptance. There is scope for further research into ways of improving the processes and these should be considered in the next stage of the TYROSAFE project preparing the "road map".

Given the complexity of the issue, it is advisable to keep all options open until the end of the project, Therefore it is proposed that a set of alternative “Road Maps”, should be developed, with some based on realising a "common scale" for skid resistance measurements through harmonisation and others following the standardisation approach.

Ultimately, it may prove best to adopt a single common device across Europe to provide standardised measurements for the main purposes of new surfacing acceptance and in-service network monitoring. However, there will still be a need for measurements using various techniques to assess specific aspects of the tyre/road friction phenomena and a means to interpret those in a wider context, so some form of harmonisation would still be of value.

1 Introduction

The safe passage of road traffic needs a certain amount of grip (friction) between the tyres of the vehicles and the road surface. The frictional forces are necessary for the vehicle to accelerate, decelerate or safely change direction. The level of frictional forces that can be built up depends on the properties of both the road surface and the tyres. Much research has shown that the limiting frictional forces for a given road surface and tyre combination depend on many factors, including tyre load, tyre tread compound and depth, road surface characteristics, the presence of water, ice or other contaminants in the tyre/road interface and vehicle speed (see Andresen & Wambold 1999, among others).

In order to characterise road surfaces with respect to friction, for decades many countries have derived their own test methods. These are, of necessity, very much simplified in order to assess specifically the condition of the road surface. They all measure in some way the frictional force developed between a moving tyre or slider and the road surface (which is usually wetted) and record the quotient of the measured force with the applied vertical load (a friction coefficient).

For each test method the effects of many of the potential influencing factors are controlled by standardising the measuring conditions. The standard conditions chosen reflect the practicalities of carrying out the particular test and are assumed to be relevant for characterizing the complex reality of friction in the tyre/road interface. Usually the measurement is called the “skid resistance” and is represented by a single value. Because the test methods and the chosen conditions vary, the actual numbers recorded can differ widely for the same road surface.

Several European countries have investigated the link between skid resistance level and accident rates. The result of this research is that with a sufficiently-high value of skid resistance the safety of roads can be improved by reducing the risk of skidding and hence the number or severity of accidents. Many European countries have developed their own skid policies for the road networks for which they are responsible. The approaches vary between countries but they often contain elements such as periodic routine monitoring of skid resistance of in service road and comparing the results with pre-determined values. In some countries the measurements are also used for comparison with acceptance levels for new works.

As has been explained, the available standardised test methods all simplify the reality of the complex friction process in the tyre/road interface during vehicle manoeuvres and they do that in different ways. Therefore, it should be no surprise that a direct comparison of skid values from country to country is not an easy task. Also the relevance of the different test methods with respect to safety will be different since the techniques and standardised test conditions reflect different aspects of the tyre/road friction mechanism. For example, at one extreme, some methods simulate conditions close to those experienced by a tyre braking under the control of an anti-lock braking system while, at the other, some devices use a skidding locked wheel.

Some individual countries set standards for skid resistance on their road networks (or parts of them) based on measurements with devices local (and often unique) to them. However, the absence of an accepted common scale for characterizing road surfaces with respect to skid resistance properties is a serious hindrance for developing consistent policies for skid resistance that would make the European road network safer.

The TYROSAFE Project is a Coordination and Support Action (CSA) in the Seventh EU Framework Programme. It aims at coordinating and preparing for European harmonisation of essential tyre/road interaction parameters, including the optimisation of their assessment and management, to increase safety and support the greening of European road transport.

This work is being carried out in the following six work packages (WP):

- WP1: Policies of EU countries for skid resistance / rolling resistance / noise emissions;
- WP2: Harmonisation of skid-resistance test methods and choice of reference; surfaces
- WP3: Road surfaces properties – skid resistance / rolling resistance / noise emissions;
- WP4: Environmental effects and impact of climatic change – skid resistance / rolling resistance / noise emissions;
- WP5: Dissemination and raising awareness;
- WP6: Management.

The objective of Work Package 2 of TYROSAFE is to arrive at a widely-supported road map towards future skid-resistance harmonisation policy by 2020, including aspects such as testing equipment, quality assurance and implementation strategy. The major field of application in mind is for monitoring the skid resistance quality of the European road network and for new work acceptance control.

Basically, the lines being followed are those formulated in 2005 by the CEN working group on Surface Characteristics (CEN/TC227 WG5), to prepare in the longer term (over 10 years) “a harmonised standard based on the measurement of a friction index with a common and single European friction measuring equipment”. The harmonisation process is illustrated in Figure 1.1, along with actions to be carried out in WP2 of TYROSAFE.

To reach its objective, WP2 is split into four Tasks:

- In Task 2.1 knowledge of current national skid resistance test methods will be collated, together with findings of previous harmonisation research projects, which will be collected and analysed. Based on the outcomes of these exercises, proposals will be formulated for possible options for the specification of a Standard European Skid Resistance Device (SESRD).
- In Task 2.2 the focus will be on the use and harmonisation of reference surfaces in the Quality Assurance part of the harmonisation policy as was suggested by the HERMES project.

- In Task 2.3, based on the results of Task 2.1 and 2.2, a road map or implementation plan will be developed to point the way towards a harmonised approach to wet skid resistance test methods by 2020. Special attention will be paid to intermediate stages (2010, 2015) to allow for the need for individual countries to make a smooth transition to the new approach. The focus in this transition period will be to maintain consistency with existing historical data and to maximize the possible use of the present fleet of testing devices until the end of their technical working lives. This Task will also initiate promoting activities for finding a number of pilot countries for early implementation in their national monitoring programmes.
- To obtain constructive input from stakeholders and experts and to mobilize support for the road map/implementation plan, several workshops will be organised in Task 2.4.

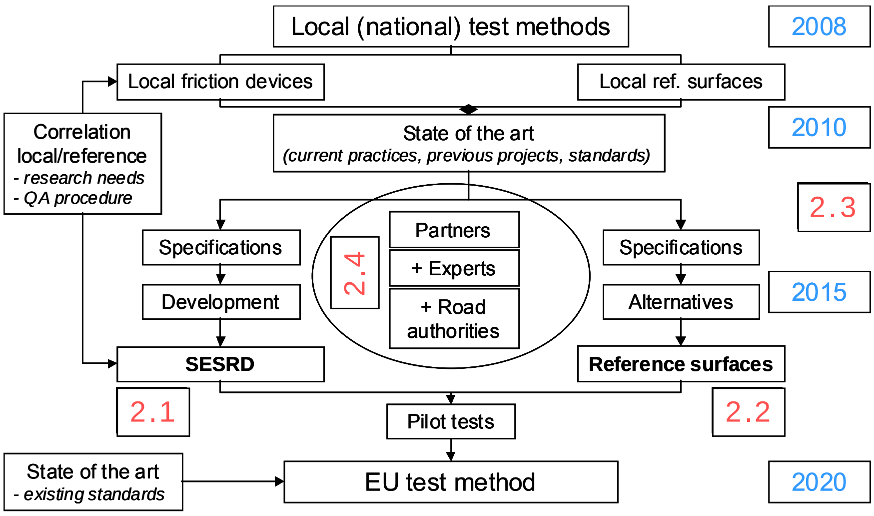


Figure 1.1 Harmonisation scheme and actions carried out in WP 2

Table 1.1 gives an overview of the major outcomes planned for the individual Tasks of WP 2.

Table 1.1 Overview of the major outcomes of the individual Tasks of WP 2

Task	Deliverable	Name
2.1	D04	Report on state-of-the-art test methods
2.1	D05	Report on analysis and findings of previous skid resistance harmonisation research projects
2.2	D07	Report on state-of-the-art of test surfaces for skid resistance
2.3	D09	Road map and implementation plan to future harmonised test methods and reference surfaces
2.4	-	Two dedicated workshops

This report is part of Task 2.1 and constitutes the deliverable D05. Its main purpose is to carry out a review and analysis of previous attempts at harmonisation of test methods and to assess the lessons learned. The outcomes of this part of the study, in conjunction with deliverables D04 and D07 will then feed into the next stage of the project to develop a road map for future harmonisation.

Chapter 2 of the report provides some background, explaining the main issues involved in the harmonisation of skid resistance measurements, together with a summary of the history of work in this field. Chapters 3 to 5 then describe in more detail the main experimental work that is of significance today. Chapter 6 describes work that has been carried out attempting to put some of the main principles into practice. Chapter 7 provides a full discussion of the issues raised and lessons learnt overall and their implications for future harmonisation. The final chapter makes some recommendations for further consideration and discussion as part of the TYROSAFE project road map review.

2 Background

Skid resistance has been described as the contribution that the road surface makes to road/tyre friction. It is normally measured using some kind of friction measurement technique, hence the definition used by CEN TC227 Working Group 5 (see table of definitions above): "characterisation of the friction of a road surface when measured in accordance with a standardised method". However, a great many factors influence skid resistance (Figure 2.1) and the ways in which these are standardised for any particular measurement device or measurement type have a significant effect on the levels and precision of any measurements that are made.

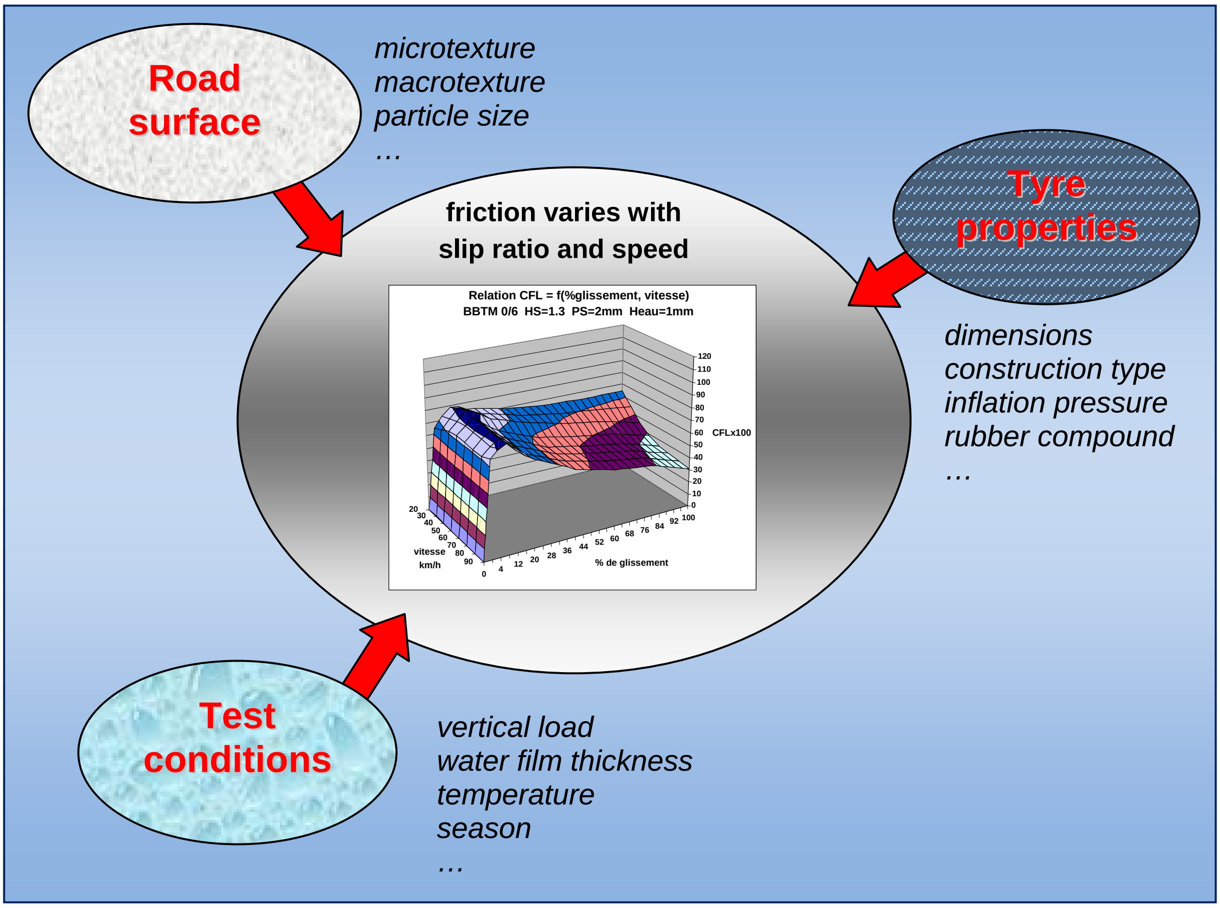


Figure 2.1 Many factors interact to influence skid resistance measurements

As explained in more detail in the companion report, TYROSAFE Deliverable D04 "Report on state-of-the-art of test methods", skid resistance test equipment typically utilises one of three basic principles:

- Measure longitudinal friction (using a measurement wheel that is forced to rotate more slowly than the vehicle speed requires, so it slips or skids over the surface).
- Measure transverse friction (using a measurement wheel that can rotate freely but is set at an angle to the direction of the test vehicle, so that it slips over the surface).

- Use a slider mechanism (in which a pendulum arm with a rubber pad attached, or a rotating head with a number of rubber feet attached slows down as it passes over the surface).

Task 2.1 of the TYROSAFE project has found that, currently, at least 24 different devices are in use across Europe to measure skid resistance for various purposes. All three of the basic principles are represented but the ways in which these principles are implemented differs from one device to another (some devices can use combinations of them). There is also a wide range of specific test conditions, such as test speed and test tyre properties (for vehicle methods), and different approaches are taken to processing the recorded data for different uses.

Consequently, there is considerable variety in the measures of skid resistance used and interpretation of them in order to understand their potential relevance outside their specific context can be very difficult or even impossible. This is a serious hindrance for developing consistent policies for skid resistance that would make the European road network safer. The challenge of Work Package 2 of TYROSAFE is to find a solution for this by developing a road map towards future skid-resistance harmonisation policy by 2020.

In the remainder of this chapter, the concept of harmonisation is introduced, and a short history of experiments is offered to set a context for the review that follows in subsequent chapters.

2.1 What is harmonisation and who can benefit?

It is important to emphasise at the outset that *harmonisation* is not *standardisation*. Harmonisation of skid resistance measurements does not mean making all standards and thresholds the same for all roads in all countries, although in the longer term it might prove worthwhile to encourage a more consistent approach across borders at least on the main trans-European routes. Rather, harmonisation provides a way of making comparisons between the different approaches used in different countries or between different measurement techniques in a consistent manner.

Harmonisation of measurements has been described as "the adjustment of the outputs of different devices used for the measurement of a specific phenomenon so that all devices report the same value" (ASTM E2100). The concept of harmonisation of skid resistance measurements as discussed in this report, therefore, can be simply explained as the definition of a common scale, against which measurements from different sources or standards based on different measurement types can be compared and understood.

However, in practice "the same value" on a harmonised scale will always be subject to a certain amount of inaccuracy. If this is too great for practical purposes (and what is acceptable in terms of accuracy may vary with different purposes), it may not be possible to harmonise measurements for a particular purpose. In that case a better technical solution might be to use a common test method. As will be seen, accuracy (particularly precision) has proved to be an important issue in relation to the previous attempts at skid resistance measurement harmonisation that this report reviews.

In considering those who might have an interest in harmonisation, three broad groups have been identified:

a) *Countries (or different road authorities within individual countries) who already have a policy and monitor skid resistance in some way*. These may have large fleets of similar devices or sets of different devices and so harmonisation is important in the process of accreditation of monitoring equipment, understanding measurements made by different devices on different networks and for comparing measurements made for different purposes.
b) *Countries that do not have a policy at present and may have no background in measuring skid resistance*. These are likely to want to know how they can make measurements (perhaps by hiring in services from a neighbour); they will need to understand how whatever threshold values they might choose compare with experience elsewhere, especially if they want to draw on experience in a similar country to choose those thresholds.
c) *Organisations that make measurements and wish to ply for trade across borders*. These (and those considering buying the service) need to understand how the measurements that they will obtain are likely to compare with the thresholds and measurement practice that they are used to.

It is recognised that that there will always be some situations where a specific measurement technique has a particular application and that direct comparison with a different technique may not be practicable or appropriate. However, if greater consistency is to be encouraged, then some form of harmonisation is needed.

2.2 Factors to be considered in harmonisation

As illustrated in Figure 2.1, a great many factors influence skid resistance and its measurement and although these can be standardised reasonably well for any specific measurement device, the different levels chosen for any particular parameter or the response of the particular device to specific conditions can have a marked effect on the results that it gives.

We have seen that all current measurement techniques are based on measuring in some way the friction developed between a rubber surface (a tyre or a slider) moving across a wetted road surface. (Non-contact methods that attempt to measure the microtexture properties of the surface itself and hence predict skid resistance are still in their infancy and are beyond the scope of the TYROSAFE project.)

The main difficulty with harmonisation is to find a way to take account of the interactions between the factors that have the greatest effect on the measured friction in order to arrive at a common scale. Key factors include:

- *The slip ratio of the device for wheel-based systems.* This influences the speed at which the test tyre slides over the surface (the slip speed).
- *The test speed*. This acts in combination with the slip ratio to affect slip speed.
- *The difference between longitudinal and sideways-force friction coefficient.* This difference is often addressed by converting yaw angle to slip ratio, but this possibly does not eliminate all differences.
- *The properties of the test tyre (tyre size, load and pressure, tread pattern, rubber properties).* These have a direct impact both on the level of friction recorded and the way in which the tyre responds to changes in other factors.
- *The properties of the road surface itself.* These, particularly macrotexture (both in terms of texture depth and form), influence both the friction levels and the way in which friction changes with speed.

The concept of providing a common scale on which different techniques can be compared is greatest challenge to harmonisation. For values to be considered harmonised, it must be possible to make a measurement with one device under one set of test conditions and to calculate a value on the common scale that can be replicated by other devices measuring on the same surface under their own, different, test conditions.

There are two issues to be resolved. The first of these is the setting of a reference level for the skid resistance that can be used to calibrate individual devices to the common scale. Here, there is a major difficulty because there are no absolute levels of friction against which devices may be compared. The idea of providing such levels by means of reference surfaces that can be made repeatably to have and maintain predictable known properties is also being addressed by the TYROSAFE project but, as yet, such surfaces do not exist. Therefore, other options must be considered and these are essentially two:

3. Use the “average” result from all devices as a reference level.
4. Use the result from a single “reference device” as a reference level.

All harmonisation attempts to date have been based on one of these, with the major efforts being towards the former of the two. This approach has the advantage of not being linked directly to any particular current device and therefore is potentially easier to move forward, especially for countries with well-established policies and equipment.

The second issue to be resolved is that of the major physical factor, the way in which the measured value changes with the test speed and how that change is influenced by the road surface macrotexure. On any one surface, this varies from device to device as a result of their different characteristics. For instance, measurements with a device that operates with its test wheel locked respond to speed markedly differently to one that operates with only a small amount of slip on a different part of the slip versus speed curve. It may also be that the nature of the response varies from one type of surface to another as well as varying with the magnitude of the macrotexture.

Another major factor influencing all aspects of harmonisation is that of accuracy (trueness and precision), both in the basic measurements themselves and in any common scale.

Repeatability and reproducibility must be properly understood so that they can be taken into account in any standards or procedures and the setting of thresholds that will use the data. Annex G gives an overview of matters pertaining to accuracy.

It is inevitable that, because it involves adjusting actual measurements to match a common scale, the precision of values on such a scale will be less than might be achievable with a single device. Nevertheless this need not be a bar to adopting a harmonised approach provided that the precision can be established at practically acceptable levels for the purpose for which the measurements are to be used.

These issues will be discussed in more detail in the following chapters in relation to the various experiments and in the discussion in Chapter 7.

2.3 A short history of harmonisation attempts

Road research organisations, such as the Road Research Laboratory (now TRL) in the United Kingdom, began to develop different methods for measuring skid resistance in particular, and road/tyre friction more generally, in the period between the two World Wars. From the late 1940s interest in these techniques spread and more types of device were developed in more countries, albeit using one of the three basic measurement principles.

However, for the most part, the measurement systems were confined to research use and often existed as individual examples. Researchers who used more than one system recognised that the different techniques gave different results and did not generally use them interchangeably.

As the measurement techniques developed, and small fleets of similar machines began to emerge, variation in the measurements became more noticeable and strategies for dealing with these situations began to be developed in some individual countries. These mainly addressed the issue of precision (repeatability and reproducibility) within fleets of similar devices rather than comparisons between different devices. Such comparisons were largely confined to localised empirical correlations of one device to another.

However, serious international attempts at harmonisation of road skid resistance measurement devices and measurement conditions were not made until the early 1990s, when a large experiment was carried out under the auspices of PIARC (the World Road Association). The PIARC experiment brought together a wide range of devices from different countries for comparison for the first time and introduced the concept of a common, harmonised, scale that became known as the International Friction Index (IFI).

The PIARC exercise was followed by a number of smaller experimental programmes, in which application of the principles of the IFI were evaluated by individual countries, especially those that were considering what their approach to skid resistance measurement should be. The 1990s also saw the beginning of a series of regular exercises in the USA to compare different types of equipment used for monitoring the friction characteristics of airfield runways which led on to a winter measurement programme and the development of an International Runway Friction Index (IRFI).

Meanwhile, in Europe, the European Committee for Standardisation (CEN) had set up Working Groups to pursue the development of harmonised European Standards for use across the European Union. A key requirement of CEN was that only one test method should be used as the harmonised standard test for any one property. This created a significant problem for the CEN Task Groups that were charged with developing such standards for road surfacing materials. In measuring skid resistance they were faced with a complex physical property (which was really an inter-related group of properties) with a wide range of test methods that all gave different answers. Because their use was well established in their parent countries the different tests could not be easily harmonised by the approach used elsewhere, in which one method was identified from those available (often after considerable negotiations) and making that the harmonised standard technique.

In response to this difficulty, the committee responsible for the skid resistance standard (CEN/TC227/WG5) developed an idea that had been suggested by research carried out in Belgium as one of the follow-on exercises from the IFI work (Descornet, 1998) and proposed a “Skid Resistance Index” (SRI, but more commonly known as the European Friction Index, or EFI). This would be a common scale derived from the IFI but specifically designed for those skid resistance measurement devices regularly used in Europe. Only devices that had been calibrated to the new scale (through rather complex processes in which individual “reference” devices could be calibrated to the new scale and in which national fleets could be calibrated to them) would be able to report the new SRI or EFI values.

The procedure was written down as an Appendix to a draft standard, prEN 13036-2:2003. However, it had not been verified that such an approach would work in practice so, in order to test the first stage of the calibration process, a major pre-normative experiment was organised through FEHRL (Forum of European national Highway Research Laboratories). This exercise, known as HERMES (Harmonisation of European Routine and research Measurement Equipment for Skid resistance of roads and runways), was carried out in the early 2000s. The main aims of the project were to check that the proposed calibration procedure was workable, to assess the precision of the new scale, to verify that the index remained stable over time and if necessary to refine the mathematical models and measurement procedures in the light of the practical experience of using them. The project also considered alternative approaches to the draft calibration procedure, in particular through defining a specification for a new single reference device or the use of reference friction surfaces that would reduce the need for a complex pattern of multiple-device calibration meetings.

The HERMES experiment (see section 4 below for a more-detailed description and analysis) was only partially successful and although further studies have looked at some aspects of the work, it has still not proved possible to develop a reliable way of harmonising skid resistance measurements with sufficient precision to be of practical application.

In 2005 the CEN TC227 Working Group 5 discussed, based on the findings of the HERMES experiment, their view on the harmonisation strategy of skid resistance and defined the following three step strategy (see also Annex B):

- For the short term it was suggested that a set of Technical Specifications for the measuring devices in use in Europe should be developed.
- For the medium term (3-5 year) it was suggested that a draft of a harmonised Standard should be prepared that would be based on the measurement of a "new" EFI, defined according to the calibration of data provided by the existing equipment in service in Europe against an elected reference device and reference surfaces.
- For the longer term (over 10 years) it was suggested draft of a harmonised Standard should be prepared for the measurement of a friction index with a common and single European measuring device, which has yet to be defined and designed.

To realise this strategy the CEN TC227 Working Group asked FEHRL to make initiatives to conduct a new pre-normative research project. The TYROSAFE project is designed in part to assist in moving this strategy forward.

Table 2.1 below provides a summary of the history of the various trials and experiments that have been made in the field of harmonisation of skid resistance measurement techniques. The more significant of these are described and analysed in greater detail in Chapters 3, 4 and 5 (which deal with the main harmonisation experiments) and Chapter 6, which covers a range of other investigations. Table 2.1 also refers to some smaller comparison exercises in some countries which are less relevant to the harmonisation topic and therefore are not discussed in any greater detail this report.

Table 2.1 Summary of historical development of skid resistance harmonisation

Date/ period	Country	Commentary
1970s	UK	Parallel measurements with new SCRIMs and older side-force skid cars previously used to measure sideway-force coefficient (SFC) found that SCRIM gave systematically higher values than the earlier systems. This led to the introduction of the “Index of SFC” value in the UK to harmonise SCRIM Coefficients with older measures of SFC.
1980s	UK	Voluntary comparative trials with UK SCRIM fleet begun, to harmonise the machines used on the UK network. Basic requirement for all machines to record very similar values but no formal or published definition of what is acceptable.
1980s	Netherlands	Introduction of regular comparison exercises for Dutch friction trailers (and, later, ROAR)
1983	Sweden	Comparisons between Stradograf (a side-force device in service in Denmark at that time) with other devices used in Sweden and Finland
1988	UK	Introduction of Skid Resistance Standards for in-service trunk roads. Successful attendance at annual SCRIM comparison exercise becomes compulsory.
1992	Many countries involved	**The PIARC International Harmonisation Experiment.** Wide range of devices to measure skid resistance and texture depth are brought together for measurements in Belgium and Spain. Used a series of “golden curves” to take account of speed variation and texture depth, developed into the IFI.
1992-1993	UK	GripTester Mk1/SCRIM precision tests and comparison exercises
1993 onwards	USA	Annual NASA Tire/Runway Friction workshop (application of IFI)
1997 onwards	UK	Annual SCRIM correlation exercise becomes standardised with statistically-defined and published acceptance criteria. Based on the principle that reproducibility is controlled to the lowest practical value consistent with the skid resistance standards so that all machines could be assumed to measure the same, with only small random variations.
1996-1999	Many countries	Joint Winter Runway Friction Measurement Program (JWRFMP), resulting in IRFI
1997	Netherlands	Trial application of IFI to harmonise different measurement speeds
1997	Denmark	Comparisons of Stradograf, ROAR and GripTester using IFI principles
1999	Denmark	Direct Comparisons of Stradograf and ROAR
1998	France	Demonstration of IFI application to harmonise SCRIM and Adhera (the latter at different speeds)

Date/ period	Country	Commentary
Mid-1990s	Belgium	Initial study of reduced set of European devices to improve IFI precision (led directly into HERMES study)
1998	Denmark, Germany, Netherlands	Trial application of IFI principles (but with 30 km/h reference speed, not 60) to six different devices
2001-2002	Various European countries involved	**The FEHRL HERMES project**, with measurements in Belgium, France, the Netherlands, Spain and the UK – assessing the proposed calibration process and stability of the EFI. Resulted in revisions to the EFI models and proposals for a “Reference Device” as an alternative reference level in stead of a pooled average.
2001 onwards	New Zealand and UK	SCRIMs for work in New Zealand cross-checked annually for consistency with UK fleet. Individual checks also made in the UK on SCRIMs used in Slovenia and France.
2003	Austria	RoadSTAR developed, implementing the HERMES reference device proposals. Some tests to check whether assumptions about controlled slip speed are valid.
~2005	Germany	Development of comparison system for German side force machines (SKM) based on a “golden” reference device of the same type.
2002-2008	Netherlands	Dutch studies for airfield measurement using the ESDU model.
2004-2007	UK	Comparative studies at TRL to assess: • applicability of EFI to UK skid-resistance standards • EFI second and third stage calibration methodology • use of “old” EFI to harmonise UK devices.
2005	UK	Further GripTester/SCRIM comparisons using MkII GripTester
2005	Australia	Desk-study evaluation of suitability of IFI for use in Australia. However, limited by basing results on PIARC 2006 values for calibration coefficients with no direct link to devices used in Australia or New Zealand.
2005-2008	Chile	Harmonisation studies for SCRIM and GripTester for use on Chile main road network.
2008	USA	Evaluation of the IFI coefficients for five devices on 24 pavement test sections on Virginia smart road
2008	Austria, Chech rep. Hungary Norway, Poland, Slovenia, Slowakia	SPENS project for harmonisation of measurement devices for skid resistance (besides unevenness and bearing capacity) in European new member states

3 The 1992 PIARC International Experiment

3.1 The main experiment

In 1992, PIARC conducted the International Experiment to Compare and Harmonize Skid Resistance and Texture Measurements (Wambold et al 1995, Henry 1996). This included comparative measurements of 37 friction measuring devices and 14 macrotexture measuring devices on 26 sites in Spain and 28 sites in Belgium. Annex A contains tables listing the participating devices. Sites were selected to encompass all combinations of high and low values of microtexture, macrotexture, polishing and wear.

The PIARC experiment resulted in the development of the International Friction Index (IFI) as a common scale for reporting friction values. The IFI consists of two parameters: F60 and Sp. F60 is a measure of the friction at a slip speed of 60 km/h, and Sp is a texture-dependent measure of the (slip) speed influence on friction, see 3.1.1. The IFI is standardised as ASTM E1960, see section 3.2.

3.1.1 Definitions and formulae

The IFI is based on the following formulae:

$$F60 = A + B * FR60 + C * MPD = A + B * FRS * e^{(S - SR) / Sp} + C * MPD$$

$$Sp = a + b*MPD$$

where:

- F60 is the device estimate of the "true" friction index or "Golden Value" GF60 of a specific surface,
  where GF60 is the "grand average" of all device estimates F60 for that surface.
- A, B and C are device-specific parameters (where C=0 for smooth tyres).
- FR60 is the slip-speed corrected estimate for the device specific friction coefficient at a slip speed of 60 km/h.
- FRS is the measured friction coefficient at slip speed S.
- S is the slip speed between tyre and road surface in km/h and
  S =τ *V for the LFC measurement principle;
  S =V *sin(α) for the SFC measurement principle
  where: V is the operating speed of the vehicle in km/h
  τ is the slip ratio and
  α is the yaw angle of the test wheel.
- S_R is a reference slip speed set to 60 km/h.
- Sp is a speed parameter in km/h related to the tested surface characteristics.
- MPD is the Mean Profile Depth in mm as defined by ISO 13473-1.
- a & b are constants.

The calculation of the IFI is illustrated in Figure 3.1. The measured friction value FRS is specific for the device, its slip ratio and its operating speed: in this example a BV11 with 17% slip ratio at 70 km/h. First, the measured value FRS is transformed to (an estimate of) the device-specific friction value FR60 at the standard slip speed of 60 km/h. This is done using the exponential term $e^{(S\ -SR)/Sp}$, where Sp is dependent on the macrotexture. Then, the device-specific value FR60 is converted to the device-independent (at least that is the aim of this conversion) F60, which is the estimate of the "true" or "golden" friction value for the measured pavement. This conversion uses the device-specific parameters A, B and C. Note that these parameters may differ slightly between several specimens of the same device type.

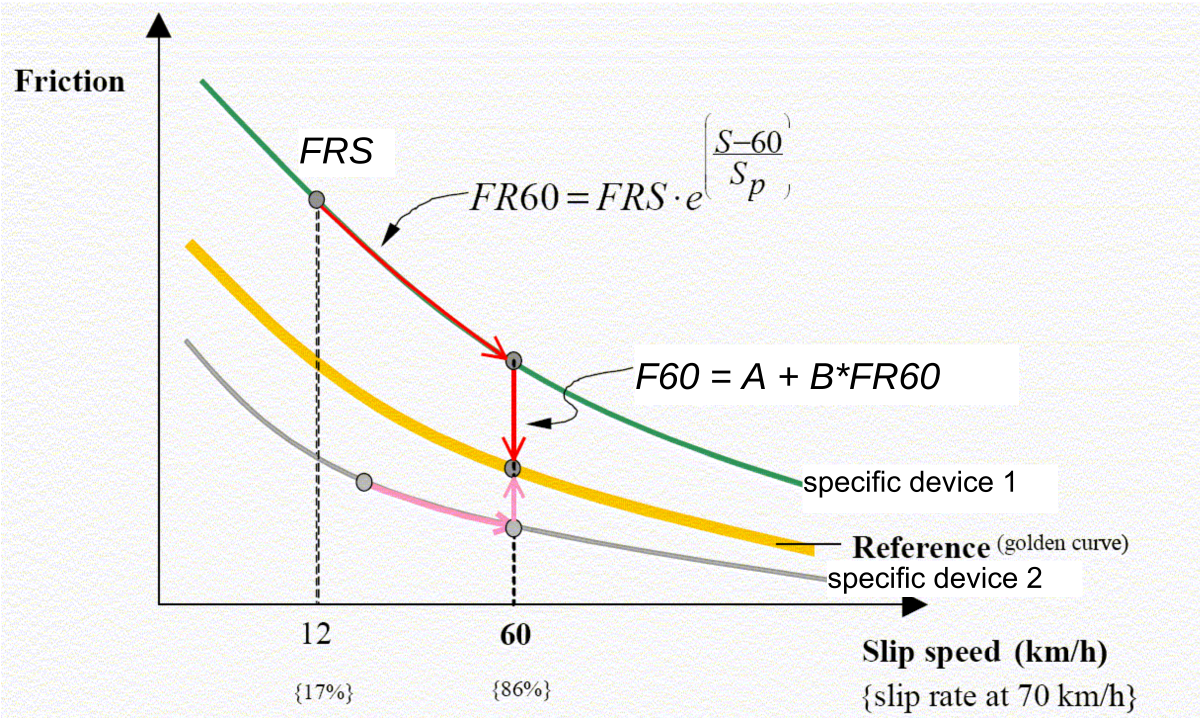


Figure 3.1 Demonstration of the calculation of the International Friction Index (adapted from Wallman & Åström 2001)

The reference slip speed of 60 km/h was probably chosen because it corresponded to locked wheel measurements at an operating speed of 60 km/h, which is standardised in ASTM E274 and mostly used in the USA.

3.1.2 Accuracy

Repeatability of the friction measuring devices was assessed in the PIARC experiment. The results are shown in Table 3.1. This table shows a grand average repeatability standard deviation of about 0.03, resulting in an average repeatability of about 0.08.

Table 3.1 Average (over a group of devices) repeatability standard deviation in the PIARC experiment (in various friction units) (after Wambold et al, 1995)

	Side force	Fixed slip	Locked wheel
Low speed	0.034	0.033	0.028
Medium speed	0.029	0.032	0.024
High speed	0.028	0.031	0.027
Low friction	0.027	0.023	0.015
Medium friction	0.031	0.031	0.023
High friction	0.028	0.026	0.029

PIARC also reported the average correlation coefficients (NB: R, not R^2) of the simple device-to-device linear regressions for the friction devices, shown in Table 3.2.

Table 3.2 Average correlation coefficients (NB: R, not R^2) of device-to-device linear regressions for the friction devices (after Wambold et al, 1995)

Device type group	Side force	Fixed slip	Locked wheel	Pendulum
Side force	0.863	0.819	0.795	0.665
Fixed slip	0.819	0.834	0.783	0.732
Locked wheel	0.795	0.783	0.843	0.670
Pendulum	0.665	0.732	0.670	0.830

This shows a fair correlation within each device category (R>0.83, i.e $R^2>0.69$), slightly lesser correlation between the different high-speed categories (R>0.78, i.e $R^2>0.61$) and poorest correlation of the low-speed pendulum with the high-speed categories (R>0.67, i.e. $R^2>0.45$)

PIARC also reported the error of the predicted F60, relative to the Golden Value Friction Number GF60, compared with "the error in the ability of a device to predict the Golden Value at the slip speed of the device", as shown in Table 3.3.

Table 3.3 Accuracy of PIARC model (Wambold et al, 1995)

	Side force	Fixed slip	Locked wheel	Pendulum
Absolute error "Before" [1]	0.065	0.076	0.065	0.086
Absolute error "After" [2]	0.028	0.032	0.030	0.037
Correlation coefficient "Before"	0.81	0.81	0.78	0.65
Correlation coefficient "After"	0.94	0.92	0.93	0.89

[1] Understood by the authors of this report as the average (over a group of devices, and over all surfaces and speeds) of the absolute difference between FRS and GF60

[2] Understood by the authors of this report as the average (over a group of devices, and over all surfaces and speeds) of the absolute difference between F60 and GF60

However, other values have been reported regarding the precision of the PIARC experiment (Wambold, 2005), summarised in Table 3.4. The authors of the present report do not know the reason for the differences between Table 3.3 and Table 3.4.

Table 3.4 Accuracy of PIARC model (Wambold, 2005)

	Side force	Fixed slip	Locked wheel
Absolute average difference	0.030	0.030	0.026
Correlation coefficient R	0.928	0.915	0.944
Standard deviation SD	0.023	0.025	0.021

The authors of this TYROSAFE report do not know exactly how the average absolute error, as reported in the PIARC report, relates to the "reproducibility standard deviation" according to ISO 5725. If this average absolute error is roughly equal to the reproducibility standard deviation, this would mean that the reproducibility is about 0.08, in IFI units. On the other hand, the values given in Table 3.4 seem to suggest a reproducibility standard deviation of about 0.023, giving a reproducibility of 0.07 (in IFI units).

At first glance, this would seem to indicate that the reproducibility (i.e. precision over all devices and all speeds) is equal to (or even better than) the repeatability (i.e. precision per device and speed). This, in turn, would mean that no precision would be lost at all in the process of conversion from values from the single devices at separate speeds to the grand total of all devices, with values at several speeds converted to a reference slip speed. This seems highly unlikely. It possible that the reported values should not be interpreted in the way that has been followed here but more complicated statistical conversions would be necessary to explore this.

It should be noted however, that repeatability and reproducibility are not expressed here in the same units. Reproducibility is expressed in IFI units, whereas repeatability is expressed in various friction units, i.e. in units reported by different devices, with different configurations and measurement conditions, hence measuring different values (and variations thereof), for the same pavement. It seems probable that the range of the final IFI values is much smaller than the range of the original friction values. This means that a 0.03 standard deviation in IFI (related to the total range of IFI values) is relatively much larger than a 0.03 standard deviation in friction values (related to the total range of friction values).

3.1.3 Conclusions and lessons learnt

MPD was chosen as the characterisation for macrotexture, as this parameter had best reproducibility of all participating devices.

PIARC (Wambold et al, 1995) concluded "that IFI can be reported with acceptably small error (typically within ±0.03 friction number)". However, the value reported was the average absolute error being about 0.03, and some doubt exists about the interpretation of this value.

3.2 ASTM E1960 (standardising IFI)

ASTM have standardised the calculation of the International Friction Index IFI in standard E1960, first released in 1998 but with later revisions in 2003 and 2007. For this TYROSAFE review, only the 2003 and 2007 editions were studied.

ASTM E1960 follows most of the ideas from the PIARC experiment (Wambold et al. 1995) but deviates in some significant aspects:

- E1960 uses the Dynamic Friction Tester (DFT) at 20 km/h (as per ASTM E1911) as a reference rather than the average of a group of devices.
- E1960 refers to ASTM E1845 for the measurement of Mean Profile Depth, not to ISO 13473-1, or to one of the many other texture parameters considered by PIARC.
- E1960 uses fixed parameters in the formulae for Sp and F60:

  Sp = 14.2 + 89.7 * MPD

  F60 = 0.081 + 0.732 * DFT_{20} * exp (-40/Sp).
- E1960 uses only the A and B parameters in the calibration of a device to the reference, not the C-parameter in the PIARC IFI-formula:

  F60 = A + B * FR60.

The choice of the DFT as the reference is debatable, as it has the handicap of measuring only a small circular track on the pavement, whereas most routine measuring devices measure a continuous track along the road. Besides, although the DFT measures dynamic friction, in use it is stationary on the road and must be placed in position, requiring temporary closure to traffic.

The fixed parameters in the formula Sp = 14.2 + 89.7 * MPD correspond to only one of five parameter sets reported by PIARC (Wambold et al. 1995) for five different devices, all measuring MPD but all yielding significantly different parameter sets for a and b (and significantly different correlation coefficients R, ranging from 0.956 to 0.714). The parameter set chosen was valid only for the Swedish VTI mobile profilometer, so its general use here does not seem to be correct. The fixed parameters in the formula for F60 correspond to the values found in the PIARC experiment for the DFT at 20 km/h.

The omission of the C parameter in the calibration formula corresponds to the original PIARC experiment only for smooth tyres. This limitation is not applied in ASTM E1960, however. ASTM E1960 requires that calibration of devices is done on at least 10 pavements, covering the whole range of $0.25 < MPD < 1.5$ and $0.30 < DFT_{20} < 0.90$.

ASTM E1960 states that the reproducibility of texture profiling systems was found in the PIARC experiment to be 0.15 mm, corresponding to 10% of the average MPD values included in the experiment. E1960 also states that *"the reproducibility of the friction devices varied, but was generally within 0.03. However, at low friction values 0.02 should be obtained."* This is not correct, however, because, as already explained in section 3.1.3; PIARC (Wambold et al. 1995) reported the average absolute error being about 0.03, not the reproducibility.

4 The FEHRL HERMES project

4.1 The main study

As explained in 2.3, HERMES - “Harmonisation of European Routine and Research Measurement Equipment for Skid Resistance of Roads and Runways” was a co-operative pre-normative research study conducted by FEHRL (Descornet 2004a, Descornet et al 2006). It aimed at harmonising skid resistance measurement methods at a European level. One of its main tasks was to investigate the reliability and feasibility of using the draft standard prEN 13036-2:2003 proposed by CEN that defines a common scale for a tyre/road friction coefficient and specifies the procedure for calibrating measuring devices based on that scale. This common scale was termed SRI - Skid Resistance Index in the draft CEN standard, but is commonly referred to as the “EFI – European Friction Index” (as it is in this report).

The draft CEN standard, investigated in the HERMES study, contains several basic concepts, partially adopted from the PIARC International Friction Index IFI:

- A reference which is based on the floating average of a group of devices, where basically every device is free to enter after being calibrated to the existing reference, provided the device is sufficiently repeatable.
- The characterisation of a pavement by two numbers, SRI (or EFI) and Sp, respectively being the harmonised friction level and the speed dependency of friction.
- A conversion of results from different devices and operating conditions to a common slip speed of 30 km/h (PIARC used 60 km/h), using an exponential model (see 4.1.1) which incorporates measurement speed, slip ratio and road surface texture.
- A procedure for successive and repeated calibrations of varying subsets of the devices used in Europe.

HERMES incorporated field trials involving 15 different friction measuring devices and 7 different texture measuring devices that took part in 9 rounds of comparison exercises on 61 test surfaces in five countries, measuring at three speeds (30 km/h, 90 km/h and an intermediate speed corresponding to the normal operating speed of the device). The devices included 7 fixed slip devices (2 at 86%, and 5 at 15 - 18%), 3 locked wheel devices, and 5 side force devices. Some devices were specially invited because they had participated in the PIARC experiment (see Chapter 3), even though ten years had elapsed since then. These devices formed the initial "reference" group. The other devices participated voluntarily to test the principle of successive and repeated calibrations of varying subsets of devices.
Annex A provides a table listing the participating devices, together with their key characteristics. More details of the devices can be found in TYROSAFE Deliverable D04 (Do & Roe 2008).

4.1.1 Definitions and formulae

HERMES started with the definitions:

$$EFI = = A + B * F30 = A + B * F * e^{(S - SR) / S0}$$

$$S_0 = a + b*MPD$$

where:

- EFI (or SRI) is the device estimate of the "true" friction index <<EFI>> of a specific surface,
  where <<EFI>> is the "grand average" of all device estimates EFI for that surface, made by devices which had achieved "reference status" (actually "being admitted into the reference average group") in earlier calibrations.
- A & B are device-specific parameters (note that the parameter C for non-smooth tyres included in the IFI-formula is omitted from the EFI formula).
- F is the measured friction coefficient.
- S is the slip speed between tyre and road surface in km/h;
  S =τ *V for LFC measurement principle,
  S =V *sin(α) for SFC measurement principle,
  where: V is the operating speed of the vehicle in km/h,
  τ is the slip ratio,
  α is the yaw angle of the test wheel.
- S_R is a reference slip speed set to 30 km/h (where the IFI uses 60 km/h).
- S_0 is a speed parameter in km/h related to the tested surface characteristics.
- MPD is the Mean Profile Depth in mm as defined by ISO 13473-1.
- a & b are constants, which were originally set to 57 and 56 respectively.

Essentially, the exponential term $e^{(S-SR)/S0}$ in the EFI definition transforms the measurement value at a slip speed S to a device-specific friction value at the standard slip speed of 30 km/h. This transformation is dependent on the macrotexture. The device-specific parameters A and B convert the device-specific value to a device-independent (at least that is the aim of this conversion) value. It should be noted that the reference slip speed for the EFI is 30 km/h, whereas it is 60 km/h for the PIARC IFI (Wambold et al 1995, Henry 1996). The lower reference speed was chosen for EFI because most European devices regularly operate at slip speeds closer to 30 km/h than to 60 km/h, so less extrapolation is necessary to make the adjustment between test speed and reference speed. This improves the accuracy of the speed conversion (van den Bol et al. 2004).

After analysis of the experiments, the parameter A in the EFI formula was set to zero, and the general linear relationship between S_0 and MPD was replaced by a device-specific power law. This resulted in the following formulae:

$$EFI = B * F * e^{(S - SR) / S0}$$

$$S_0 = a * MPD^b,$$

where a and b are device-specific parameters (instead of the device-independent constants that the HERMES team used when they began the study).

Furthermore, some changes were made in the regression procedures to calculate the various parameters.

However, the HERMES team observed that the model applied above did not fit the experimental data in about 10% of the cases. This occurred mainly on porous surfaces and/or with devices with low slip ratio (<20%). Therefore, HERMES also tested the applicability of another model to describe the speed dependency of friction, as influenced by the pavement macrotexture. This model was based on Stribeck's curve, a model from tribology (the science of friction between lubricated surfaces) which considers three zones of friction, depending on whether the lubricant fully separates the sliding surfaces, separates them partially, or not. In the HERMES approximation of Stribeck's curve, this model was expressed as:

$$F(S) = F_0 \cdot e^{-(\frac{S}{S_0})^3} = F_0 \cdot e^{-(\frac{S}{117 \cdot (MPD)^a \cdot (slipratio)^{0,9}})^3}$$

Where: F_0 is the “theoretical” friction at 0 km/h slip speed;
S is the slip speed, in km/h,
S_0 is the speed constant, in km/h,
a is a device-specific constant.

Note that this model uses not only MPD to predict the speed constant, but also slip ratio. This model has the form of an inverted S-shape.

Although this model showed a better fit to the experimental data, the overall repeatability and reproducibility of the predicted harmonised values did not improve.

4.1.2 Accuracy

As explained above, several improvements in the definition of EFI and in the data processing method were proposed in order to optimize the consistency and precision of the calibration procedure.

After these improvements, the overall precision achieved in HERMES for the EFI values was:

- repeatability r = 0.111 in EFI units (repeatability standard deviation σ_r(EFI)=0.040),
- reproducibility R = 0.274 (reproducibility standard deviation σ_R(EFI)=0.099).

For the original friction coefficients, as reported by the various devices, the average repeatability was r = 0.069[1]. Thus it can be seen that some precision (repeatability) was lost for each device when converting from the measured friction coefficient to the EFI scale. This is due to the conversion from the different individual device slip speeds to a common slip

[1] Repeatability standard deviation σ_r(F)=0.025 (in various friction units)

speed of 30 km/h. A larger loss in precision occurred when considering the values of EFI predicted by the various devices (reproducibility).[2]

Some reasons for this poorer precision may be:

- Some errant individual devices or errant performances of devices (possibly because of improper maintenance/calibration).
- Differences between the LFC and SFC principle;
- Differences in tyre characteristics;
- The wide range of slip ratios between LFC devices, combined with lack of fit of the speed conversion model. This is especially relevant to the extrapolation of the results of devices with a low slip ratio to the reference slip speed of 30 km/h, which may cause large inaccuracies (van den Bol et al 2004).

It was concluded that the improved procedures provide a stable, common scale of friction but that the reproducibility of the EFI values delivered by the different devices remains too large to be considered satisfactory. Therefore, it was also concluded that further research was needed to find a model that would better suit all the various devices, or that other approaches are needed. One such an approach could be to limit the number of devices, possibly ultimately to a single common European device configuration for reference purposes, or even to a single common European device configuration for routine measurement purposes.

4.1.3 Calibration procedures

In draft standard prEN 13036-2:2003, three levels of calibration are distinguished:

- Type 1 is for a reference device to be compared to other reference devices and so prevent the divergence of the EFI scale between the reference devices over time.
- Type 2 is for a non-reference device to be compared to existing reference devices and so acquire the status of a reference device. This allows for the progressive integration of new devices and, hence, for the EFI to follow developments in testing methods.
- Type 3 is for non-reference devices to be compared to an existing reference device of the same brand. This allows a fleet of similar devices to calibrate themselves against a reference device of the same family without all of them having to cross borders to take part in calibration meetings of Type 1 or 2. In this case, they keep the link with the EFI scale while staying outside the set of reference devices.

The HERMES project included type 1 and 2 calibration experiments. These showed that the basic concept of these levels of calibration works well under practical conditions.

[2] Some loss of precision is bound to occur when changing between various devices, which is why the reproducibility imprecision is always larger than the repeatability imprecision. In this case however, the loss is particularly large.

4.1.4 Conclusions and lessons learnt

The conclusions from the HERMES project were grouped in several categories, summarised below.

Experimental procedures for calibration trials.

Although it could be assumed that the participating devices were in good condition, direct comparison of devices revealed that significant changes may have occurred to some of them from one trial to the next. It is not known to what extent this could have influenced the outcome of the HERMES experiment. This stresses the importance of regular checks and calibrations of devices.

The project demonstrated that the methodology proposed for bringing different groups of devices together for calibration trials is practical to achieve and can be carried out successfully. However, the process can be expensive. A guideline was developed for organising such exercises in future, based on the lessons learnt from the running of the trials.

Problems can occur with devices that use servo systems to develop a fixed slip ratio, when changing from high- or medium-friction surfacings to low- friction surfacings during a test run. The servo system applies a certain force to the brakes to control the slip on the higher-friction surface. However, that is then too great for the low-friction surface and so the control system enters a lock-and-release cycle to re-adjust the brakes to find the correct slip. As a result, stable conditions may not be established in time to gather meaningful data.

Some practical issues can be identified:

- Great care is required in selecting test surfaces with a sufficiently wide range of friction and texture.
- To prevent invalidation of a trial as a result of the unforeseen withdrawal of participants (which would be the case if fewer than three devices remained), at least four or five devices should be invited to attend; for practical reasons, six to eight seems an advisable maximum.
- Detailed planning is required to ensure that test runs do not interfere with each other (speed differences, set-up stopping time, crossing tracks, etc.).
- Great care is required to ensure that all devices measure the same test line (i.e. the same transverse position). This is complicated by devices having left, right or centre mounted test wheels. Careful selection of test sites and marking of the test line where possible is necessary.
- Water accumulation from successive tests was no problem in dry weather, when the pavement generally provided sufficient drainage. During periods of rain, problems may occur, however.
- The provision of a water supply to fill and replenish the tanks on the test vehicles needs careful attention (quantity, cleanliness, matching fitting systems, etc).

Analysis methods and improved models.

The exponential model for the variation of the friction coefficient (F) with slip speed (S) did not fit the experimental data in a significant number of cases. Unfortunately, exploration of the use of polynomial models or Stribeck's curve did not yield better results, so the exponential model was retained but this required the exclusion of the results from the GripTester and IMAG devices, as these did not fit the model. The problem was attributed to the low slip ratio (15%) of these devices, resulting in large extrapolations to the reference slip speed of 30 km/h. However, three other devices in the experiment used only slightly higher slip ratios (18-20%) but were not excluded. It is stressed that the exclusion of the GripTester and IMAG devices from the analysis in the HERMES project was a function of the models, and not a criticism of the devices themselves.

The prediction of the speed parameter (S_0) from texture depth (MPD) is too imprecise, even using the power model with device-dependent regression parameters that was finally chosen. This leads to a significant residual influence of operating speed on EFI. Analysis showed that slip ratio has an independent influence on the speed parameter, and that the type of surfacing (influencing shape of macrotexture, separately from texture depth) also influences S_0. Porous asphalts often were found to have larger deviations in S_0 - MPD relations.

The results showed that two families could be distinguished within the devices, namely those using the LFC and SFC principles. However, it was not clear whether the distinction between these two families was due to the difference between LFC and SFC principles, or because of differences in the range of slip ratios between these two groups in the HERMES project. The SFC family members in the HERMES project all used the same yaw angle of 20°, corresponding to a slip ratio of 34%. The LFC family in HERMES used slip ratios between 14 and 100%.

The different devices included in the experiment (and, of course, still currently used across Europe) measure on three quite different parts of the friction/slip curve: around the peak at low slip ratios (below 20%), at intermediate slip ratios (around 34%) or at high slip ratios (over 0.85%). For this reason, it is difficult to find a general model to describe the speed dependency of the friction measurement.

General conclusions regarding the EFI concept.

Regarding consistency, it was concluded that the calibration method works satisfactorily: the procedure led to a stable EFI scale even though limited subsets of devices operating on different sets of test surfaces were compared in each calibration exercise.

Regarding precision, it was concluded that the reproducibility of the EFI value delivered by different devices was acceptable for SFC devices with the same slip ratio but not for LFC devices, which use a wider variety of measurement conditions.

Based on the data from the HERMES project using the models developed so far, it is not yet practical to harmonise satisfactorily all the device principles currently used in Europe by using the EFI approach.

Analysis of the sources of deviations has shown that further improvements to the models used for F(S) and S_0(MPD) are unlikely to significantly improve the reproducibility of EFI.

4.2 Alternative approaches

The HERMES project proposed a specification for a reference device configuration, measuring both friction and texture. This reference device could serve as an alternative to the EFI approach. It would provide the common harmonised scale, into which the results of all other devices could be transformed. In the long term, this device configuration even might become the sole device configuration used in Europe.

Summarised, the HERMES specifications for the reference device configuration are:

- An ability to make continuous measurements, without excessive tyre wear.
- The device should use the LFC principle and operate with a fixed slip ratio (or a set of different fixed slip ratios) chosen to provide the same slip speed at each operating speed.
- Standard operating speeds of 40, 60 and 80 km/h should be used.
- Different slip ratios at each of these operating speeds (75% at 40 km/h, 50% at 60 km/h, 37.5 at 80 km/h) to achieve the constant slip speed of 30 km/h
- PIARC smooth tyre;
- Statically applied vertical load of 3000 N, measured as often as the horizontal load, to account for dynamic variations;
- Theoretical water film thickness of 0.5 mm.

More information about these specifications is given in Annex C.

Also, a set of requirements for reference surfaces was developed in HERMES. Such surfaces should provide stable and reproducible levels of friction, so that friction measuring devices can be periodically checked and calibrated. Such calibrations are desirable for all devices in use, irrespective of whether the common scale is provided by a single reference device configuration as discussed in the previous paragraph, or a common scale based on the grand average of a set of different 'reference' devices such as in the EFI concept. (Reference surfaces are discussed in more detail in TYROSAFE Deliverable D07, Report on state-of-the-art of test surfaces for skid resistance.)

5 Harmonisation and correlation studies related specifically to airfields

5.1 The Joint Winter Runway Friction Measurement Program and the International Runway Friction Index

Wambold et al (2000, 2001) describe the International Runway Friction Index (IRFI) for winter runway surfaces (i.e. with snow and ice conditions), which is part of a government/industry project called the Joint Winter Runway Friction Measurement Program (JWRFMP), led by Transport Canada and NASA. In this project, 17 different devices of about twelve different types were compared on nine occasions on three airports, from 1996 to 1999 (Wambold et al 2000). Testing was continued at least through 2000 (Wambold et al 2001) until 2003 (van Es & Giesberts, 2003) and perhaps in subsequent years, but further details were not available for this TYROSAFE report.

5.1.1 Definitions and formulae

Wambold et al (2001) state:

"A statistical model was developed into ASTM Standard E 2100-00, Standard Practice for Calculating the International Runway Friction Index. The equation below represents a linear regression of the data for each friction measuring device to an IRFI reference.

$$IRFI = a + b * \text{device friction measurement}$$

where a is the intercept and b is the gradient that were determined by the regression to an IRFI reference device (primary reference) or to a master device that was calibrated to the IRFI reference device (secondary reference).

This method thus harmonizes reported values of friction measurements to a common reference and units of friction measures worldwide. An Instrument de Mesure Automatique de Glissance (IMAG) (Figure 5.1), donated to the JWRFMP by Service Technique des Bases Aériennes (Paris), is currently being used as the primary reference and has been designated the International Reference Vehicle (IRV)."

ASTM E2100 was revised in 2002 and 2004. For this TYROSAFE review, only these revised editions were studied. E2100 elaborates more explicitly on the possible two-stage calibration of “local” friction measuring devices, first to a master device and then to the IRFI scale, by stating that:

$$IRFI = A + B*a + B*b*FR_{local}$$

where

- FR_{local} = the friction value measured by the local device
- A, B = harmonisation constants for the master device, from comparison with the reference device through regression: $FR_{ref} = A + B * FR_{master}$
- a, b = harmonisation constants for the local device, from comparison with the master device through regression: $FR_{master} = a + b * FR_{local}$

ASTM E2100 requires the local device to be harmonised to the master device (or to the reference device) by conducting parallel friction tests on at least 10 surfaces, covering a range of 0.1 to 0.7, as measured by the master device. To achieve master status, a device should be harmonised with the IRFI reference device on at least 35 surfaces, covering a range of 0.1 to 0.7, as measured by the IRFI reference device.
E2100 states that “The harmonisation constants shall be determined for the speed at which the device normally operates.” The authors of this report take this to mean that comparison of devices is to be conducted at equal operating speeds, and that any influence of different slip ratios is included in the constants of the linear regression.

ASTM E2100 also includes a description of the IMAG, the IRFI reference device (see also TYROSAFE Deliverable D04, Do & Roe 2008)

Figure 5.1 IMAG friction measurement device

5.1.2 Accuracy

Wambold et al (2001) state:
"The average correlation (R^2) in 1998-99 was 0.85; in 1999-2000 it was 0.46; and in 2000-01 it was 0.73. The 1999-2000 data include Munich testing, where the snow conditions were poor. If Munich data are removed, the R^2 goes up to 0.81. The average sensitivity[3] was 0.018 and the average standard error of estimate was 0.04.

[3] Wambold et al. (2001) define "sensitivity" as the change in the predicted value, IRFI, for a given change of the device measured value μ_{device}.

Currently, the recommended procedure for harmonizing ground vehicle friction measurement data is outlined in ASTM Standard E 2100-00. The method requires annual calibration and typically reduces the present variations per 100 m surface length from a maximum of 0.2 down to 0.04 (standard error of IRFI estimate)."

The authors of this TYROSAFE report do not know exactly how this value relates to the "reproducibility standard deviation" according to ISO 5725. As the standard error generally is smaller than the standard deviation (see Annex G), this last statement would mean that the reproducibility R is probably well over about 0.11.

ASTM E2100 gives an example table of typical harmonisation results for nine devices (related to the IRFI reference vehicle only) from the 1998-99 JWRMP, also given in Wambold et al (2001), giving an average standard error of estimate of 0.04, and an average correlation coefficient of 0.82. However, E2100 states this correlation coefficient to be R (not squared), whereas Wambold et al (2001) state it to be R^2.

5.1.3 Conclusions and lessons learnt

Relative to EFI, the accuracy of IRFI seems rather good, especially considering that its regression formulae are much less sophisticated than those of EFI. The main reasons for this are probably:

1. Different characteristics reported for the accuracy.
2. A fairly homogeneous set of devices (mostly LFC, 12-20% slip ratio).
3. No attempt to harmonise different speeds – probably only two test speeds were used (ICAO: 65 and 95 km/h) and correlations were only made at the same speeds – although Wambold et al are not clear about this).
4. Application to winter friction conditions (so the friction values are very low, and a small absolute deviation is a large relative deviation).

5.2 Annual NASA Tire/Runway Friction Workshop, since 1993

Since 1993, after the PIARC International Experiment (Chapter 3), annual workshops have been hosted by NASA at Wallops Flight Facility in Virginia, mostly in May. A wide variety of devices (differing from year to year) has participated, measuring texture, friction and profile on a gradually increasing range of about 30 test surfaces (Wambold et al. 2004, Yager 2005).

Wambold et al. (2004) do not mention any calculations of EFI, but do present a history of the IFI parameters F60 and Sp for the various test surfaces (see Annex E). These parameters show that the calculated IFI of the same surface can show considerable variation over the years. Of course, this may be caused by real variation of the friction properties of these pavements as a result of the effects of weather and traffic, for example. However, these variations may also be caused by the wide yearly variation of participating devices and the resulting variations in the averages over all devices and variations in the fit of the speed conversion formulas.

5.2.1 Accuracy

Wambold et al. (2004) do not present data on repeatability or reproducibility of the calculated IFI values. They do present some data on reproducibility of some device configurations, of which more than one specimen has participated in the same year. Table 5.1 presents these data, as the linear regression parameters of one device versus the other. Perfect reproducibility would yield a coefficient of 1, an intercept of 0, and R-squared of 1. The table shows that only the Dynamic Friction Tester, Circular Track meter, and ASTM E274 trailer (locked wheel) with a smooth ("Bald") ASTM E524 tyre come close to these requirements.

Table 5.1 Device reproducibility in NASA Friction Workshops (Wambold et al. 2004)

Device 1	Device 2	Coefficient	Intercept	R-Squared
BPN VADOT	BPN PSU	0.982	0.114	0.837
BPN VADOT	BPN FHwA	1.496	-0.407	0.308
DFTESTER JAPAN	DFTESTER PSU	1.005	0	0.946
CTMETER JAPAN	CTMETER VADOT	1.005	0	0.991
MTD NASA	MTD PSU	1.465	-0.016	0.901
OFT NASA	OFT SKIDABRADER	0.800	0.796	0.942
VADOT SN65B	PSU SN65B	0.985	0	0.978
VADOT SN65R	PSU SN65R	0.254	0.396	0.927

Note: BPN = British Pendulum, DFTester = Dynamic Friction Tester, CTMeter = Circular Track meter, MTD = Mean Texture Depth ("sand patch"), OFT = Outflow meter, SN65B = ASTM E274 trailer (locked wheel) with smooth ("Bald") ASTM E524 tyre, SN65R = = ASTM E274 trailer (locked wheel) with Ribbed ASTM E501 tyre. Other abbreviations indicating device owners.

Andresen at al (2001) investigated repeatability of nine different self-wetting friction measurement devices, tested on 12 different surfaces in the 2001 Tire/Runway Friction Workshop. They report a repeatability standard deviation of 0.027 (in mixed units of friction coefficient), corresponding to a coefficient of variation of 5%.

5.2.2 Conclusions and lessons learnt

Yager (2005) gives an overview of lessons learnt from these experiments, mainly focusing on the practical execution of the measurements. The lessons include, amongst others:

- *General:*
    - Daily test equipment checkout and calibration is critical to collecting acceptable data.
    - Cannot mix different speeds when conducting tests with more than one device.
- *Regarding friction measurement:*
    - Self wetting at 1 mm provided repeatable and reliable data.
    - Wet surface evaluation for hydroplaning requires a minimum of three speeds.
    - For vehicle data comparisons, a minimum of 6 repetitive runs is needed.
    - Normally, data from the first two runs are found to be outliers.
    - Test surfaces must be at least 100 m long and 1 m wide.

    - For vehicle data comparisons, lateral test surface (or vehicle) displacement is desired.
    - Vehicle order must be changed for each test run on a given surface, especially if lateral displacement is not possible.
    - Vehicle data considered acceptable if within ± 3% of other similar vehicles.
- *Regarding texture*
    - Requires pavement to be not only dry but also free of any loose material.
    - Sand patch texture measurement requires wind protection.
    - A minimum of 3 texture measurements required for each test surface.
    - For data comparisons on a given surface, use data average for each technique.

5.3 The ESDU model

In 2003, the ESDU company (Engineering Sciences Data Unit) published a "comprehensive method for modelling performance of aircraft tyres rolling or braking on dry and precipitation-contaminated runways" (Balkwill 2003, referring to ESDU 2000). This method (a set of models) was not primarily designed to harmonise skid resistance measurements. However, it was recognised that it could be used to relate skid resistance measurements to aircraft braking performance, and possibly reconcile differing tyre-pavement friction values produced by differing devices or device configurations.

The ESDU method assumes that the decelerating force on a flexible tyre, which is rolled and braked on a pavement that is covered with a fluid or a particulate substance, is the sum of three independent components:

1. Rolling resistance due to the absorption of energy in the tyre carcase.
2. Rolling resistance due to moving through or compressing the contaminant.
3. Braking resistance due to the frictional interaction between the tyre compound and the pavement.

These individual components are described by a set of models, using nine independent variables:

1. Depth of macro-texture
2. Depth of contaminant
3. Density of contaminant
4. Speed
5. Slip ratio (or range of slip ratios of an aircraft antiskid system)
6. Tyre inflation pressure
7. Vertical loading
8. Nominal tyre width
9. Nominal tyre diameter

The models give a mathematical-statistical description of the decelerating force, based on physical modelling with empirical adjustments. The models describe the following cases (numbering refers to the components of the decelerating force distinguished above):

1. Rolling on any paved surface.
2a. Rolling through fluid.
2b. Rolling though snow.
3a. Coefficient of friction for static braking on a dry pavement.
3b. Coefficient of friction for a full skid on a dry pavement.
3c. Coefficient of friction for (partial) slipping on a dry pavement.
3d. Coefficient of friction for a full skid on a wet pavement.
3e. Coefficient of friction for (partial) slipping on a wet pavement.
3f. Coefficient of friction for braking on ice- and snow-covered pavements.

Actually, models 3a to 3e are a set of nested models with increasing complexity. Model 3e is the most comprehensive and contains all the simpler models. For example, the case of slipping on a flooded runway (3e) will default logically to static braking friction (3a) if speed and water depth are set to zero in the model. Model 3f treats an ice- and snow-covered pavement as a dry pavement with a lower reference friction value.

For the skid resistance measurements considered in this TYROSAFE report, snow conditions are not relevant. Therefore, the decelerating forces on the test tyre, measured by the friction measuring devices, can be described by the sum of models 1, 2a and 3e, according to the ESDU assumptions. These models are given in Annex F.

It should be noted that the first two components (rolling resistance through tyre deformation and fluid drag) are generally not treated separately from the third component (friction for (partial) slipping on wet pavement), when considering skid resistance measurements. This may be justified, as these first components are expected to be small relative to the friction component. However, their relative magnitudes seem to deserve some investigation, to determine whether these might be a source of error in skid resistance evaluations and harmonisation.

5.4 Dutch studies for airfield measurement 2002-2008, using a simplified ESDU model

In the Netherlands, harmonisation of friction measurements for airfields has been undertaken since 2003. After a literature survey (van Es & Giesberts, 2003), and an evaluation of the ESDU model (CROW, 2003), this model was chosen to correlate different devices with differing characteristics. Note however, that the model used in these studies is much simpler than the model, later published by ESDU (2003), which is discussed in section 5.3 and Annex F.

Comparative calibration trials were carried out in 2003, 2005 and 2008 (CROW 2004, 2006a, 2009). Measurements are made on some twenty-five 100 m segments (some with multiple test lines), with MPD ranging from 0.3 to 1.2 mm. At least three replicate runs are made at each of the target operating speeds of 40, 65 and 95 km/h. In 2005, repeatability was tested on two sections, using six replicate runs each at 65 and 95 km/h, separate from the harmonisation trial.

In 2003, eight devices participated; in 2005 seven devices (from the Netherlands and the UK) were involved and seven also took part in 2008 (in this case from the Netherlands, UK and Denmark). Details of these devices are shown in Table 5.2. All tests were conducted with a theoretical water film thickness of 1 mm.

In the 2003 trials, only the statistical parameters ("friction database", see below) for each device were established, but no cross-conversions or harmonisations reported. In the 2005 and 2008 trials, the Douglas Mu-meter was used as the "reference device".

Table 5.2 Devices participating in the 2003, 2005 and 2008 Dutch airfield trials (CROW 2004, 2006a, 2009)

code 2003	code 2005	code 2008	name	organisation	country	tyre	infl. pres. (kPa)	%slip
MS6	A	A	ASFT Sharan F1	Amsterdam Airport Schiphol	NL	Unitester T520 ribbed	700	15
MS3	B	B	Douglas Mu-meter Mk 6	Douglas Equipment Ltd	UK	Titan 400/4.80-8 smooth	70	2 x 7.5° yaw
MS1	C	C	Grip tester	KOAC•NPC	NL	Findlay-Irvine A24-0120 smooth	140	14.5
MS2	D	D	ROAR/RUNAR	Rijkswaterstaat	NL	ASTM E1551 smooth	210	15
MS7	E	E	RWS Trailer	KOAC•NPC	NL	PIARC 1998 D98022 smooth	200	86
MS8	F	F	ASFT Sharan F2	Amsterdam Airport Schiphol	NL	Unitester T520 ribbed	700	15
MS5	-	-	Sarsys Friction Tester Saab	DC Spezialfahrzeuge	DE	Unitester T520 ribbed	100	15
MS4	-	-	Skiddometer BV11	Airfield Pavement Management Systems APMS	NL	ASTM E1551 smooth	210	15
-	G	-	SAAB Friction tester	Rotterdam Airport	NL	Unitester T520 ribbed	700	15
-	-	G	Dynatest 6875 RFT	Dynatest	DK	ASTM E1551 smooth	700	13

5.4.1 Definitions and formulae

The ESDU method as quoted by CROW (2003), and subsequently used in the Dutch correlation trials, is a statistical approach, which can be loosely described as: "When the friction on a particular surface, as measured with device configuration A, is equal to the *xx*th-percentile point of the statistical range of all measurement values of device configuration A, then the friction of that surface, as measured with device configuration B, will be equal to the same *xx*th-percentile point of the statistical range of all measurement values of device configuration B". To use this approach, "the whole statistical range of all measurement values" of both device configurations A and B should be known, and stored as the "friction database" for each device configuration.

The ESDU model as quoted by CROW (2003), but simpler than described by ESDU (2003), and subsequently used in the Dutch correlation trials, is:

$$\mu = \frac{\mu_{datum}}{1 + \beta \frac{0.5 \rho V^2}{p}}$$

in which

- μ is the coefficient of friction for a braked tyre on a wet surface.
- μ_{datum} is the datum coefficient of friction at zero ground speed on a dry surface. This is a function of tire pressure, tire tread material, and braking slip ratio. Tire tread pattern and runway texture have no significant influence on μ_{datum}. Experimental data have shown that the influence of ground speed on the dry runway friction coefficient is usually small.
- β is a dimensionless empirical variable, related to surface macrotexture.
- ρ is the density of the surface contaminant (water in the case of routine skid resistance measurements) [kg/m²].
- V is the operating speed ("ground speed") [m/s].
- p is the inflation pressure of the tyre [Pa].

With a sufficient comprehensive data set for a friction measuring device, each value of β can be combined with the corresponding macrotexture d of the tested wetted surface. A variable κ (runway interaction parameter [$mm^{1/2}$]) is defined as

$$\kappa = \sqrt{\beta d}$$

with d the macrotexture depth [mm]. This variable κ should conform to a normal distribution (to be checked as part of the harmonisation procedure):

$$\kappa = \overline{\kappa} + z\,\sigma[\kappa]$$

with $\overline{\kappa}$ the mean value, $\sigma[\kappa]$ the standard deviation, and z the percentage point of the normal distribution.

The values $\overline{\kappa}$, $\sigma[\kappa]$ and μ_{datum} form the "friction database" for a particular friction-measuring device. These values are unique for a particular type of friction measuring device with a given tyre type and inflation pressure. The friction database cannot be used for another friction measuring device unless it is of the same type and has the same tire type and tyre inflation pressure. To use the friction database it must also be shown that for every combination of friction-measuring device (for which parallel test data are available), the values of κ are normally correlated. The values of κ of two devices A and B are normally correlated when a linear relationship exists, of the form:

$$\frac{(\kappa_A - \overline{\kappa}_A)}{\sigma[\kappa_A]} = r\,\frac{(\kappa_B - \overline{\kappa}_B)}{\sigma[\kappa_B]}$$

with the values of κ for each device A and B being normally distributed. If such a correlation exists and is statistically significant, then the values of κ of two devices A and B are normally correlated. This implies that the transfer of probabilities at all levels is appropriate, which is essential for correlating the results of different friction-measuring devices.

When a friction database has been established, the measured friction coefficient of a particular friction-measuring device A from the database can be correlated with any other friction-measuring device B listed in the database. A schematic overview of this correlation process is given in Figure 5.2.

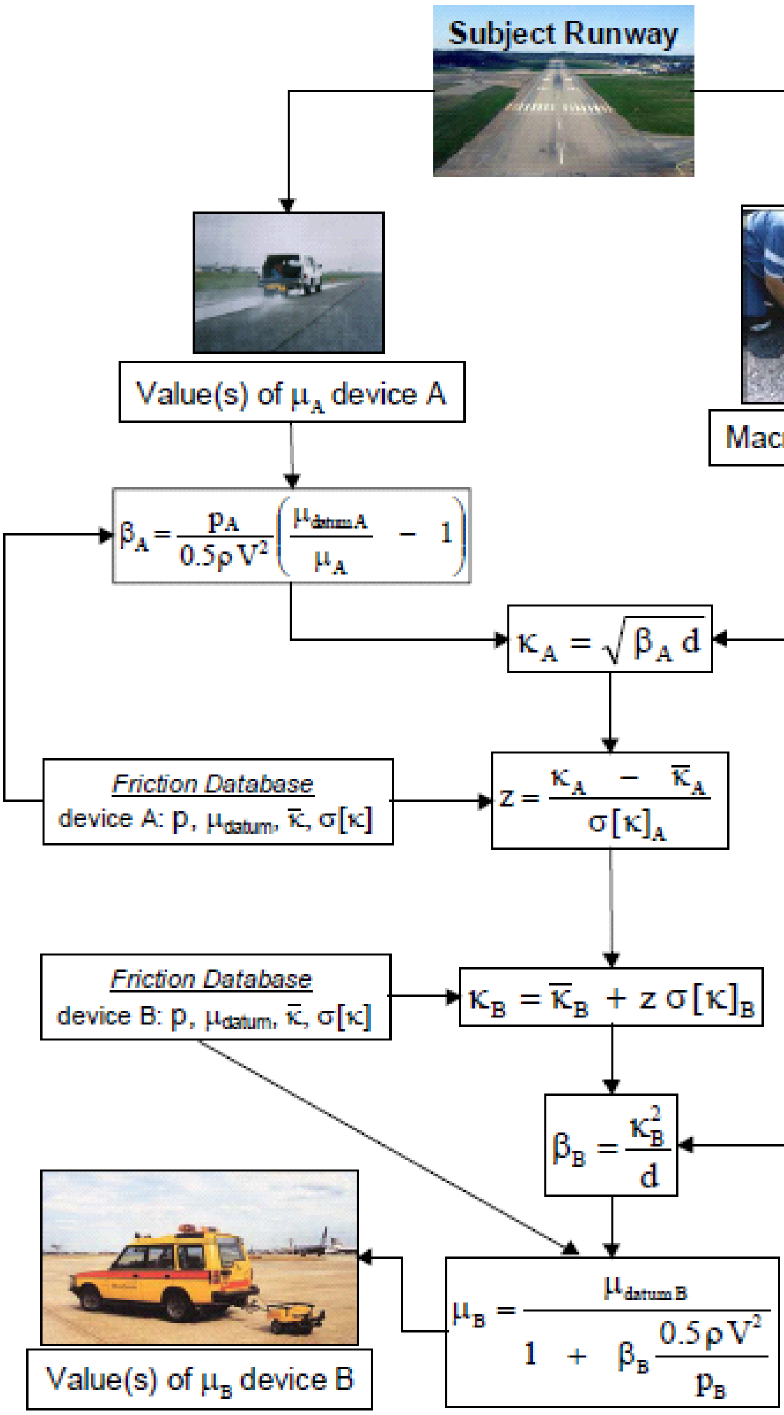


Figure 5.2 Schematic overview of the ESDU correlation process between devices A and B (CROW, 2003)

5.4.2 Accuracy

CROW (2004) reports no precision values for the 2003 trials.

CROW (2006) reports confusing values for repeatability and reproducibility at the 2005 trials. On two pavement sections, six repeat measurements were executed at two speeds.

Repeatability (2.77*SD) values from 0.03 to 0.08 (in mixed friction units) are reported, with an average about 0.05. The reported reproducibility values for these measurements (around 0.35 in mixed friction units) are useless because they mainly reflect the differences in scale between the different devices.

In the main harmonisation experiment, using the ESDU method, three repeat runs were made at three speeds on 16 pavements. This yielded repeatability values between 0.01 and 0.06 (in reference Mu-meter friction units) with an average of about 0.03, and reproducibility values from 0.03 to 0.10, average about 0.07. Note that the repeatability values in the main experiment were much better than in the special repeatability experiment.

The results of the 2005 comparative trial were used to develop a qualification protocol, defining the requirements that a device should meet, before being approved to perform routine friction measurements on Dutch airfields (CROW 2006b), in addition to the previously approved devices. These requirements can be summarised as:

- The repeatability coefficient of variation (CV), over six or more repetitions per test segment and test speed, should be equal or less than 4%, for 75 percent or more of the investigated combinations of test segment and test speed. No limits are set for individual CV values.
- For each device (per segment, test speed and test run), the measured friction values should be converted to "predicted reference values", using the ESDU model in the procedure outlined in the protocol. Then (again per segment, test speed and test run) the ratio of the predicted reference friction value over the actual reference friction value should be calculated. Then, the mean and standard deviations of all these ratios should be calculated. This standard deviation should be equal or less than 0.090. No requirements are set to the mean of all ratios.

The protocol also gives requirements for the range of surfaces to be used for qualification testing (at least three levels of MPD, from 0.5 mm to ≥1.5, with at least 2 friction levels per texture level), the number of test segments, test speeds and number of repeat runs.

In 2005, all devices met the second requirement (SD of ratio of predicted over actual reference friction value). In 2008, however, only one device complied (of course not counting the Mu-meter reference device).

5.4.3 Conclusions and lessons learnt

In 2005, good precision was obtained, but in 2008 precision was worse. Reasons for this could not be identified.

The good precision in 2005, relative to EFI, could have been caused by:

- The fact that there were no attempts in the Dutch experiments to harmonise over different operating speeds.
- Limited differences between participating device configurations in the Dutch experiments (all LFC, most at approximately15% slip ratio).

Most friction measurement devices working on airfields use slip ratios around 15%. This is not surprising, as this corresponds with the peak friction coefficient, approximated by ABS systems, with which almost all aircraft have been equipped for decades. Furthermore, devices with a high slip ratio (e.g. the Dutch RWS-trailer with 86% slip) are likely to suffer from excessive tyre wear on the kinds of high-grip surfaces used for many runways.

Practical recommendations for harmonisation trials include:

- Test pavements should encompass a sufficiently wide range of macrotexture (MPD at least from 0.5 to 2.0 mm) and friction level.
- Testing on public roads gives many problems, both operational and in regard to safety.
- Logistics and planning is of paramount importance.
- Test pavement locations should allow for adequate lengths for acceleration and braking.
- Calibration of equipment and verification of conditions (e.g. tyre pressure) prior to start of the trials is very important.
- Three repeat runs per device/speed/surface is considered to be too few for statistical analyses; targeting five or more seems advisable.

5.5 Determination of repeatability and reproducibility of Saab Friction Testers for airfields

Rado & Radone (2003) report on a comparative trial of 12 friction measuring devices for airfields carried out at Prague Airport in 2002. Although no attempts were made at correlation or harmonisation, the results are relevant for this TYROSAFE report, as the repeatability and reproducibility of a group of similar (perhaps nominally identical) device configurations were investigated.

The devices were:

- Nine Saab Friction Testers from four different manufacturers (ASFT, Sarsys, Safegate, Saab).
- The IMAG International IRFI Reverence Vehicle.
- A Skiddometer BV11.
- A Tatra Friction Tester.

Tests were executed on two 100 m sections of bare asphalt and one 60 m section of painted pavement (runway touchdown marking).

Five sets of measurements were carried out:

1. With all devices in "as is" condition and configuration (with several different tyre types, without checks and calibrations) at 65 km/h.
2. As the previous set, but at 95 km/h.

3. As the first set, at 65 km/h, but with all calibrated and all with equal tyre inflation pressure of 210 kPa (but still with several different tyre types).
4. Calibrated measurements at 65 km/h with smooth ASTM E1551 tyres at 210 kPa.
5. As the previous set, but at 95 km/h.

Each set consisted of 10 repeated measurements by each device on each of the pavement sections. All runs were made at a theoretical water film thickness of 1 mm.

Rado & Radone (2003) extensively elaborate the statistical processes of pooling data over the repetitions of a measurement, over devices, over the measurement sets, over the surfaces, and over combinations of the above.

For the Saab devices, they report an average repeatability standard deviation of 0.07, an average repeatability coefficient of variation of 6.6%, a reproducibility standard deviation of 0.10, and a reproducibility coefficient of variation of 11.4%.

6 Other work relating to device comparisons or application of harmonisation ideas

6.1 French application of IFI to harmonise SCRIM and Adhera

Gothié (1998) reported a comparison of SCRIM (34% slip, 60 km/h) and ADHERA (100% slip, 40, 60, 80, 90 and 120 km/h), using the IFI formulae, on 19 pavement sections, with macrotexture (ETD) 0.22 – 2.89 mm and IFI 0.03 – 0.80. A fairly good correlation was found and the benefits of harmonisation were stressed.

The main results were:

- Hardly any scale compression occurred when converting from original friction readings to IFI values.
- IFI(Adhera) values per pavement, derived from measurements between 40 and 120 km/h, were much closer than original values.
- IFI(SCRIM) blended in well with the IFI(Adhera) values, while original SCRIM values were considerably higher than the original Adhera values.
- However, some speed influence on IFI remained, with higher speeds generally yielding slightly higher IFI values.
- Repeatability: SD SCRIM 0.04 (average SD over 19 pavements); SD Adhera <0.02 (average SD over 19 pavements and 5 speeds).
- Reproducibility IFI(Adhera) (average over 19 pavements of SD over 5 IFI(Adhera) values (from 5 speeds) per pavement): SD = 0.03.
- Reproducibility IFI(all) (average over 19 pavements of SD over 6 IFI values (1 from SCRIM and 5 from Adhera) per pavement): SD = 0.04.

These results are illustrated in Figure 6.1, which shows the original measurement values over the range of surfaces, and Figure 6.2, which shows the IFI values. The latter are clearly much closer to each other than the original values.

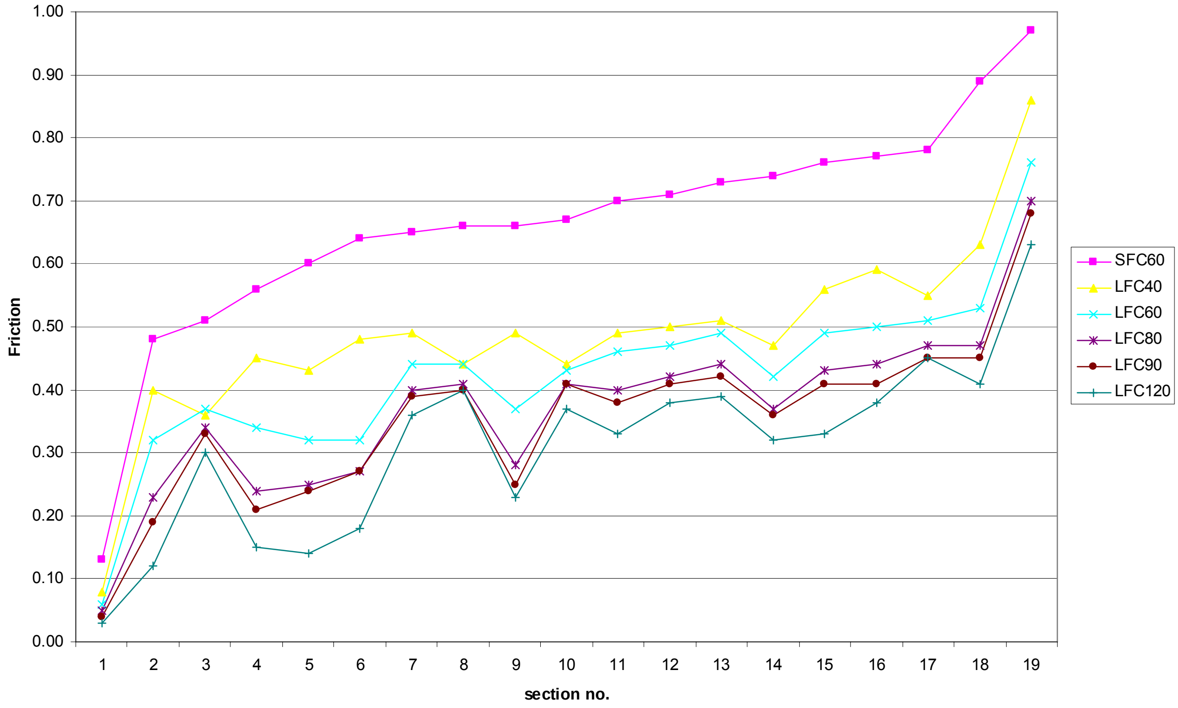


Figure 6.1 Original measurement values of SCRIM (at 60 km/h) and Adhera (at five different speeds) over 19 surfaces with widely varying friction levels

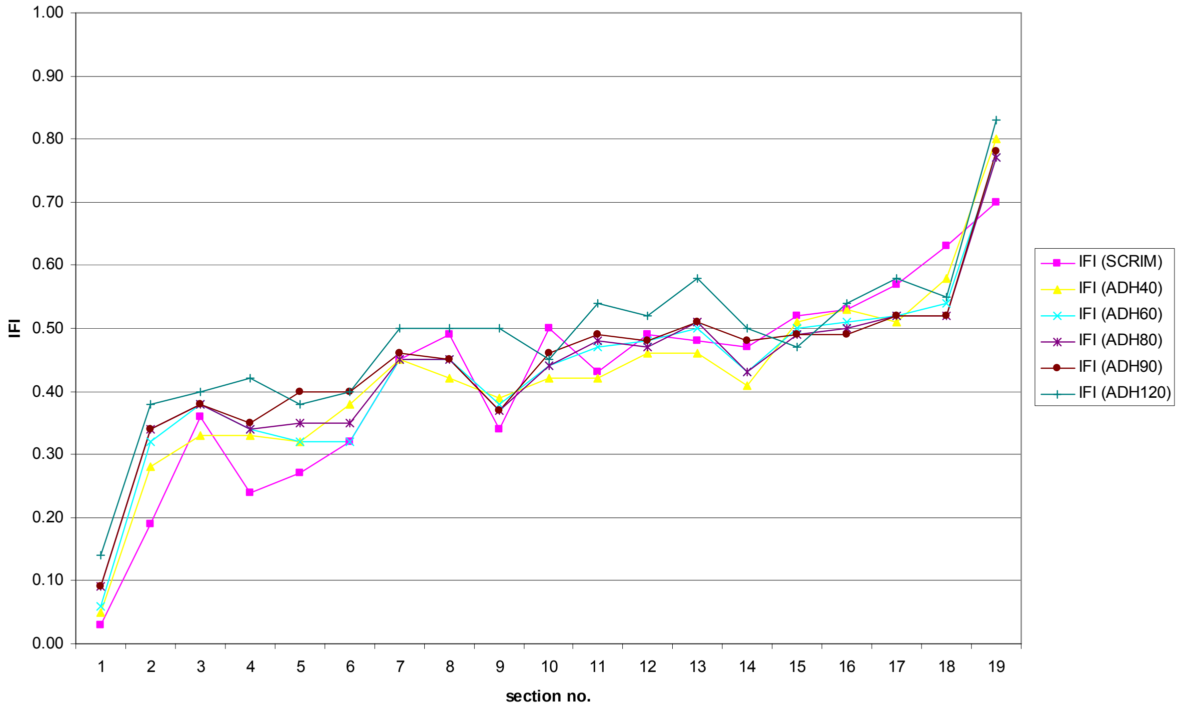


Figure 6.2 IFI values derived from the measurement values of Figure 6.1

6.2 Dutch trial application of IFI to harmonise different measurement speeds

Gerritsen et al (1997) tested the applicability of the IFI formulae to harmonise measurements at different speeds for one friction measurement device, the RWS trailer operating at 86% slip with a smooth PIARC tyre and 0.5 mm theoretical water depth (see Do & Roe 2008). Repeat runs were made at speeds of 30, 50, 70 and 90 km/h. The tests were conducted on eight different pavements on a provincial road: 0/6, 0/8 and 0/11 mm SMA; 0/16 mm dense asphalt concrete; 2/6 mm double surface dressing; 0/3 mm slurry seal and a 0/16 mm porous asphalt 0/16). The surfaces had MPD values between 0.6 and 1.2 mm. These are fairly representative for Dutch pavements, although higher MPD values may occur on some porous asphalts. Both the friction and the macrotexture measurement devices had participated in the PIARC experiment in Belgium (see Chapter 3), so their parameters for use in the IFI formulas were known. However, when these were applied, it was found that measurements at different speeds yielded markedly different values for F60. This is shown in Figure 6.3.

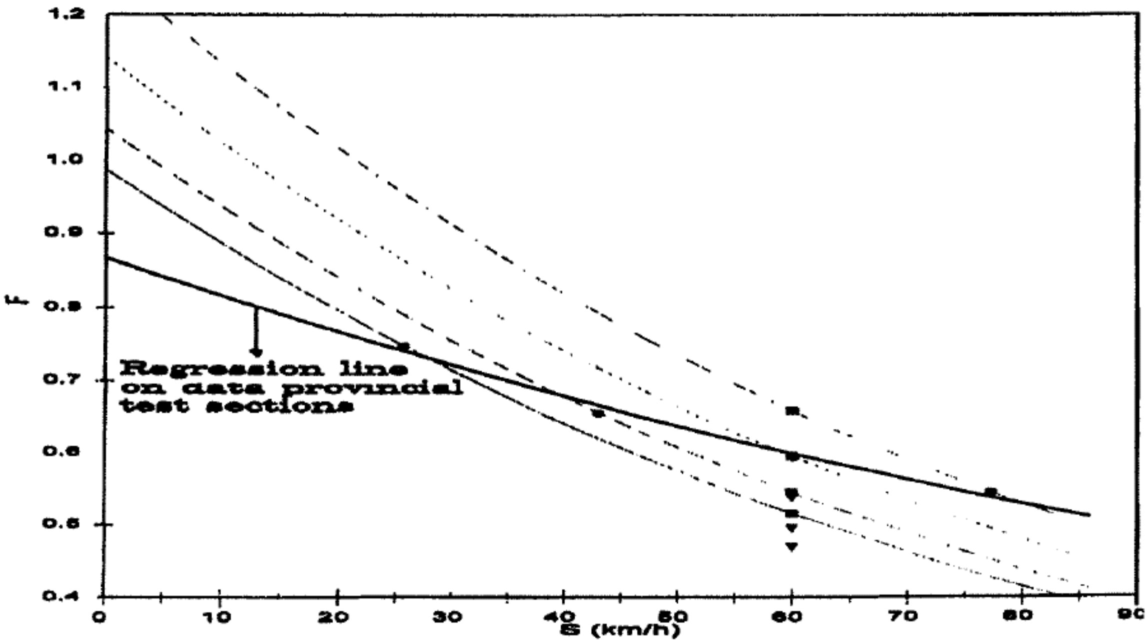


Figure 6.3 Comparison between measured and IFI-calculated relationships between friction coefficient F and slip speed S

It was therefore concluded that the parameters a and b for the texture-dependent speed correction for this device found in the PIARC experiment did not work well in practice.

Therefore, the data from the test sections were used to calculate extra pairs of data Sp-MPD (speed factor as a function of texture depth). These, together with the original PIARC data, are shown in Figure 6.4. This also shows the original PIARC Sp-MPD relationship, derived over a range of texture depths between 0.6 and 2.7 mm, and the regression line on the Dutch data, combined with the Belgium PIARC data with MPD values up to 1.2. It should be noted that the Dutch data fitted in well with the scatter of Belgian PIARC data in that texture range. The figure shows that there is a huge difference between both Sp-MPD relationships.

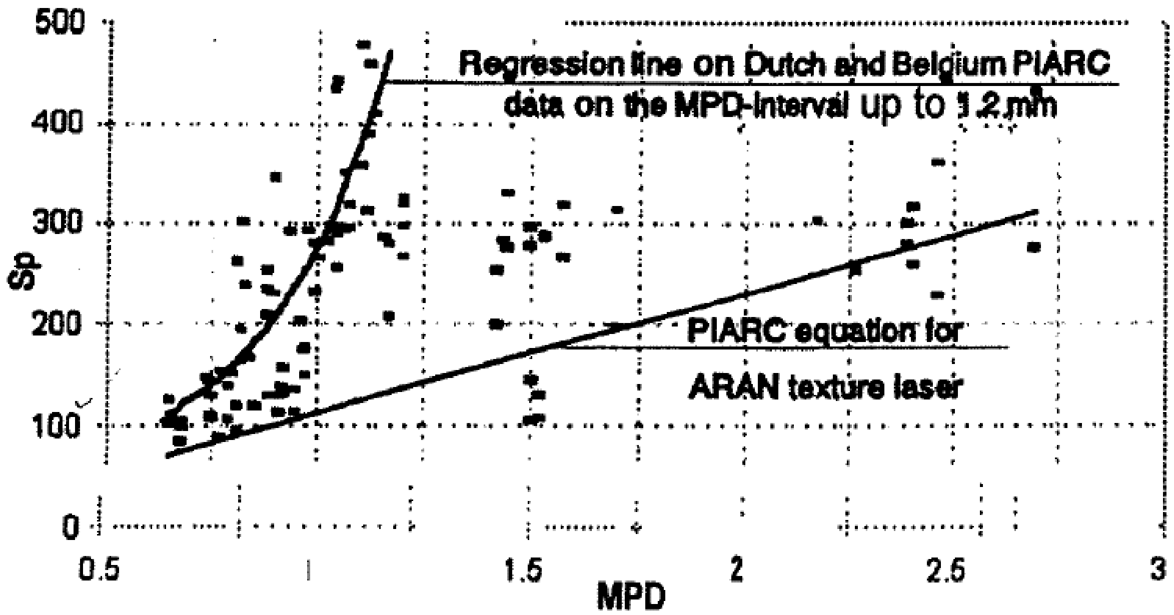


Figure 6.4 Comparison of the Sp-MPD relationships, measured in the Dutch and the PIARC test program

It was concluded that the determination of the Sp-factor, as it was done in the PIARC experiment, was insufficiently accurate for practical use, and that such determination required more attention to other possible influencing factors.

6.3 Trial application of IFI principles to six different devices

Around 1998, a joint project of BASt, RWS, and DRI investigated using the IFI principles to harmonise six friction devices:

- SCRIM (SFC, 20° yaw angle corresponding to 34% slip ratio, smooth tyre)
- Stradograf (SFC, 12° yaw angle corresponding to 21% slip ratio, smooth tyre)
- ROAR (LFC, reportedly operated at 16% slip ratio, smooth tyre)
- GripTester (LFC, 15%[4] slip ratio, smooth tyre)
- RWS-trailer (LFC, 86% slip ratio, smooth tyre)
- SRM Stuttgarter Reibungsmesser (LFC, 100% slip ratio, ribbed tyre)

Tests were carried out on 14 test sections with different surfacings, each divided into five subsections 100 m long. Measurements were made at 40, 60 and 80 km/h, with three measurement runs at each speed. Calculations were performed, using the IFI formulae (see Chapter 3), except that a reference speed of 30 km/h was used instead of the original 60 km/h (Van den Bol & Bennis, 2000).

[4] Van den Bol & Bennis (2000) report 18% slip ratio, but other sources state that GripTester has always operated at about 15% slip ratio.

From the analysis, several conclusions were drawn:

- The parameters (a and b) in the relation between speed factor Sp and macrotexture depth MPD (the IFI speed conversion model) are different for each device, instead of being general for all devices, as treated in the IFI formulae.
- These parameters a and b differ between porous and non-porous pavements (whereas all the non-porous pavements tested could be grouped together).
- In these measurements the parameter b was found to be linearly dependent on the natural logarithm of the slip ratio: b = -212.1 + 88.994 * ln(%slip) with R^2 = 0.99, see Figure 6.5.
- Even when using the device-specific values for a and b, significant residual influence of operating speed was found. (This means that the speed conversion model did not yield the same results, when starting from different operating speeds.) This may be caused by the fact that the data (FRS v. speed) show more curvature than the IFI speed conversion model can fit.
- When determining the device-specific regression coefficients A and B, a good fit was achieved for the SCRIM, Stradograph, GripTester and ROAR (all R^2 > 0.95), but a poor fit for the RWS-trailer (R^2 = 0.36). A possible cause for this might be that the RWS-trailer, at 86% slip ratio, is the only device measuring at slip speeds over 30 km/h in this experiment. Hence, its results had to be converted to a lower slip speed, whereas results for all other devices are converted to a higher slip speed

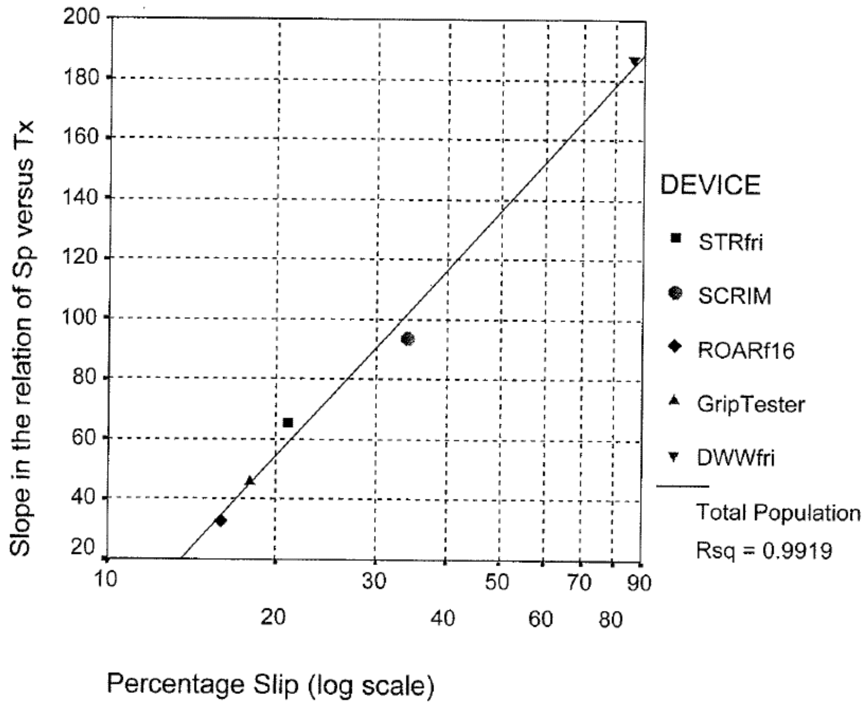


Figure 6.5 Dependency of slope parameter b on slip percentage (van den Bol & Bennis 2000) (DWWfri = RWS-trailer)

6.4 Friction tester comparative experiment within the SPENS program

Within the EU funded research program "Sustainable Pavements for European New member States" (SPENS), an experiment was carried out to compare measuring devices in use in the European Union New Member States. Other experiments within SPENS included devices measuring longitudinal evenness and bearing capacity, but these are not relevant to this TYROSAFE report. Overall, the objective of the SPENS project is to develop appropriate tools and procedures for the rapid and cost-effective rehabilitation and maintenance of roads in the New Member States.

The comparison of friction measuring devices was carried out in Vienna in the spring of 2008. Nine devices (1 sideways coefficient, 8 longitudinal coefficient) participated (see Do & Roe 2008 or Annex A for more details of individual devices):

- 1 SCRIM
- 1 SRT3 (the Polish locked wheel tester, see table A3 in Annex A)
- 1 SRM
- 2 GripTesters
- 1 TWO (Traction Watcher One from Norway, smooth ASTM tyre, 600 N load, 18% slip ratio)
- 1 TRT
- 1 Skiddometer BV11
- 1 ASFT runway friction tester trailer (patterned Trelleborg T49 tyre, 1400 N load, 12% slip ratio)

Of these devices, two measured in the left wheel track, two in the centre of the lane and five in the right wheel track. This means that the devices did not measure the same test line (lateral position) on the test pavements. Theoretical water film thickness was 0.5 mm for all the measurements.

The test design was made following the Draft European Standard prENV13036-X “Surface characteristics of road and airfield pavements – Assessment of the skid resistance of a road pavement by the use of a dynamic measuring system” rev. 4, April 2008. Six different surfaces with μ-levels from very low to very high and different texture levels were chosen. Tests were performed at 30, 60 and 90 km/h. From the raw data, SRI (EFI) values were calculated following the procedure set out in prENV13036-X.

At the time of writing this TYROSAFE report, the results of the SPENS project had not been reported. However, it is possible to indicate some preliminary conclusions (Spielhofer 2008):

- Through the SRI calculation, a very good speed independency could be reached. Standard deviations of SRI calculated over 9 runs with (3 at 30, 3 at 60 and 3 at 90 km/h) were found to be between 0.009 and 0.05, with an average of 0.016)
- The reproducibility between devices was poor, however. This was probably a result of the different lateral positioning of the test wheels during the tests.

6.5 British comparisons of SCRIM and GripTester fleets

6.5.1 SCRIM fleet comparison trials

In the UK, the SCRIM fleet undergoes an annual comparison exercise organised on behalf of the Highways Agency that is used to validate machines for operation on the trunk road network. This process has operated, with some developments to operational practice, since the early 1980s and although not referred to as such, is in effect a harmonisation exercise based on the average of the whole fleet on selected road surfaces as a reference level.

UK practice, however, is to maintain the fleet within a controlled level of precision so that all machines can be assumed to be the same rather than to "harmonise" individual machines to a defined reference.

During the exercise the machines are operated under controlled conditions over a number of surfaces on the TRL test track chosen to provide a range of levels of skid resistance and texture depth that enable the performance of the machines to be assessed over their full working range. Some artificial surfaces are included to represent extremes, such as un-chipped epoxy resin which provides a very low level of skid resistance.

Each machine (fourteen were involved in 2008) makes a number of measurement passes over the test sections using a standard set of tyres that are interchanged between the machines so that the influence of different tyres on the results can be minimised. Ultimately, the average value produced by each machine is calculated and used for the accreditation assessment. Since there is no absolute reference level against which individual machines can be compared, the overall average value for a selected set of the test surfaces is used, excluding those with known unusual characteristics such as the epoxy resin.

Checks are made on repeatability, using the standard deviation between individual test runs on each test section as the basis. The current requirement is that the standard deviation between a set of three runs with one machine using a single tyre should not be greater than 3 units of SCRIM Reading (SR). SR is the value output by the machine, equivalent to the sideway-force coefficient multiplied by 100. Occasionally, individual runs on individual sections may be deleted as outliers where it is obvious that an incorrect test line has been followed on that occasion. If this happens repeatedly, then the line followed by the driver is checked and corrected if possible.

The second check is on the performance of the fleet overall. For this check, the grand mean for all machines and all of the selected "reference" surfaces is calculated, together with the standard deviation (SD) of the individual machine mean values on those surfaces. The SD between machines should not exceed 2.6 units of SR. This value represents a coefficient of variation of about 4 percent on a typical overall mean of about 70 SR. It has been chosen to represent a practically-achievable level of precision that minimises the risk of sites being incorrectly classified during routine surveys.

The third check is on individual machines in relation to the rest of the fleet. Any machine that records an average SR that is 7.8 or more (i.e. three times an SD of 2.6) from the all-machine mean will be rejected outright and the mean and standard deviation recalculated. Any machine that records an average SR between 5.2 and 7.8 (i.e. between two and three times an SD of 2.6) from the mean will be subject to further investigation in the context of the overall distribution and performance on the full range of surfacings. If the between-machine SD is markedly below the required criterion, then the 2 x SD or 3 x SD rules may be relaxed so that machines are not unfairly rejected due to random errors in a small population.

In practice, real-time analysis of the measurements allows machines with problems to be identified early in the test programme. These are withdrawn from the trial for investigation and repair, and then are re-tested at the end of the exercise. If they cannot be repaired during the trial they must return for a separate small-scale trial before being approved.

6.5.2 GripTester fleet comparison exercises and comparisons between SCRIM and GripTester

There are no formal arrangements for comparing the many GripTesters operated in the UK. The current fleet comprises examples of machines of various build periods, including both Mark 1 and Mark 2 machines. From time to time, comparison exercises are organised through a user group.

The earliest of these were made in the early 1990s in which machines were compared on a range of surfaces laid on public roads for the purpose. In a major exercise in May 1992, a number of GripTesters and a number of SCRIMs were operated in parallel on the same surfaces and also on the surfaces at TRL used for the annual SCRIM comparison exercise (Roe, 1992). This study found that although there was a strong linear correlation between the two types of device, the reproducibility of the GripTester was not as good as that of SCRIM at the time.

After work to improve the GripTester, a further exercise was carried out in May 1993 in which 24 examples were compared to re-assess their precision. This showed a sufficiently encouraging improvement for another comparison to be made between the two types of device, so in October 2003 four SCRIMs were compared with four GripTesters. The results confirmed a strong linear correlation between the SCRIM and GripTester, but the relationship was different from that tentatively suggested in 1992. Comparison of results over the two years indicated that the changes made to the GripTester following the 1992 trials had changed the level of Grip Number recorded.

Further developments were made to the GripTester over the years leading to the Mark 2 design. A further comparison exercise was carried out in 2004, in which seven Mark 2 GripTesters were operated over the TRL test sections at the time of the annual SCRIM comparison exercise. There were difficulties with controlling the test lines for the GripTesters in this exercise, which led to yet another equation to describe the relationship with SCRIM.

This experience has demonstrated the difficulty of harmonising two devices based on simple linear correlation unless test conditions and the standards of construction, maintenance and calibration of the equipment are very carefully controlled. Even then, these exercises were limited to a single test speed and did not attempt to compare results where different speeds on different surface textures were involved and so full harmonisation was not possible.

6.6 British research into use of EFI

As a follow-up to the HERMES project, TRL was commissioned by the Highways Agency to carry out a series of short studies of the application of the EFI in the UK context. Three aspects were considered: the implications of applying the EFI to UK skidding standards; the use of the EFI to harmonise different devices used to measure skid resistance in the UK (SCRIM, Pavement Friction Tester and GripTester) and an assessment of the secondary calibration process to link the UK SCRIM fleet to the EFI. It should be noted that these studies, described in the next three subsections, used the "old" formulas for the EFI model that applied at the start of the HERMES project rather than the adjusted versions included in the final report (see Chapter 4).

6.6.1 Application of EFI to UK skidding standards

The investigation into the implications of using the EFI as the measurement scale in the context of UK skidding standards focussed on three main aspects:

- *Texture depth measurement:* Both the method of texture depth data collection and the sensitivity of EFI to changes in texture depth on the road were reviewed.
- *Correcting for variations in speed*. This part of the investigation established how the UK Standard method for correcting measurements for variations in speed (a linear relationship with respect to test speed) compared with that of EFI (an exponential form using slip speed and texture depth). This was carried out to establish whether one method showed any advantages over the other and if there were any implications for applying the EFI in the UK.
- *Network monitoring.* It was important to assess how the EFI would translate into current methodology for assessing network condition. This included establishing skid resistance investigatory levels based on EFI.

The analysis used data from a variety of sources, including tests made during the HERMES project, related follow-up research (6.6.2 and 6.6.3) and historic texture and skid resistance data relating to part of the trunk road network. The analysis assumed that SCRIM would continue to be the normal monitoring device but that the EFI would provide the skid resistance scale.

The study found that the EFI index could, in principle, be used in the context of the UK standards instead of normal SFC measurements. Importantly, it would be acceptable to use network level texture measurements made as part of routine condition surveys, rather than fitting texture sensors to the whole SCRIM fleet so that texture measurements could be made simultaneously with the skid resistance measurements. This was an important observation because the latter approach would also require all measurements to be restricted to periods when the road surface was dry prior to the test.

Of interest was the comparison between the EFI method (which uses texture data) and normal UK method (which does not) for speed correction. In this analysis the device-specific parameters of the EFI that bring measurements to the common scale were removed because they compress the scale of EFI, which made it difficult to assess the speed correction and compare it with the UK Standard. When compared on the same scale, there was little between the EFI exponential method and the normal UK method. However, because they correct to different reference speeds, they were found to perform differently across the speed range. The UK Standard method performed better at slower tests speeds, whereas the EFI performed better on some sections at the higher speeds. Overall, the data corrected using the EFI method (without device parameters) showed a higher variation across the speed range, although the difference was not of a significant level.

In terms of repeatability, both methods were very similar and tended to alternate in rank of repeatability depending on the surface. This, coupled with the close variation across the speed range, meant that the difference between the two methods was not enough to conclude a significant advantage of using either to report skid resistance. However, a different conclusion might be drawn if different types of device were used to measure skid resistance in the first instance and the EFI used to harmonise them. The compressed range of values that are obtained when applying the EFI with device parameters in comparison to SFC, would reduce the ability to distinguish differences between skid resistance levels and so EFI would need to be reported to an extra decimal place.

6.6.2 Application of the EFI secondary calibration process to the UK SCRIM fleet

An important practical aspect of applying the harmonisation principles of the EFI is the secondary calibration process by which a larger fleet of similar machines in one country is linked to a representative member of the fleet that is a member of the group of EFI “reference machines”. Although the CEN draft standard includes the so-called “Type 3 calibration” to cover this situation, the procedure was not tested during the HERMES experiment. Therefore, TRL (Brittain, Dhillon et al, 2007) carried out a trial of this process in parallel with the annual comparison trials in 2005 and 2006, making a number of additional tests over a range of speeds (rather than just the usual 50 km/h standard speed). This enabled analysis of the calibration constants and subsequent EFI calculations under a number of different conditions.

The study raised concerns about the application of the EFI principle in this context of harmonising a fleet of similar machines with one another and to the index scale. These related to the robustness of the values of the calibration constants calculated for individual devices and to an apparent trend for the sensitivity of the scale to decrease with time. Two reasons for the poor results were proposed.

The first of these was that the secondary calibration process might not be robust, either because of the way the data is collected or the subsequent processing method. A problem with this particular study, it was suggested, was the small range of texture depth in the surfaces included in the calibration. The normal SCRIM trial uses a wider range of surfaces, but it was not possible to include all of them in this study because of safety constraints relating to the higher speeds needed and the need to limit the impact of the additional testing on the normal operation of the correlation trial.

Alternatively, it is possible that the UK SCRIM fleet is currently controlled within such a tight tolerance that the remaining differences between machines are mainly due to random variation. If this were the case then the EFI secondary calibration process may be fundamentally unsuitable for calibrating a fleet of similar devices. The secondary calibration procedure was developed from theoretical concepts and it had not previously been subjected to practical tests, so it is possible that the procedure is flawed.

It was suggested that if the problems related mainly to the characteristics of the test surfaces used, this could be resolved by a change of practice in the comparison exercise, possibly with other improvements to the calibration procedure that might be identified to make it more robust. However, if the problem stemmed from random small differences between machines, it was concluded that the concept of defining calibration constants for individual machines in a fleet is flawed. It would still be possible to use the EFI for reporting skid resistance measurements: for example, all machines could use the same calibration constants as the reference machine.

The study also pointed out that even if the issues surrounding the secondary calibration process were to be successfully resolved, the EFI calibration could not simply replace the current UK comparison trial process because that includes checks to highlight machines which are giving different values from the rest of the fleet, allowing these machines to be investigated and fixed where necessary. In its current form, the EFI process realigns the raw values to the EFI scale and systematic errors will not be detected. Checks on the raw values, analogous to the current system would need to be continued in some form otherwise the consistency of different machines in the fleet can be expected to worsen over time.

6.6.3 Use of EFI to harmonise SCRIM, GripTester, and Pavement Friction Tester

Brittain, Read and Roe (2007) describe an application of the EFI principles to one SCRIM (34% slip ratio), one Mk2 GripTester (15% slip ratio) and one Pavement Friction Tester (PFT) (100% slip ratio). Tests were carried out on six sections at the TRL test track and on seven sections of a major road close to TRL, with MPD-values overall ranging from 1.12 to 3.47 mm. The test track measurements included both tests at identical slip speeds (but with different operating speeds) and at identical operating speeds (but with different slip speeds). Resulting EFI values ranged from about 0.58 to about 0.68.

Results showed that reproducibility between the three devices improved when the raw measurement values were converted to "old" EFI values. Although the application of the "old" EFI scale decreased the variation in friction values between the different pavement sections (the "spread of surfaces"), the variation between devices ("spread of machines") was decreased even more. Hence the "resolution" (the ability of the measurement to distinguish between different levels of friction) was improved.

However, even after application of the "old" EFI formulas, a small influence of operating speed remained, with higher speeds generally yielding lower EFI values.

6.7 Harmonisation of SCRIM and GripTester in Chile

Work has been carried out in Chile by the Pontifical Catholic University of Chile in Santiago (PUCC) to develop proposals for skidding standards for that country's main road network (De Solminihac et al, 2008). The project included a study to find a practical way to harmonise SCRIM and GripTester measurements. These are the two types of device normally operated in Chile and SCRIM (there is just one of these machine operated by the Ministry of Works) is regarded as the reference measurement. A means of harmonisation was therefore needed to deal with skid resistance measurements on those parts of the network that were normally surveyed using GripTester (typically routes operated under concession arrangements with the Chilean Government).

After a review of the published literature relating to the various harmonisation approaches (i.e. those discussed elsewhere in this report), the decision was made that SFC measurements made with SCRIM at 50 km/h would be the standard scale and that GripTester measurements would be "harmonised" to this scale using an approach similar to that used by the IFI/EFI to deal with the correction for different slip speeds. The study also allowed for possible harmonisation of texture measurements because a number of different devices for measuring texture depth were used in Chile.

Extensive measurements were made using the three GripTesters and one SCRIM that comprised the Chilean "fleet" of skid resistance measurement devices at a range of speeds on examples of the three types of surfacing normally used on paved roads in Chile, namely:

- *Dense asphalt concrete.* This normally has a medium texture depth when new but under traffic can show very low levels of texture depth.
- Portland Cement Concrete. The concrete surfaces are sometimes lightly brushed transversely but are often subject to diamond grinding to provide an even ride and so frequently have low levels of texture depth
- Double surface treatment. This is, in effect, a double surface dressing and generally has high texture depth.

An initial assessment of precision established that the reproducibility of the three GripTesters was good and so one machine (that operated by the Ministry of Works) was selected as a reference machine to be used for harmonisation with SCRIM, assuming that similar harmonisation coefficients would serve for the other two machines.

The objective was to determine harmonisation equations that would enable an equivalent SFC value to be calculated from the Grip Number recorded by the GripTester. However, rather than use a simple linear correlation, it was decided that a similar approach to that used in the IFI would be used to take account of the influence of texture on the measurements at different speeds. For the calculations, the sensor-measured texture depth (SMTD) was used in preference to MPD used in IFI and EFI because this was the value routinely measured on the Chilean network. (SMTD is an rms-derived value and the PIARC experiment had shown that this value of texture was almost as good as MPD). Another difference from the standard IFI was that, as with the EFI, a reference speed of 30 km/h was chosen.

The harmonisation study utilised repeated measurements at three test speeds (30, 50 and 70 km/h) on a number of 200 m sections of all three surface types, chosen to represent a range of texture levels for each type. The PUCC team found that the relationships between the devices differed on the different types of surface and consequently they identified different harmonisation parameters for each surface type and defined texture depth ranges for which these could be considered valid. In practical terms, this was a reasonable approach given the distinct nature of the surfacings used and identifying them would be reasonably straightforward. This contrasts with the situation in much of Europe, where a greater range of surfacing types are used and surfaces may change frequently both during the course of a survey and as a result of maintenance work on individual networks.

6.8 Application of IFI in the United States

6.8.1 Introduction

Flintsch et al (2008) evaluated the IFI coefficients for five devices on 24 pavement test sections on Virginia smart road with a wide range of surface textures.

The devices tested were:

- Dynamic Friction Tester (DFT) as per ASTM E1911.
- GripTester, as per ASTM E1844.
- Locked wheel tester[5] 1 as per ASTM E274, with a smooth tyre.
- Locked wheel tester 1 as per ASTM E274, with a ribbed tyre.
- Locked wheel tester 2 as per ASTM E274, with a smooth tyre.

Macrotexture data were collected using a Circular Track Meter (CTM) as per ASTM E2157, and used to calculate the Sp values. Two equations were used:

- The formula from ASTM E1960: Sp = 14.2 + 89.7*MPD (see section 3.2 of this report).

[5] A European specimen of this locked wheel tester is the Pavement Friction Tester used in the UK, described in TYROSAFE report D04 (Do & Roe 2008). The only practical difference is that the ASTM standard normally operates with 0.5mm water depth rather than the 1 mm typically used in the UK. The E274 smooth tyre is the normal standard in the UK.

- The formula for the CTM from the NASA Tire/Runway Friction workshops (Wambold et al. 2004): Sp = 110.72*MPD - 1.02

The latter formula gave much better correlation between the F60 values of the DFT on the one hand and those of the other devices on the other hand.

6.8.2 Conclusions and lessons learnt

Flintsch et al (2008) conclude: "Discrepancies in the IFI values for the different devices were observed. This suggests that the original coefficients determined during the PIARC experiment may need to be adjusted for the devices evaluated before the IFI can be implemented in the participating agencies." However, in adjusting the A and B values for the devices, A increased, while B significantly decreased (from about 0.9 to about 0.5). This was also observed in the HERMES experiment and was found undesirable, because it means the IFI scale becomes less sensitive to differences in actual friction levels between pavements.

The authors also observe significant differences in the Sp-factors per pavement section calculated from the CTM measurements and those found fitting the PIARC exponential speed correction model to the measured friction values. Especially the Sp factors from fitting the DFT data differed widely from those calculated from the CTM data.

Flintsch et al (2008) also conclude: "The results suggest that there is a better correlation of the speed gradient constant value with the power model recommended on the HERMES project than with the linear model as used on the PIARC model, particularly for the measurements using smooth tires." However, the correlation coefficients R^2 for the power model ranged from 0.32 to 0.56 for the smooth tyres, while it was 0.22 for the DFT and only 0.08 for the ribbed tyre.

6.9 Other sources

6.9.1 The VERT project

The BRITE-EURAM project VERT - “Vehicle-road-tyre interaction: fully integrated physical model for handling behaviour in potentially dangerous situations” - was carried out between 1997 and 2001 (Mancosu 2001, Mancosu et al 2000, La Torre et al 2001, VERT 2001). The aim of VERT was improved modelling of vehicle-road-tyre interactions, which could assist in the development of road surfaces, tyres and vehicles to reduce the severity of potentially dangerous driving conditions. In short: to improve traffic safety through better understanding of vehicle handling. Among other tasks, the VERT project included:

- Development and validation of a new road-tyre-vehicle simulation model. This included the development of sub-models concerning:
    - Friction prediction models in presence of water, ice, snow and slush on the pavement.
    - Development of tyre-pavement interaction models in presence of water, ice, snow and slush.
    - Development of a vehicle simulation model using the previous sub models to asses the vehicle stability under adverse weather conditions.

- Development of specifications in order to improve friction measuring equipment in low (especially snow and ice) adherence conditions; construction of a new generation test devices.

In the course of these activities, many friction measurements were made, both with longitudinal and sideways friction measuring devices, with standard skid resistance test tyres and with commercial car tyres. The longitudinal measurements investigated straight-ahead, locked-wheel braking (measuring throughout the braking cycle from rolling to locked wheel, when the test device permitted). The factors considered in the measurements were: water depth, road surface microtexture and macrotexture, operating speed, tire dimensions, tread depth, tyre compound and load. In addition to these new friction measurements, previously existing friction data were added to the database, converting them to VERT reference values using the IFI correlations where necessary.

Although the VERT project and its friction measurements did not aim to harmonise skid resistance measurements, they are relevant for this TYROSAFE report, as the factors mentioned above also need to be taken into account when harmonising skid resistance measurements. From the measurements a friction prediction model was derived, of the following form:

$$FVC = F\ (V, WD, TTD)\ /\ F\ (V_0, WD_0, TTD_0)$$

where:
FVC is a Friction Variation Coefficient,
F is the friction coefficient, measured at speed V (km/h), water depth WD (mm) and tyre tread depth TTD (mm),
V_0, WD_0, TTD_0 are the respective reference values for speed (60 km/h), water depth (1 mm) and tyre tread depth (4 mm).

This model was applied and calibrated to three friction parameters independently:

- Longitudinal locked wheel friction.
- Longitudinal peak friction (which occurs at a slip ratio of about 15%).
- Sideways peak friction.

This approach formulates a reference value (for each of these three friction parameters) for each pavement, and then describes the variation of these friction parameters with changing speed, water depth and tyre tread depth.

For the relationship between FVC and speed in the longitudinal measurements, a modified logistic function was adopted:

$$FVC_{long} = b0 + (b1\ /\ (1+b2*\exp(b3+b4*V)))$$

where b0 – b4 are parameters related to macrotexture, microtexture, tyre width, WD and TTD. Two sets of parameters b0 - b4 were determined, one for longitudinal locked wheel friction and one for longitudinal peak friction. More details about the model and the parameters are given by La Torre et al (2001).

The FVC model was calibrated and validated for both the locked-wheel and peak-friction values of the longitudinal measurements, resulting in R^2 of 0.81 for locked-wheel data (n=1115) and R^2 of 0.69 for peak-friction data (n=1229).

For the sideways measurements, a model could only be developed for one test surface:

$$FVC_{side} = b5 + b6 * V^2$$

where b5 and b6 are again functions of the parameters considered for the longitudinal friction values and of the vertical load.

6.9.2 COST 354

The aim of European research program COST 354 is to define Performance Indicators for Road Pavements. Friction is one of the aspects covered, together with longitudinal and transverse evenness. COST 354 (2008) distinguishes between:

- A performance *index*, defined in COST 354 in a dimensionless range 0 - 5 (where 0 = excellent; 5 = extremely bad; practical serviceability levels may be between about 1.5 and 3.5, depending on local needs, economic situation and political choices).
- A performance *indicator*, generally derived from a "technical parameter" such as a measured friction coefficient or a calculated friction index, derived from such a friction coefficient.

COST 354 made an inventory of the different ways in which the European countries measure skid resistance and concluded that most countries use their own national standards. Most measure a friction coefficient, using a variety of measuring devices, sometimes augmented by measurements of macrotexture, mostly using mobile laser equipment.

COST 354 only identified four European countries that convert friction coefficients to a "performance indicator". These countries are Austria, Belgium, Germany and Poland. COST 354 presents the conversion formulas from these countries and attempts to correlate these formulae, with varied degrees of success.

COST 354 also compares the different European limit values for the friction coefficient, in relation to the operating speed. However, the differences found may be caused both by differences in measurement method and by differences in (more or less arbitrarily or even unknowingly decided) target skid resistance levels. The latter may be related to different target safety levels, or may reflect identical desired safely levels but under different circumstances (such as climatic conditions or the average technical state of the vehicle fleet).

As the present TYROSAFE study only focuses on the performance indicator, or even only the "technical parameter", and does not assess its conversion to a performance index, the work of COST 354 has no impact upon this study.

6.9.3 VTI Meddelande 911A

Wallman & Åström (2001) in Sweden published a literature survey on friction measurement methods and the correlation between road friction and traffic safety (the latter topic will not be elaborated here). The review includes a discussion of the various factors involved in friction measurements and different measurement devices (see Chapter 2 and TYROSAFE deliverable D04), with a particular focus on Nordic countries. They stress the need for harmonisation where the results of studies made with different types of measurement are to be compared.

The review summarises some comparative studies made in Sweden and Denmark:

1. *A comparison by Arnberg & Sjögren (1983) between the Danish Stradograf, the Swedish BV11, and a Finnish measurement truck*. According to Wallman & Åström, they found a rather poor correlation. This is of limited relevance to the TYROSAFE study since, although the BV11 is still used in Sweden and elsewhere, Stradograf (a side-force device unique to Denmark) is no longer used (ROAR having taken over as the standard device in Denmark at present). However, this early study makes the point that devices operating on very different principles may not correlate well directly.

2. An exercise by Lund (1997). Wallman & Åström summarise this study thus: "He compared the Danish Stradograph, the GripTester and ROAR and used the Friction Index FI (with 60 km/h slip speed) concept to correlate the results. After calibration and adjustment of the device specific constants, with the Stradograf as reference device, the calculated FI values for the different devices fit well together. In the conclusions it is recommended to include also the operating speed in the FI calculation, not only slip speed."

3. A comparison by Schmidt (1999) of the Danish Stradograf and ROAR. According to Wallman & Åström, Schmidt found a good correlation.

Wallman & Åström conclude: "There is a need for a continued harmonisation work regarding road friction measurement in order to achieve better specifications of acceptable road surface friction and to facilitate the comparisons of friction and accident rate data between different countries."

7 Discussion

7.1 General: from friction to skid resistance

As explained in chapter 2, the friction between tyre and pavement is influenced by many factors. Often these are grouped by the three agents involved: the measuring tyre, the road surface, and some kind of contaminant between road and tyre (like water, snow, dust or wear particles etc.).

"Skid resistance" is the contribution from the pavement to this complex friction phenomenon, and is defined as "Characterisation of the friction of a road surface when measured in accordance with a standardised method".

It is often desirable to characterise skid resistance not with a single parameter, but with two or more parameters: one giving the skid resistance under well-specified conditions, and the other(s) giving the influence of vehicle speed (and/or slip ratio) and possibly the influence of other factors such as tyre tread depth, water depth, etc.

7.2 TYROSAFE scope of harmonisation

It discussing the findings of the review in this report, is important to bear in mind key aspects of the scope of TYROSAFE project in relation to harmonisation:

- The project is considering the concept European harmonisation of skid resistance measurements for roads and similar paved surfaces for land traffic. It is not aiming for harmonisation of skid resistance measurements for airfields.

- The project is specifically considering harmonisation of skid resistance measurements for roads in dry or water-wet conditions. Winter conditions, such as ice or snow are not within its direct scope.

- The project is considering harmonisation of skid resistance measurements primarily for routine network monitoring, but with a secondary application in relation to acceptance testing for new works.[6] It is not addressing specifically the f harmonisation of skid resistance measurements for research purposes or for accident investigation (although some of its findings may prove to be relevant to these topics).

- TYROSAFE aims to harmonise skid resistance measurements over all types of roads and all ranges of measurement operating speeds (mostly chosen from standard values to more or less match traffic speed on the particular road). However, if full

[6] Skid resistance measurements on new works should take due consideration of many processes which can cause large fluctuations of the skid resistance of new pavements over time in the early weeks or months after construction and/or opening to traffic.

harmonisation over all road types and operating speeds proves not to be sufficiently accurate, then partial harmonisation (for example, distinguishing between "low" speeds for urban situations and tight curves and "high" speeds for highways) could be considered as a practical "second best" solution.

7.3 Harmonisation versus standardisation

Harmonisation is not standardisation. Harmonisation brings the output of different measurement methods / device(configuration)s to a common scale; whereas standardisation forces a single scale by specifying a single method / device configuration. Standardisation can be seen as an extreme example of harmonisation, achieving a common scale by abolishing all other scales.

When considering harmonisation or standardisation of skid resistance, it is necessary to distinguish between 1) the measurements, and 2) the subsequent use of the measurement results in policies and requirements for pavements.

1. *skid resistance measurements*
   In the short term, the TYROSAFE goal is to establish a path towards harmonisation of measurements, not the standardisation of a device configuration and/or test speed. In the longer term, the goal could be either harmonisation of measurements (if sufficiently accurate) or standardisation of measurements. CEN TC227 WG5 chose standardisation as its long term goal.

   Standardisation has the advantage of having the best precision in principle, although the challenge remains of maintaining consistency between devices of nominally the same type, both within and across national boundaries. Disadvantages of standardisation are the costs in replacing existing fleets and revising current standards and policies to align with the new measurements. Other potential obstacles could be the commercial interests of current device manufacturers, and a possible lack of political will to adopt a single device.

2. *policies, requirements and thresholds for pavements*
   Whatever approach is eventually followed in relation to measurements – whether to do nothing, choose harmonisation, opt for standardisation, or to do something else – this does not necessarily imply that policies, requirements and/or thresholds for pavements should be standardised or even harmonised across Europe. The topic of harmonisation of policies and associated issues is being considered specifically in Work Package 1 of TYROSAFE.

7.4 Matters addressed in harmonisation experiments

In the harmonisation experiments described in the previous chapters, several matters were addressed which will be discussed in the following sections:

1. The choice of a common scale or reference: either use the “average” result from all devices or designate a particular device as the reference device.
2. The influence of slip ratio and test speed, either separately or combined.
3. The assessment of pavement surface macrotexture, as main determining factor for the influence of operating speed or slip speed on the measured friction levels.
4. Accuracy: repeatability and reproducibility.
5. Scale compression.
6. Procedures for successive harmonisation trials and the long term stability of results.
7. Quality assurance.
8. Execution of harmonisation and calibration trials.

Remarkably, the influence of tyre characteristics was hardly ever explicitly investigated in the various experiments reviewed (except in part in the VERT project). Generally, it has been assumed that the influence of the tyre is taken into accounted implicitly in the regression coefficients used to relate individual device configurations to the reference. Very often, details of the tyres are omitted from the experimental reports, or are limited either to statements about the inflation pressure and general characteristics (typically the dimensions and tread type: smooth/ribbed/patterned) or a reference to a standard specification for the tyre.

Another factor not explicitly considered in most experiments (except the VERT experiment and the ESDU studies) is the (theoretical) water depth on the pavement surface. Most friction measuring devices have a built-in system for wetting the road surface, applying a water film with a typical target depth of 0.5 or 1.0 mm. For vehicle-based systems this is usually achieved by spreading the water at a known width, applying the volume of water at a known rate matched to the target test speed so that the area covered will give the required theoretical depth. Generally, but not always, the amount of water is automatically adjusted to match changes in the operating speed so that the theoretical water thickness remains constant.

However, there is wide variation between devices in the way the water is deposited onto the pavement surface, including for example, the nozzle design, its height above the pavement and distance in front of test tyre. Consequently, the actual water film thickness may differ widely between devices using the same nominal value. Also, the pavement's draining capability (influenced by factors such as porosity, macrotexture and crossfall) will also influence the actual water film thickness, and may do so differently at different operating speeds because of the differences in drainage time in the interval between its striking the surface and the arrival of the test tyre.

Although there is experimental evidence (cited in CROW 2003) that the influence of differences in water depth between 0.5 and 1.0 mm is small, the variations mentioned above might have some influence on skid resistance measurements. In this context, the ability of the jet of water to “clean” (or not) detritus from the road surface ahead of the tyre has sometimes been commented on, although this issue is probably of greater relevance to routine monitoring on in-service roads than for harmonisation. Some devices (RoadSTAR for example) are fitted with a pre-wetting facility that can be used for this specific purpose.

7.4.1 Type of reference, or basis of a common scale

There is no absolute reference for friction, as it is essentially the outcome of an interaction of many factors. When defining a common scale or reference for skid resistance, to which individual devices can be harmonised, there are essentially two options[7]:

- Use the “average” result from all devices as a reference level.
- Use the result from a single “reference device” (or group of nominally identical devices) as a reference level.

The first approach was used in the PIARC and HERMES experiments, and later trial applications of the results from these studies. It was also applied in the UK calibration and correlation trials of the SCRIM and GripTester fleets. However, "all" devices was of course limited to those devices participating in the particular experiment. This may seem trivial, but the inclusion or exclusion of some devices will influence the resulting reference value, particularly if some devices produce values which differ widely from the results of other devices. In the case of HERMES, a number of successive calibration trials were executed, as proposed by the draft standard prEN 13026-2:2003, in which different devices participated in each trial. This implies that the average in the HERMES experiment can be described as "floating".

The second approach was also used in a number of cases.

1. In the development of the International Runway Friction Index IRFI, a dedicated specimen of the IMAG was chosen as the reference.
2. ASTM 1960, standardising the International Friction Index IFI, uses the Dynamic Friction Tester DFT as the reference (although the PIARC experiment which developed IFI used the group average as the reference). It should be noted, however, that a specific specimen of this device is not designated, but the whole group of nominally identical devices is used.
3. In Germany, the BASt-owned specimen of SKM is designated as the reference device in all calibration and correlation trials.
4. In the Dutch correlation trials for friction measuring devices for airfields, a Mu-meter is designated as the reference device.

Both approaches have advantages and disadvantages:

- Advantages of floating average:
    1. New developments are automatically included and the influence of outdated devices fades away.

[7] As stated in section 2.2, another option would be the use of special reference surfaces, with known friction properties which need to remain stable over time, even under environmental influences and even after repeated use for testing of friction measurement devices. As such ideal surfaces do not yet exist, they are not considered here, but will be in other parts of the TYROSAFE project.

2. One errant device will only slightly disturb the average.
3. It is probably easier to gain political consensus in a context in which "All animals are equal".

- Disadvantages of a floating average:
    1. A floating average is not stable over time, almost by definition, as the level changes over the time when new devices come.
    2. In a larger group there are always some outliers (e.g. due to widely differing measurement principles, or due to incidental errant behaviour or failures, which will disturb the average.
    3. It is possible that different device configurations might respond very differently to some differences in pavement characteristics (e.g porous or non-porous). If the relative proportions such factors, e.g. porous pavements or porosity-sensitive devices, changes in successive calibration trials, this could disturb the reference.
    4. A floating average needs more complicated procedures for checking other systems, either bringing all systems together on a regular basis, or arranging sequences of partial trials with complicated calculation procedure leading to loss of accuracy.
    5. At present, some devices have poor repeatability, which negatively influences the accuracy of the floating average.

- Advantages of a single reference device configuration (these advantages are basically the opposites of the disadvantages of a floating average):
    1. The reference shows the most consistent behaviour (i.e. stable over consecutive calibration/harmonisation trials), because no diverging responses to pavement parameters have to be averaged.
    2. Individual countries can achieve the greatest accuracy relative to the reference by adopting the reference device configuration as their routine standard.
- Disadvantages of a single reference device configuration:
    1. The state of the art is frozen and new developments are excluded until the reference specifications are updated.
    2. If the reference device (or the particular specimen of the group of reference devices, which participates in a calibration trial) displays errant behaviour, the whole reference scale is disturbed;
    3. There may be political resistance to accept a "foreign" device as a reference (even if the national devices may continue to be used);

If a specific reference device configuration was to be chosen as the basis for harmonisation of routine measurements in Europe, in the long term this could be developed into a single and common measurement method used throughout Europe. As this would probably give the best accuracy, this could be considered an advantage. However, it could also be considered a disadvantage by those wishing to maintain their present measurement methods.

If a single reference device and configuration was to be chosen as the basis for European harmonisation of routine measurements, there are currently several candidate devices and configurations (in alphabetical order):

- IMAG operating at 15% slip ratio (because the IMAG is already the reference device for the IRFI, and therefore choosing the IMAG would harmonise measurements for roads and airports).
- The proposed HERMES reference device (because of historic support). Although this does not exist as a fully validated standard device, its principles have been applied in RoadSTAR.
- RoadSTAR operating in its standard configuration at 18% slip ratio (because it matches the HERMES proposal, except for the three different slip ratios)
- SCRIM (because of present widespread use).

However, for many reasons, both technical and political, it is possible that another device configuration (either existing or yet to be developed) would eventually be adopted.

It should be stressed that choosing a reference device configuration (either a single specimen or a group of nominal identical devices), even with good repeatability, will NOT eliminate all accuracy problems. Even with a single specimen, checks are needed to make sure that the device is not behaving erratically incidentally and does not drift in absolute terms (not that we know what the absolute is, of course, in the absence of reference surfaces to check with). Furthermore, it is probable that more than one example would be needed to serve Europe as a whole, in which case managing the reproducibility and consistency of this group or devices has to be addressed. This would also be necessary if every country eventually were to purchase or build a machine or fleet of machines matching the reference device for routine use.

7.4.2 Influence of slip ratio and operating speed

As tyre-pavement friction may vary markedly in response to many influencing factors, a one-parameter-characterisation of skid resistance may not give enough information for practical purposes. This is recognised in the IFI and EFI concepts, which use a two-parameter characterisation, giving a (harmonised) friction level at one speed plus a texture-related parameter to take account of the change of friction with speed.

It should be stressed that differences in slip ratio (which depends on the device type and its configuration) and operating speed are basically two different things. The IFI and EFI approaches attempt to harmonise both aspects at the same time, using an exponential model for slip speed in relation to pavement surface macrotexture. This necessitates calibration experiments to be conducted over a wide range of operating speeds, much wider than the practical range of operating speeds (which are often nationally fixed to a single value for a certain device type and road category).

Several studies use different models to describe the influence of vehicle speed (sometimes combined with slip ratio):

- The IFI and EFI use an exponential model (see Chapters 3 and 4):
  IFI: Fref = A + B * FRS * $e^{(S - 60/ (a + b*MPD)}$ + C * MPD
  EFI: Fref = A + B * FRS * $e^{(S - 30/ (a * MPD\^b)}$
- The HERMES experiment (see 4.1.1) also investigated the use of Stribeck's curve:
  Fref = A + B * FRS * $e^{\{S / (a * MPD\^b * (slip\ ratio)\^c)\}\^3}$
- The VERT project (see 6.9.1) uses a modified logistic function:
  Fref = FRV / (b0 + (b1 / (1+b2*exp(b3+b4*V))))
- The ESDU model (see 5.3) uses:
  Fref = FRV * (1 + 0.5*$\beta\rho V^2$/p)

As yet, it is not clear which of these models gives the best results. It seems that the process of speed harmonisation is a major source of imprecision in most experiments, a point discussed further below. Further investigation seems advisable. If (but only if) it is determined that different speeds need to be harmonised then such research is absolutely necessary.

Another point emerging from the review stage is that where devices are compared directly, under fixed conditions, they usually can be well-correlated. Nevertheless the correlations still have scatter which may well be due in major part to the way the particular devices respond to particular textures at the particular test speed chosen (which of course still means a different slip speed for devices of markedly different types).

There is a large remaining influence of operating speed in EFI. This is shown in Figure 7.1, where the solid line gives three different friction values at the same slip speed, which is realised at three different operating speeds by using three different slip ratios. (If there were no remaining influence of operating speed, the solid line would have to be horizontal.)
This indicates that the reproducibility of EFI is negatively influenced by the attempt to harmonise over the full range of operating speeds in the HERMES experiments.

It is well-known that the friction coefficient is dependent on both slip ratio and operating speed. This is shown in Figure 7.2. Note that this figure is only one example, valid for the given values of texture depth, tyre tread depth and water depth. The figure will be different if these parameters change (see Gothié et al, 2001), and may also be influenced by other parameters not listed here.

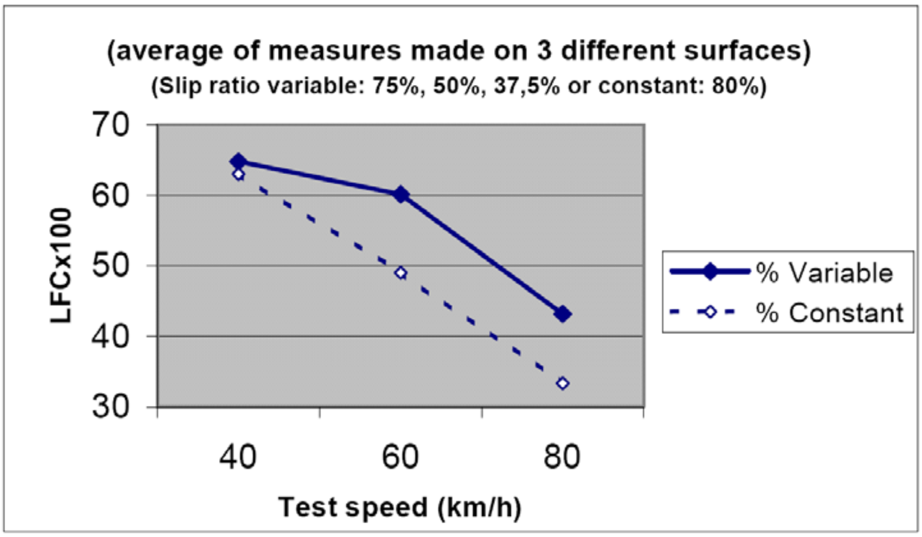


Figure 7.1 Influence of slip ratio on the LFC obtained at different test speeds (HERMES report, Descornet et al 2006)

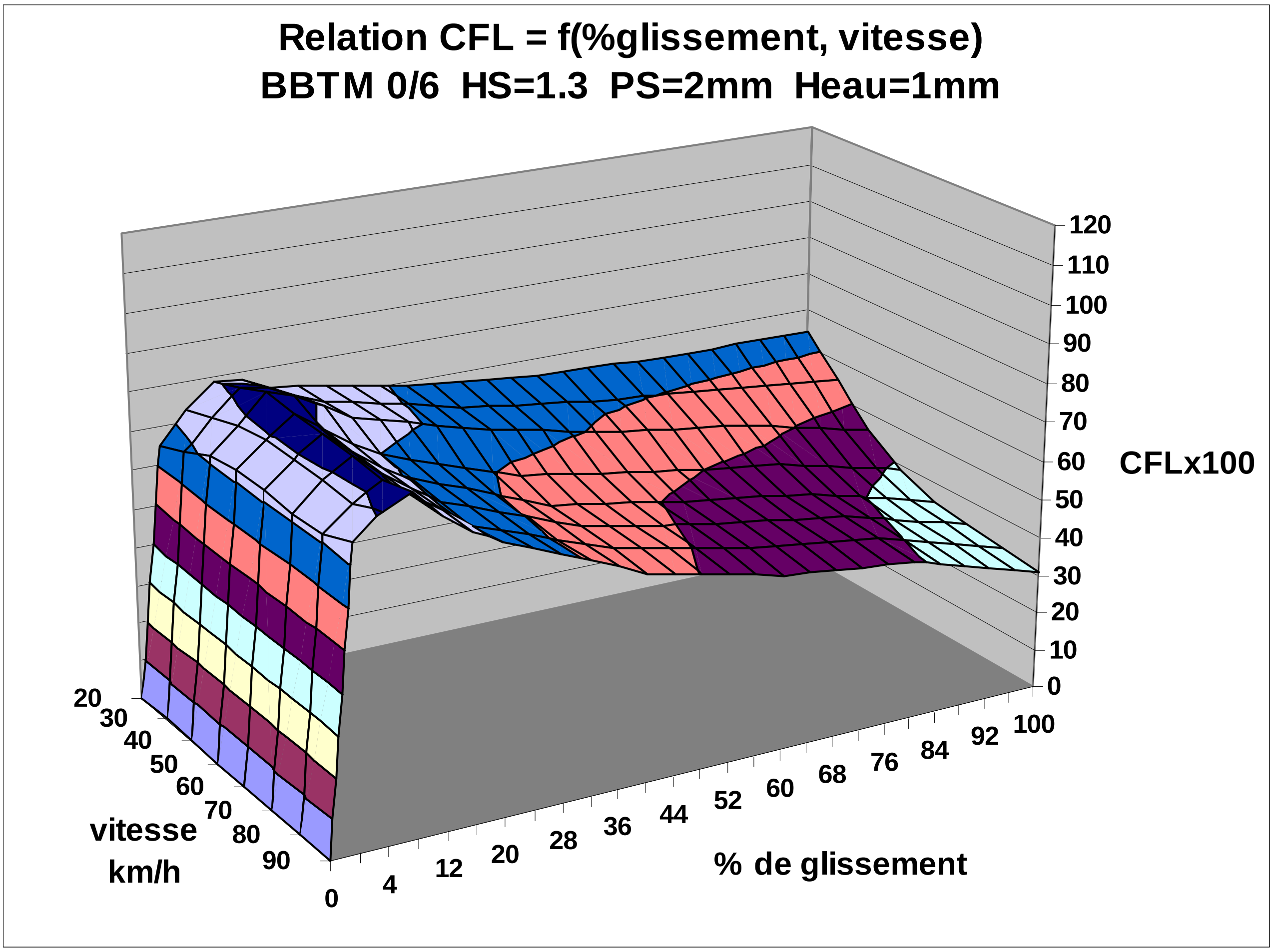


Figure 7.2 Relationship between LFC (CFLx100), slip ratio and speed

This example, (taken from the VERT project, in Descornet 2004b) shows the relationship on a BBTM 0/6 ("Beton Bitumineux Tres Mince" – 0/6 mm very thin asphaltic concrete) with a texture depth (HS= "Hauteur de Sable")of 1.3 mm, a tyre tread depth (PS = "Profondeur de Sculpture") of 2 mm and a water film thickness of 1 mm.

This picture in Figure 7.2 shows that the LFC has a peak value around a slip ratio of about 12%. The slip ratio at which this peak occurs does not change much when the speed changes, nor does the peak LFC value itself[8]. Both facts do not match with one of the basic assumptions in the IFI and EFI concepts, being that the LFC value is mainly dependent on the slip speed as a combination of slip ratio and operating speed, and not on slip ratio and operating speed separately. According to Figure 7.2, this assumption seems to be sufficiently accurate for slip ratios away from the peak (say above 30%), but clearly is very inaccurate near the peak values. This seems to indicate that harmonisation of "peak" and "non peak" devices, based on slip speed alone, may be very difficult or even impossible.

As stated above, Figure 7.1 indicates that even at slip ratios over 30% the friction coefficient is still dependent on operating speed, even when the slip speed has been made constant. If this is so, then Figure 7.1 and Figure 7.2 seem to partly contradict each other. This problem remains to be solved.

These facts may make a significant contribution to the imprecision in the EFI calculations. If harmonisation of various devices with differing slip ratios is desired, it seems advisable to pursue models that take into account the independent influences of slip ratio and operating speed.

To reduce the influence of operating speed on the common scale, there seem to be two basic options:

1. Try new formulae for speed conversion, for example including operating speed and slip ratio and/or other factors, although on the basis of the data that it had available the HERMES report concluded that "further improvements to the models used for F(S) and S_0(MPD) are unlikely to improve the reproducibility of EFI."
2. Adopt different scales for different speed ranges, such as "low" speeds for urban roads and similar, and "high" speeds for highways and similar (i.e. partial harmonisation instead of full harmonisation)

If a reference slip speed is to be adopted, the EFI reference slip speed of 30 km/h seems preferable to the IFI reference slip speed of 60 km/h, because it requires less extrapolation for devices with a low slip ratio (devices with 15% slip ratio, when operated at 30 - 90 km/h, have slip speeds of only 4.5 - 13.5 km/h). However, locked wheel devices (i.e. 100% slip) typically operate at high slip speeds, but can usually be operated at 30 km/h or even lower speeds in harmonisation trials.

Each of the slip ratios in the different measurement configurations currently used has its advantages and disadvantages:

- "Low" slip ratios around 15% have the advantage of measuring close to the peak friction value, which is representative for modern cars with Antilock Braking Systems.

[8] At low macro texture values, however, a significant decrease of peak friction with increasing vehicle speed may be found for ribbed tyres, and an even much larger friction decrease with increasing speed for smooth tyres (Viner et al, 2000).

This also has the advantage of reducing tyre wear, especially compared with locked wheel systems. The disadvantage of this configuration is that small variations in slip ratio (as a result of wear of the measuring tyre, for example) may cause substantial changes in measured value,

- 100% slip ratio (locked wheel) is representative for the braking behaviour of cars without ABS, which is a "worst case" scenario. However the considerable tyre wear makes this mode unsuitable for continuous measurements,
- "Intermediate" slip ratios around 35% are a compromise between the extremes described above. The measurement results are not particularly sensitive to small variations in slip ratio, tyre wear is acceptable, and measurement results are neither "best case" nor "worst case" but somewhere in between.

7.4.3 Characterisation of pavement surface texture

The pavement surface texture is generally divided (see Definitions) into:

- Microtexture ("harshness" of the surface as felt by human fingers, with wavelengths below 0.5 mm, mainly influenced by the surface of the mineral aggregates in the pavement, or by any coating on those aggregates).
- Macrotexture (with horizontal wavelengths between 0.5 and 50 mm, mainly influenced by the grading curve of the mineral aggregates).
- Megatexture (roughness with wavelengths between 50 and 500 mm).

Microtexture is generally considered to be the property that determines the friction level at low speeds, whereas macrotexture is deemed to determine the speed dependency of the friction level.

In the various skid resistance harmonisation experiments reviewed, characterisation of microtexture was generally not undertaken, although skid resistance at low speed, such as measured with the British Pendulum Tester, was sometimes used as an indicator of microtexture. Experimental stationary laser-based methods for measuring microtexture are available but currently there are no methods which can measure at traffic speeds.

Megatexture, too, was commonly not characterised in the experiments. Generally, the studies tried to minimise its influence by selecting test pavements with low megatexture.

Macrotexture is assessed in all skid resistance harmonisation experiments, often with various methods. The most common of these are:

- Outflow meters.
- Volumetric methods, such as the well-known "Sand Patch" (now glass beads) method (EN 13036-1), yielding a value known as Mean Texture Depth (MTD).
- Laser profilometers.

The volumetric method has been shown to have poor reproducibility because of a large operator-dependency. Laser profilometers have better reproducibility, and therefore have been the preferred option since the late 1990's. Currently, most profilometer measurements are evaluated using ISO 13473-1 and 13473-2, yielding a Mean Profile Depth (MPD) which is analogous to MTD in that it is based on estimating the average depth below the peaks in the surface. However, it seems that not all values reported as MPD, especially before about 2000, conform to ISO 13473, including some in the PIARC International Experiment (CROW 2003). Other methods of characterising macrotexture from laser profilometers, are still used including those that are based on the root mean square of the profile, for example, the British SMTD (Sensor Measured Texture Depth). ASTM E1960, standardising IFI, specifies the use of the Circular Track Meter, which has the large practical disadvantage of being a stationary device, however.

Although the laser profilometers are stated to have good reproducibility, experience indicates that substantial differences may exist between devices (De Solminihac et al 2008).

In all the harmonisation experiments studied, the macrotexture influence on friction was characterised using only one parameter (mostly MPD, but also MTD, SMTD or other). However, indications are that two other factors (that are not adequately incorporated in to current parameters like MPD) should not be neglected:

1. The porosity of the pavement, with a possibly sufficient practical distinction between "porous" (i.e. with substantial sub-surface draining capacity) and "non-porous".

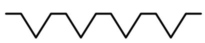
    - On porous asphalt, the laser-measured MPD gives an underestimation of actual texture depth and of the pavement drainability. Therefore, the MPD-based formulas in IFI and EFI for conversion of a measured friction coefficient to a reference slip speed may yield less accurate results.
    - Research seems advisable to investigate texture-based speed conversion of friction values on porous asphalt. Possibly a simple "trick" of increasing the measured MPD-values in the formulas (e.g. by an arbitrary factor of 2 or so), when dealing with porous asphalt, could improve accuracy.

2. The shape and form of the texture, often described in terms of the difference between a "positive" and a "negative" texture.

    - A positive texture has irregularities protruding upwards from a relatively smooth plane (like in a surface dressing or British Hot Rolled Asphalt, which both have aggregate chippings being rolled into the underlying surface):

    - A negative texture has a rather flat surface, where the texture is formed by depressions, like in some asphalt concrete or stone mastic asphalt and its derivatives:

Finally, it is worth noting that subjective qualifications such as "high" or "low" for macrotexture can be very misleading, because they are based on personal experience or national practices. For example, most non-porous pavements in the Netherlands, both on roads and runways, will have MPD ranging from 0.5 to 1.5 mm whereas in the UK, where a minimum standard for new surfaces applies on most major roads, MPD values typically may range between 1 and 3 mm with a few lower exceptions. Clearly, Dutch "highs" are British "lows".

7.4.4 Scale compression

It is often mentioned that the IFI and EFI scales are "compressed" scales, relative to the range of original friction values determined by many different devices at different speeds. However, this is largely caused by the huge difference between different devices and between different speeds. Therefore, such a scale compression does not mean that the IFI and EFI scales have a smaller difference between "grippy" and "slippery" pavements than individual devices at their normal operating speed.

Furthermore, Figure 6.1 and Figure 6.2 in section 6.1 show that the IFI scale is somewhat compressed relative to the SCRIM scale, but hardly compressed relative to the ADHERA scales. This is because SCRIM has a lower slip ratio than ADHERA and therefore generally yields higher friction values.

Scale compression in EFI can be expected to be less than in IFI (as the EFI F30 values generally will be higher than the IFI F60 values). Furthermore, scale compression in EFI is counteracted by the abolishment of the regression factor A.

7.4.5 Accuracy: trueness, repeatability and reproducibility

General

The accuracy of measurements of tyre-road friction or skid resistance, and of the results of harmonisation procedures thereof, is a confusing matter, as the reports differ considerably in what and how they report. This is aggravated by possible misunderstanding, due to differences in terminology between British English, American English, and the international Anglo-American scientific language which deviates from both the others.

As stated in the Definitions, according to ISO 3534-1 and 5725-1, accuracy is "the closeness of agreement between a test result and the accepted reference value". This is a measure of the deviations of the measured values from the "true" value or any agreed reference value. These deviations are composed of a combination of random error (the precision component) and a systematic error (the trueness component). Precision is "the closeness of agreement between independent measurement results under stipulated conditions". Trueness (often inversely called "bias") is "the closeness of agreement between the average value obtained from a large series of test results and the accepted reference value".

It is important to note that systematic deviations from the reference are generally ruled out when individual results are harmonised to the reference by using regression, because this forces the average bias to zero. Therefore, trueness often is not discussed and most reports are limited to precision.

It is important to determine what "units"[9] are being used, as these are often fundamentally different. For instance, a GripTester measurement at 95 km/h is something completely different from a SCRIM measurement at 60 km/h, even though both are friction coefficients. An IFI F60 value is something else again, as is an EFI F30 value. (As F60 is based on higher speeds, it may be expected to have lower values, and a smaller range of values, than F30.) This is also true for characterisations like standard deviation derived from these friction values, and still expressed in these units.

It is also important to understand the characterisation being reported: standard deviation, coefficient of variation, standard error, minimum-maximum range, "average absolute difference", etc. (see Annex G for some explanations). Unfortunately, many of the reports studied are insufficiently clear in defining their characterisation, and specially in reporting how "grouped" characterisations are made over groups of pavements, groups of devices, groups of speeds, etc.

Which characterisation is most useful depends on the desired application:

- For routine skid resistance measurements, generally only a single measurement is made on each section length of pavement surface. That single measurement result serves as an estimate for the "true" value. In this context, the Standard Deviation would be the most meaningful characteristic, as it is the best estimate for the random difference between a single measurement result and the average of a large series of measurements. If that average also is the "true" or accepted reference value, there is no systematic error to be considered. If, however, the average value may differ from the reference value, then the trueness also must be considered in assessing overall accuracy.
- Standard Error is the most meaningful characteristic if multiple measurements are made and averaged to estimate the "true" value.
- Repeatability/reproducibility in the sense of 2.77 x SD are most useful when comparing two single measurements and judging their difference. Therefore this value is relevant to those people who might consider using the harmonised scale for their pavement specifications (either for acceptance testing or for new works acceptance) but would be concerned as to how the "single estimate" made by an unfamiliar device configuration might differ from the "single estimate" made by their familiar device configuration.

Accuracy achieved in several experiments

The PIARC experiment reported a repeatability standard deviation of the participating devices of around 0.030 (in various friction units). The reported accuracy of IFI could not be confidently translated to reproducibility characteristics according to ISO 5725. However, it

[9] As friction coefficients are dimensionless, "units" is not a proper scientific term. It serves to show, however, that friction coefficients, reported by different device configurations, may differ just as much as inches and centimeters.

seems to suggest a reproducibility of about 0.08 (standard deviation around 0.023), but this suggestion is probably wrong.

HERMES reported the following values for precision:

- Repeatability of friction values of participating devices (in various friction units): SD 0.025.
- Repeatability of harmonised EFI values of participating devices (in EFI units): SD 0.040.
- Reproducibility of harmonised EFI values over all devices and tests (in EFI units): SD 0.099.

This precision of the EFI (reproducibility standard deviation of 0.10, hence ISO reproducibility of about 0.27) seems to be much worse than that of the IFI, although EFI was an attempt to improve upon IFI. It should be noted, however, that this high (im)precision is partly caused by the extremely wide range of variables in the HERMES experiment:

- A wide range of measuring principles (both SFC and LFC, with slip ratios from 0 to 100%)
- A wide range of measuring speeds (30 to 90 km/h).
- A wide range of surfaces (both porous and non-porous with a wide range of texture depths).

Also the overall repeatability of the individual devices already amounted to 0.11 (standard deviation = 0.04), which is larger than in some other studies. In many practical applications, the variations will be much smaller, and therefore the practical reproducibility will probably be better. However, it remains curious that PIARC seems to yield so much better precision than HERMES, as the range of variables mentioned above was comparable in both experiments.

In their comparative experiment involving nine Saab friction measurement devices from four manufacturers (and three other device types), Rado & Radone (2003) report an average repeatability standard deviation of 0.07 for the Saab devices, an average repeatability coefficient of variation of 6.6%, together with a reproducibility standard deviation of 0.10, and a reproducibility coefficient of variation of 11.4%.

Andresen at al (2001) report on the repeatability of nine different self-wetting friction measurement devices, tested on 12 different surfaces. They report a repeatability standard deviation of 0.027 (in mixed units of friction coefficient), corresponding to a coefficient of variation of 5%.

The accuracy of IRFI is given as a standard error of IRFI estimate of 0.04. Again, this could not be confidently translated to reproducibility characteristics according to ISO 5725. However, it seems to suggest a reproducibility of well over 0.11. Compared with EFI, the IRFI seems to have surprisingly good precision, considering its relative simplicity. This is probably mainly due to:

- A fairly homogeneous set of devices (all LFC, 12-20% slip ratio)
- No attempt to harmonise speeds (only 2 test speeds, 65 and 95 km/h, correlation at the same speeds)

- Application to winter friction conditions (so the friction values are very low, and a small absolute deviation is a large relative deviation).

CROW (2006) report confusing values for repeatability and reproducibility of seven different devices. From a limited experiment, repeatability (2.77*SD) values from 0.03 to 0.08, average about 0.05 (in mixed friction units) are reported.

The main harmonisation experiment, using the ESDU method, yielded repeatability values between 0.01 and 0.06, average about 0.03, (in reference Mu-meter friction units), and reproducibility values from 0.03 to 0.10, average about 0.07. Notice that the repeatability values in the main experiment were much better than in the limited repeatability experiment.

The different values reported above are summarised in Table 7.1

Table 7.1 Precision values reported by different sources.
Note the differences between the different "units".

Experiment/report	Unharmonised values, in different mixes of various friction "units"		Harmonised values, in different harmonisation "units"	
	Repeatability SD	Reproducibility SD	Repeatability SD	Reproducibility (expressed in different characteristics)
PIARC (1995)	0.03	-	-	SD 0.025 Ave. abs. err 0.030
Andresen ea (2001)	0.027	-	-	-
Rado ea (2003)	0.07	0.10	-	-
IRFI (2000)		-	-	Std.err. of estimate 0.04
HERMES (2006)	0.025	-	0.040	SD 0.099
CROW (2006)	0.02	-	0.01	SD 0.025

Comparison and discussion
The repeatability values reported by the different sources differ widely, in so far as they can be compared directly. Repeatability standard deviations range from 0.01 to 0.07; reproducibility standard deviations range between 0.02 and 0.10.

The repeatability values reported by Rado & Radone (2003) for the family of Saab friction devices are much worse than most other values. A cause for this was not identified within the scope of this TYROSAFE study, but possibly Rado & Radone used different ways of pooling their data than other authors, as they present different statistical evaluations. The reproducibility SD (without harmonisation) that they report is of the same order of magnitude as that of EFI/HERMES. Both seem to be much worse than the numbers reported for other studies, but it seems likely that these numbers actually represent different properties rather than of different values for the same property.

The more advanced skid resistance policies currently in use are based on measurements with only one device configuration and measurement speed, executed by a group of similar devices which are subject to rigorous quality assurance, including comparative calibration trials to ensure good reproducibility. In those conditions, repeatability (2.77*SD) of less than about 0.05 (in friction coefficient units, $\sigma_r \leq 0.02$) and reproducibility (2.77*SD) of 0.05 to 0.10 (in mixed friction units) can be achieved. Inevitably, some precision will be lost when expanding the group of devices with other device configurations, even after harmonising the measurement results.

It cannot yet be defined what values for precision are achievable. The actual spatial and temporal variability of the road surface and its friction characteristics impose limits on the possible repeatability and reproducibility of friction measurements.

Achievable values might be derived from the repeatability and reproducibility values stated in the CEN Technical Specifications for twelve of the device types. However, a rough view of the HERMES repeatability data (average repeatability 2.77*0.025 = 0.07) seems to suggest that:

- Either there were a number of devices in HERMES with much worse repeatability than the above-mentioned values.
- Or the devices, as described in the Technical Specifications, may have performed with poorer repeatability in HERMES than the Technical Specifications state.

A more detailed analysis of the HERMES repeatability data seems necessary to resolve this issue.

7.4.6 Procedures for successive harmonisation and long term stability of results

The HERMES experiment showed that it was possible to have a stable reference level, based on the floating average of the differing devices participating in several successive trials. The experiment also showed that regression correlation of individual devices to that "floating average" reference should only use the B parameter and the A should be set to zero. If A was not set to zero, successive calibrations would give a gradual compression of the common scale.

The Dutch applications of the ESDU method showed some long term instabilities when comparing data from the PIARC experiment, the HERMES experiments, and the Dutch 2003-2008 correlation trials.

7.4.7 Quality assurance

Quality Assurance of the friction measuring device configurations was not specifically addressed in the harmonisation experiments. Generally, requirements were that participating devices should be maintained and calibrated according to the manufacturer's recommendations and/or to national standards or guidelines.

However, experience (from the HERMES experiment, among others) showed that individual devices may show errant behaviour, or show marked changes between experiments, without any (officially admitted) apparent reason. This stresses the necessity of good QA procedures for measurements of friction and skid resistance. It also highlights one of the difficulties associated with comparative trials and harmonisation experiments.

7.4.8 Execution of harmonisation and calibration trials

Many aspects of the execution of harmonisation trials are covered in the subsections "lessons learnt" for the experiments, described in chapters 3 to 6, and will not be repeated here. One aspect seems important to stress though, as shown in the SPENS experiment, which is the need for all devices to measure exactly the same test lines (i.e. all with the test wheel at the same lateral position on the pavement). When devices have widely differing lateral positions of the test wheel, this may pose severe constraints on the selection of the test surfaces.

8 Conclusions and future perspectives

Scope

This report focuses on harmonisation of skid resistance measurements on roads (but not airfields). The main purposes for harmonised skid resistance measurements envisaged in this review have been either for acceptance of new road surfacings or for in-service network monitoring and maintenance planning. Formal harmonisation may not be necessary for measurements made for research, (including accident investigation). However, there is potential relevance to these fields also, since it is likely that researchers or accident investigators might wish to understand their data in the context of conditions on the wider road network. This review has concentrated on the harmonisation of measurements made in wet conditions: the frictional properties of roads affected by ice or snow or contaminants other than water are outside its scope

In preparing this report, a range of experimental studies into the problem of harmonisation have been reviewed. Although the review focussed on work relating to measurements on roads, similar work for measuring friction characteristics on airfields was included so that any cross-over of ideas could be taken into account. The main effort over recent decades has involved three major studies leading to proposals for harmonised indices: the PIARC international experiment, which led to the IFI (International Friction Index); the HERMES experiment, which assessed the proposed EFI (European Friction Index) and a study on airfields that led to the IRFI (International Runway Friction Index). There have also been numerous smaller exercises which have considered alternative approaches or attempted to test or validate these ideas in some specific situations.

Harmonisation or standardisation

Harmonisation of measurements has been described as "the definition of a common scale, against which measurements from different sources or standards based on different measurement types can be compared and understood" or "the adjustment of the outputs of different devices used for the measurement of a specific phenomenon so that all devices report the same value(s) (i.e. report in a common scale), except for some inaccuracy ".

If inaccuracy is too great for practical purposes (and what is acceptable may vary with different purposes), it may not be possible to harmonise measurements for a particular purpose. In that case a better technical solution might be to use a European wide standardised common test method. TYROSAFE is aimed at the definition of a "common scale" for skid resistance measurements, either through harmonisation or standardisation.

Choice of reference

There are no absolute references for skid resistance because skid resistance is the characterisation of the influence of the pavement on the complex phenomenon of pavement-tyre friction. Therefore, skid resistance is defined as the pavement-tyre friction measured using a standardised method. When a common scale or reference for skid resistance has to be defined, to which individual devices can be harmonised, there are essentially two options:

1. Use the “average” result from all devices as a reference level.

2. Use the result from a single “reference device” (or group of nominally identical devices) as a reference level.

Both approaches have been used in the past, with varying success. The first option is likely to be less precise and less stable than the latter. Precision of the "average" option can probably be improved by not including all devices in the averaged reference, or by limiting the number of device configurations contributing to the averaged reference.

Findings and lessons learnt from IFI and EFI

Harmonisation has been attempted in the PIARC experiment (resulting in IFI) and the HERMES experiment (resulting in EFI) with a reference base on a "floating average of all devices willing to enter" and harmonisation of different slip ratios and operating speeds by combining these to a common slip speed (60 km/h in IFI, 30 km/h in EFI). This gave unsatisfactory reproducibility of the harmonised skid resistance values. Although reproducibility of EFI in practical applications (with a limited range of variables) may be better than in the HERMES experiment (which had an extremely wide range of variables), EFI as currently defined is probably not sufficiently reproducible for practical application as a common scale for Europe.

Findings and lessons learnt from IRFI

The IRFI uses simple regression between the results of individual devices and the reference device. It does not attempt to harmonise different operating speeds. This may be a partial cause for its good precision (relative to EFI), beside the fact that most skid resistance measurement devices for airfields use rather similar device configurations (mostly LFC, mostly around 15% slip ratio).

The experience from IRFI suggests that possible improvements to IFI and EFI seem likely through two principles:

1. Reduction of number of device configurations (especially of the wide range of slip ratios), perhaps to only one reference device configuration.
2. Reduction of the number of operating speeds, perhaps not trying to harmonise different speeds but accepting different scales for different speeds.

Reduction of number of device configurations

It could be investigated whether exclusion of some devices may give better reproducibility, while maintaining the concept of a "floating average as a reference". Examples of devices that might be excluded could be those with poor repeatability or reproducibility between devices of the same type or the same configuration, or those with a slip ratio which is markedly different from the majority, for instance, below 10% or above 80%.

If precision could be improved in this way, this type of harmonisation may be practically acceptable. However, based on the results available to date, it seems probable that a reduction of the number of device configurations until only two or one are left will be necessary to achieve acceptable reproducibility.

Harmonisation (or not) of different speeds

Because of differing traffic situations in practice, it will always be necessary to make measurements at different speeds and even though target speeds are set, there will always be some variation in practice. As is common practice at present, it will also be necessary to choose target speeds that allow for safe operation in different situations, for instance, with low speed in constrained areas and higher speed on fast routes like motorways.

Different models exist for harmonisation of different speeds (the IFI, EFI, ESDU for example), but all seem to introduce additional inaccuracy because some influence of vehicle speed remains. It may be possible to address these inaccuracies by identifying other models, or improving existing ones.

As an alternative, these inaccuracies might be avoided by not aiming for full harmonisation across all vehicle speeds and instead using a partial harmonisation approach (like IRFI) which harmonises separately to specific test speeds within restricted set of two or three. These could be chosen to cover common network conditions, for example, "low" (30 or 40 km/h for urban situations and tight curves) “medium” (50 or 60 km/h for most single carriageway roads) and "high" (80 or 90 km/h for major highways and motorways).

Quality assurance

For all friction measurements, the matter of Quality Assurance of the measurement results is very important. A key issue to address is to make sure that a device gives an accurate result (i.e. within accepted limits from the "true" value) in the first place, and then continues to do so over time. This applies to all devices, including all specimens of any (or “the”) reference device.

Further consideration

In the following, different areas for further consideration are suggested. The relevancy will depend on the choices identified for the road map which is the next stage of TYROSAFE and will be reported in Deliverable D09:

- Evaluate different models (and the range of their applicability) to harmonise friction measurements over different measurement principles, different slip ratios and different operating speeds.
- Evaluate the advantages and disadvantages of using either a floating average or a particular device configuration as a reference, i.e. as a basis for a common scale.
- Evaluate the adequacy of the specification of possible candidate reference device configurations, e.g. SCRIM, IMAG, HERMES or RoadSTAR, both with respect to the precision requirements (even when built by different manufacturers) as well as for use in harmonisation models.
- Execute trials with existing and reference devices across Europe. Analyse the data to evaluate and calibrate the chosen harmonisation models and determine the possible range of test conditions over which measurements with existing devices can produce acceptably precise harmonised skid resistance values.
- Establish a quality assurance process for any reference device configuration so this device can become a Europe-wide standard (either as a reference device against

which different devices are compared or possibly ultimately as the sole European device configuration for routine measurements).

- Evaluate opportunities and challenges of switching to a sole European device configuration, also considering the duration of transition periods.
- Research seems advisable to investigate further validity of the models used for texture-based speed conversion of friction values on different types of surface texture, including that of porous asphalt.

Conclusion

This review has found that there have been a number of attempts to establish methodologies and common scales to harmonise measurements from different skid resistance devices. Although some progress has been made, there is not yet a scale or system that can harmonise the range of devices currently used in Europe with sufficient precision to be of practical application with widespread acceptance. There is scope for further research into ways of improving the processes and these should be considered in the next stage of the TYROSAFE project preparing the “road map”.

Given the complexity of the issue, it is advisable to keep all options open until the end of the project, Therefore it is proposed that a set of alternative “Road Maps”, should be developed, with some based on realising a "common scale" for skid resistance measurements through harmonisation and others following the standardisation approach.

Ultimately, it may prove best to adopt a single common device across Europe to provide standardised measurements for the main purposes of new surfacing acceptance and in-service network monitoring. However, there will still be a need for measurements using various techniques to assess specific aspects of the tyre/road friction phenomena and a means to interpret those in a wider context, so some form of harmonisation would still be of value.

9 References

Andresen A & Wambold JC, 1999, *Friction fundamentals, concepts and methodology*, Report TP 13837E, Transport Canada, Montreal CAN. http://www.tc.gc.ca/innovation/tdc/publication/pdf/13800/13837e.pdf

Andresen A, Wambold JC & Henry JJ, 2001, *Repeatability of Friction Measurement Devices in Self-Wetting Mode*, Report TP 14064, Transportation Development Centre of Transport Canada, Montreal CAN. http://www.tc.gc.ca/innovation/tdc/publication/pdf/14000/14064e.pdf

Arnberg PW & Sjögren L, 1983, *Nordiska friktionsmätare*, VTI Meddelande 333, Linköping

ASTM E274 - 06 *Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire*, ASTM International, West Conshohocken, PA, USA

ASTM E1844 - 08 *Standard Specification for a Size 10 × 4–5 Smooth-Tread Friction Test Tire*, ASTM International, West Conshohocken, PA, USA

ASTM E1845 - 01(2005)e1 *Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth*, ASTM International, West Conshohocken, PA, USA

ASTM E1911 - 07 *Standard Test Method for Measuring Paved Surface Frictional Properties Using the Dynamic Friction Tester*, ASTM International, West Conshohocken, PA, USA

ASTM E1960 - 07 *Standard Practice for Calculating International Friction Index of a Pavement Surface*, ASTM International, West Conshohocken, PA, USA

ASTM E2100 - 04, *Standard Practice for Calculating the International Runway Friction Index*, ASTM International, West Conshohocken, PA, USA

ASTM E2157 - 01(2005) *Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter*, ASTM International, West Conshohocken, PA, USA

Balkwill KJ, 2003, *Development of a comprehensive method for modelling performance of aircraft tyres rolling or braking on dry and precipitation-contaminated runways*, Report TP 14289E, Transport Canada, Quebec. http://www.tc.gc.ca/innovation/tdc/publication/pdf/14200/14289e.pdf

van den Bol-de Jong ME & Bennis TA, 2000, *Measuring Systems for the Evaluation of Skid Resistance and Texture – Relation between the friction Measurements from Different*

Devices and the International Friction Index, Proc. 4th Int. PIARC Symp. Pavement Surface Characteristics of Roads and Airfields “SURF2000”, Nantes FR, pp. 173-182.

van den Bol ME & Fafié JJ, 2004, *Precision of Friction Models*, PIARC International Symposium “SURF2004”, Toronto.

Brittain S, Dhillon N, Read C and Viner H, 2007, *Evaluation of the EFI secondary calibration procedure*, TRL report UPR IE/196/06 Transport Research Laboratory (Unpublished)

Brittain S, Read C & Roe PG, 2007, *Harmonising UK skid resistance measurement devices using the European Friction Index*, TRL report UPR IE/064/07 Transport Research Laboratory (Unpublished).

COST 354, 2008, *Performance Indicators for Road Pavements - Work Package 2: Selection and assessment of individual performance indicators*, Report, version 30052008, Brussels.

CROW, 2003 (author: van Es GWH), *Correlation of self-wetting friction-measuring devices - Evaluation of the ESDU method*, Report 03-10, Dutch information and technology centre for transport and infrastructure CROW (originally NLR-CR-2003-370 by Dutch National Aerospace Laboratory NLR), Ede NL

CROW, 2004 (author: van Gurp CAPM), *Correlation trial of self-wetting friction measuring devices for Dutch airfields*, CROW report 04-05, CROW technology platform for transport, infrastructure and public space, Ede NL

CROW, 2006a (author: van Gurp CAPM), *Correlation trial and harmonisation modelling of friction measurements on runways 2005*, CROW report 06-02, CROW technology platform for transport, infrastructure and public space, Ede NL

CROW, 2006b, *Qualification protocol for candidate self-wetting friction-measuring devices on Dutch airfields*, CROW report 06-05, CROW technology platform for transport, infrastructure and public space, Ede NL
http://www.crow.nl/shop/webshop.aspx?search=06-05&select=all

CROW, 2009 (author: van Gurp CAPM), *Correlation friction measurements De Peel 2008*, CROW report D09-xx (Not published yet), CROW technology platform for transport, infrastructure and public space, Ede NL

Descornet G, 1998, *Proposal for a European standard in relation with the skid resistance of road surfacings*, Final report, Research contract SSTC NO/C3/004, Belgian Road Research Centre, Brussels.

Descornet G, 2004a, *The HERMES Project*, Paper for PIARC International Symposium “SURF2004”, Toronto.

Descornet G, 2004b, *The HERMES Project*, Powerpoint presentation for PIARC International Symposium “SURF2004”, Toronto.

Descornet G et al., 2006, *Harmonisation of European Routine and Research Measurement Equipment for Skid Resistance*, FEHRL Report 2006/01, Brussels BE.

Do M-T, Marsac P & Mosset A, 2004, *Tribology Approach to Predict the Variation of Tire/Wet Road Friction with Slip Speed*, PIARC International Symposium “SURF2004”, Toronto CAN.

Do M-T & Roe PG, 2008, *Report on state-of-the-art of test methods*, TYROSAFE Deliverable D04, FEHRL, Brussels BE

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

EN ISO/IEC 17025:2005 *General requirements for the competence of testing and calibration laboratories*

van Es GWH & Giesberts MKH, 2003, *A literature survey on tire surface friction on wet pavements - Application of surface friction testers,* Report 03-06, Dutch information and technology centre for transport and infrastructure CROW (originally NLR-CR-2002-604 by Dutch National Aerospace Laboratory NLR), Ede NL

ESDU 2000. *Statistical analysis of wet runway friction for aircraft and ground-test machines,* ESDU Item 99015, Engineering Sciences Data Unit, London UK.

Flintsch G, de León Izeppi E, Roa J, McGhee KK & Swanlund M, 2008, *Evaluation of the International Friction Index coefficients for various devices,* 6th int. PIARC symp. on pavement surface characteristics "SURF2008", Portorož, Slovenia

Gerritsen W, Wennink M, Jacobs MMJ, Jordens RAP & van Gorkum F, 1997, *The use of PIARC's International Friction Index (IFI) to determine the skid resistance on National level¸* paper for the safety session of the XIIIth IRF World Meeting, Toronto CAN.

Gothié M, 1999, *International Friction Index - An example of application,* Routes/Roads N° 300, PIARC, Paris FR.

Gothié M, Parry AR & Roe PG, 2001, *The relative influence of the parameters influencing road surface friction*, 2nd int. colloquium on vehicle tyre road interaction "friction potential and safety: prediction of handling behaviour", Florence, IT, February 23rd 2001
http://roads.dicea.unifi.it/colloquium/VERT_proceedings/P03.pdf

Gothié M, 2004, *The HERMES Project. A new reference device*, PIARC International Symposium “SURF2004”, Toronto CAN.

Henry JJ, 1996, *Overview of the International PIARC Experiment to Compare and Harmonize Skid Resistance and Texture Measurements: the International Friction Index*, 3rd int. PIARC symp. on pavement surface characteristics, Christchurch NZ.

ISO 3534-1:2006, *Statistics - Vocabulary and symbols - Part 1: General statistical terms and terms used in probability*

ISO 5725-1:1994 (with Technical Corrigendum 1, 1998), *Accuracy (trueness and precision) of measurement methods and results – Part 1: General principles and definitions*.

ISO 5725-2:1994 (with Technical Corrigendum 1, 2002), *Accuracy (trueness and precision) of measurement methods and results – Part 2: Basic method for the determination of repeatability and reproducibility of a standard measurement method*.

ISO 5725-4:1994, *Accuracy (trueness and precision) of measurement methods and results – Part 4: Basic methods for the determination of the trueness of a standard measurement method*.

ISO 13473-1:2004, *Characterization of pavement texture using surface profiles - Determination of Mean Profile Depth*.

ISO 13473-5 CD, *Characterization of pavement texture using surface profiles - Measurement of megatexture.*

Lund B, 1997, *Friction test. Comparative testing with 3 different equipments carried out during the summer 1996,* Report 82, Danish Road Institute

Mancosu F, Parry A & la Torre F, 2000, *Friction Variation due to speed and water depth*, Proc. 4th Int. Symp. Pavement Surface Characteristics of Roads and Airfields, “SURF2000”, Nantes FR, pp. 249-257.

Mancosu F, 2001, *VERT Project : Overview*, 2nd int. colloquium on vehicle tyre road interaction "friction potential and safety: prediction of handling behaviour", Florence, IT, February 23rd 2001
http://roads.dicea.unifi.it/colloquium/VERT_proceedings/P01.pdf

prEN 13036-2:2003, *Surface characteristics of road and airfield pavements - Procedure for determination of skid resistance of a pavement surface*

prEN 13036-x, rev 4, April 2008, *Surface characteristics of road and airfield pavements - Assessment of the skid resistance of a road pavement by the use of a dynamic measuring system*

De Solminihac H, Chamorro A, Echaveguren T & Roe P, 2008, *Proposal of a comparison method to assess skid resistance and macro texture measured with different devices,* 2nd conf on Safer Roads, Cheltenham UK, May 2008

Spielhofer R, 2008, e-mails within TYROSAFE working group, december 2008

Rado Z & Radone EF, *Repeatability and Reproducibility of SAAB Friction Measurement Devices in Self-Wet Mode*, TP 14083E, Transportation Development Centre of Transport Canada, Montreal CAN https://www.tc.gc.ca/innovation/tdc/publication/pdf/14000/14083e.pdf

Roe PG, 1992, *The precision of the GripTester - report of a trial in May 1992*, TRL Project Report PR/H/15/92. (Unpublished report)

Roe PG, 1993, *A comparison of SCRIM and GripTester – Report of a further trial in September 1993*, TRL Project Report PR/H/58/93 (Unpublished).

Schmidt B, 1999, *Friktionsmålinger. Sammenlignende målinger mellem ROAR och Stradograf,* Rapport 90, Danish Road Institute

La Torre F & Domenichini L, 2001, *Friction prediction models*, paper 8B, 2nd int. colloquium on vehicle tyre road interaction "friction potential and safety: prediction of handling behavior", Florence, IT, February 23rd 2001, pp 134-147 http://roads.dicea.unifi.it/colloquium/VERT_proceedings/P08b.pdf (Note that in this pdf-version, the parameters for the locked wheel model are only partially displayed, and therefore incorrect)

VERT 2001, Proc. 2nd Int. Colloquium on Vehicle Tyre Road interaction "*Friction potential and safety prediction of handling behavior*", Florence, february 23rd 2001, http://roads.dicea.unifi.it/colloquium/VERT_proceedings/

Viner HE, Roe PG, Parry AR & Sinhal R, 2000, *High and low-speed skidding resistance: the influence of texture on smooth and ribbed tyre friction*, Proc. 4th Int. PIARC Symp. Pavement Surface Characteristics of Roads and Airfields "SURF2000", Nantes FR, pp 227-236.

Wallman CG & Åström H, 2001, *Friction measurement methods and the correlation between road friction and traffic safety - A literature review*, VTI Meddelande 911A, Linköping

Wambold JC, Antle CE, Henry JJ, Rado Z, Descornet G, Sandberg U, Gothié M & Huschek S, 1995, *International PIARC Experiment to Compare and Harmonize Skid Resistance and Texture Measurements*, PIARC Publication n°01.04.T, Paris.

Wambold JC, Andresen A, Yager T & Mazur A, 2000, *International Runway Friction Index - IRFI,* Proc. 4th Int. Symp. Pavement Surface Characteristics of Roads and Airfields “SURF2000”, Nantes FR, pp. 99-107.

Wambold JC, Henry JJ & Andresen A, 2001, *International Runway Friction Index (IRFI) - Development Technique and Methodology,* TP 14061E, Prepared for Transportation Development Centre of Transport Canada, National Aeronautics and Space Administration, and Federal Aviation Administration by DCRM Inc, State College, Pennsylvania https://www.tc.gc.ca/innovation/tdc/publication/pdf/14000/14061e.pdf

Wambold JC, Henry JJ & Yager T, 2004, *NASA Wallops Tire/Runway Friction Workshops 1994-2003*, PIARC International Symposium “SURF2004”, Toronto CAN.

Wambold JC, 2005, *International Friction Index (IFI)*, Powerpoint presentation, December 7, 2005, http://www.outreach.psu.edu/programs/tesc2005/images/1c_wambold.pdf

Yager TJ, 2005, *An Overview of the Annual NASA Tire/Runway Friction Workshop and Lessons Learned*, Int. Surface Friction Conf. on Roads and Runways, May 2005, Christchurch NZ, http://ntrs.nasa.gov/search.jsp?R=1009240&id=2&qs=N%3D4294826479

Annex A: Devices taking part in the PIARC and HERMES experiments

Table A.1 Skid resistance devices taking part in the PIARC trials

TABLE 1. FRICTION EQUIPMENT
TABLEAU 1. MATERIEL DE FROTTEMENT
TABLA 1. EQUIPOS DE MEDIDA DE FRICCIÓN

DEVICE ID IDENTIFICATION IDENTIFICACIÓN	DEVICE NAME DENOMINATION (PAYS) DENOMINACIÓN (PAÍS)	TYPE TYPE DE MESURE TIPO DE MEDIDA	TIRE TYPE TYPE DE PNEU TIPO DE NEUMÁTICO	SLIP1 TAUX DE GLISSEMENT TASA DE DESLIZAMIENTO (*) (%)	SPEED VITESSE VELOCIDAD (km/h)
A12	ROSAN (USA)	SLIDER / *CURSEUR* / ZAPATA	BLANK / *SANS SCULPTURE* / LISO	100	10
A13	DF TESTER (J)	SLIDER / *CURSEUR* / ZAPATA	BLANK / *SANS SCULPTURE* / LISO	100	0-80
A14	BRITISH PENDULUM (US)	SLIDER / *CURSEUR* / ZAPATA	BLANK / *SANS SCULPTURE* / LISO	100	10
B1-ABS	STUTT. REIBUNGSMESSER (CH)	OPTIMUM SLIP / *GLISS. OPT.* / DESLIZAMIENTO ÓPTIMO	RIBBED-P / *NERVURE-P* / ESTRIADO-P	OPT.	30, 60, 90
B1-LKD	STUTT. REIBUNGSMESSER (CH)	LOCKED WHEEL / *ROUE BLOQUEE* / RUEDA BLOQUEADA	RIBBED-P / *NERVURE-P* / ESTRIADO-P	100	30, 60, 90
B1-SLP	STUTT. REIBUNGSMESSER (CH)	FIXED SLIP / *GLISS. LONG.* / BLOQUEO PARCIAL FIJO	RIBBED-P / *NERVURE-P* / ESTRIADO-P	20	30, 60, 90
B2-LKD	SKIDDOMETER BV-8 (CH)	LOCKED WHEEL / *ROUE BLOQUEE* / RUEDA BLOQUEADA	RIBBED-P / *NERVURE-P* / ESTRIADO-P	100	30, 60, 90
B2-SLP	SKIDDOMETER BV-8 (CH)	FIXED SLIP / *GLISS. LONG.* / BLOQUEO PARCIAL FIJO	RIBBED-P / *NERVURE-P* / ESTRIADO-P	20	30, 60, 90
B3	SKIDDOMETER BV-11 (S)	FIXED SLIP / *GLISS. LONG.* / BLOQUEO PARCIAL FIJO	PATTERN / AVEC SCULTURE / CON DIBUJO	20	30, 60, 90
B4E-SLP	NORSEMETER OSCAR (N)	FIXED SLIP / *GLISS. LONG.* / BLOQUEO PARCIAL FIJO	BLANK-A / *SANS SCULPTURE A* / LISO-A	20	30, 60, 90
B4E-SWP	NORSEMETER OSCAR (N)	VARIABLE SLIP / *GLISS. VAR.* / BLOQUEO PARCIAL VARIABLE	BLANK-A / *SANS SCULPTURE A* / LISO-A	0-90	30, 60, 90
B5-ABS	STUTT. REIBUNGSMESSER (A)	OPTIMUM SLIP / *GLISS. OPT.* / DESLIZAMIENTO ÓPTIMO	RIBBED-P / *NERVURE-P* / ESTRIADO-P	OPT.	30, 60, 90
B5-LKD	STUTT. REIBUNGSMESSER (A)	LOCKED WHEEL / *ROUE BLOQUEE* / RUEDA BLOQUEADA	RIBBED-P / *NERVURE-P* / ESTRIADO-P	100	30, 60, 90
B5-SLP	STUTT. REIBUNGSMESSER (A)	FIXED SLIP / *GLISS. LONG.* / BLOQUEO PARCIAL FIJO	RIBBED-P / *NERVURE-P* / ESTRIADO-P	20	30, 60, 90
B6-501	ASTM E-274 TRAILER (US)	LOCKED WHEEL / *ROUE BLOQUEE* / RUEDA BLOQUEADA	RIBBED-A / *NERVURE-A* / ESTRIADO-A	100	65
B6-524	ASTM E-274 TRAILER (US)	LOCKED WHEEL / *ROUE BLOQUEE* / RUEDA BLOQUEADA	BLANK-A / *SANS SCULPTURE-A* / LISO-A	100	30, 65, 90
B6-CHP	ASTM E-274 TRAILER (US)	DRY PEAK / *MAX. SEC* / MÁXIMO EN SECO	PATTERN / *AVEC SCULPTURE* / CON DIBUJO	PEAK	65
B6-ULT	ASTM E-274 TRAILER (US)	DRY LOCKED / *BLOQUE SEC* / BLOQUEADA EN SECO	BLANK-A / *SANS SCULPTURE-A* / LISO-A	100	10
B7	BRITISH PENDULUM (CH)	SLIDER / *CURSEÚR* / ZAPATA	BLANK / *SANS SCULPTURE* / LISO	100	10
B10E	MUMETER (E)	SIDE FORCE / *GLISS. LAT.* / RUEDA OBLICUA	PATTERN / *AVEC SCULPTURE* / CON DIBUJO	13 (7.5°)	80

Table A.1 (continued) Skid resistance devices taking part in the PIARC trials

TABLE 1. CONTINUED
TABLEAU 1. SUITE
TABLA 1. CONTINUACIÓN

DEVICE ID IDENTIFICATION IDENTIFICACIÓN	DEVICE NAME DENOMINATION (PAYS) DENOMINACIÓN (PAÍS)	TYPE TYPE DE MESURE TIPO DE MEDIDA	TIRE TYPE TYPE DE PNEU TIPO DE NEUMÁTICO	SLIP1 TAUX DE GLISEEMENT TASA DE DESLIZAMIENTO (*) (%)	SPEED VITESSE VELOCIDAD (km/h)
C1	SKID RESISTANCE TESTER (P)	LOCKED WHEEL / *ROUE BLOQUEE* / RUEDA BLOQUEADA	PATTERN / *AVEC SCULPTURE* / CON DIBUJO	100	30, 60, 90
C3B	FLEMISH SCRIM (B)	SIDE FORCE / *GLISS. LAT.* / RUEDA OBLICUA	BLANK / *SANS SCULPTURE* / LISO	34 (20°)	30, 60, 90
C3E	CEDEX SCRIM (E)	SIDE FORCE / *GLISS. LAT.* / RUEDA OBLICUA	BLANK / *SANS SCULPTURE* / LISO	34 (20°)	30, 60, 90
C4	KOMATSU SKID TESTER (J)	VARIABLE SLIP / *GLISS. VAR.* / BLOQUEO PARCIAL VARIABLE	BLANK-A / *SANS SCULPTURE-A* / LISO-A	10-30%	30, 50, 60
C5	DWW TRAILER (NL)	FIXED SLIP / *GLISS. LONG.* / BLOQUEO PARCIAL FIJO	BLANK-P / *SANS SCULPTURE-P* / LISO-P	86	30, 50, 90
C6E	MOPT SCRIM (E)	SIDE FORCE / *GLISS. LAT.* / RUEDA OBLICUA	BLANK / *SANS SCULPTURE* / LISO	34 (20°)	30, 60, 90
C8	STRADOGRAPH (DK)	SIDE FORCE / *GLISS. LAT.* / RUEDA OBLICUA	BLANK-P / *SANS SCULPTURE-P* / LISO-P	21 (12°)	30, 60, 90
C9	WALOON ODOLIOGRAPH (B)	SIDE FORCE / *GLISS. LAT. / RUEDA OBLICUA*	BLANK-P / *SANS SCULPTURE-P* / LISO-P	26 (15°)	30, 50, 90
C10	CRR ODOLIOGRAPH (B)	SIDE FORCE / *GLISS. LAT.* / RUEDA OBLICUA	BLANK-P / *SANS SCULPTURE-P* / LISO-P	34 (20°)	30, 50, 90
D1E	SCRIM (D)	SIDE FORCE / *GLISS. LAT.* / RUEDA OBLICUA	BLANK / *SANS SCULPTURE* / LISO	34 (20°)	40, 60, 90
D2	SCRIM-GEOCISA (E)	SIDE FORCE / *GLISS. LAT.* / RUEDA OBLICUA	BLANK / *SANS SCULPTURE* / LISO	34 (20°)	30, 60, 80
D3	SCRIM (F)	SIDE FORCE / *GLISS. LAT.* / RUEDA OBLICUA	BLANK / *SANS SCULPTURE* / LISO	34 (20°)	30, 60, 90
D4	SUMMS (I)	SIDE FORCE / *GLISS. LAT.* / RUEDA OBLICUA	BLANK / *SANS SCULPTURE* / LISO	34 (20°)	30, 60, 80
D5	SCRIMTEX (UK)	SIDE FORCE / *GLISS. LAT.* / RUEDA OBLICUA	BLANK / *SANS SCULPTURE* / LISO	34 (20°)	30, 50, 90
D6	ADHERA-LCPC (F)	LOCKED WHEEL / *ROUE BLOQUEE* / RUEDA BLOQUEADA	BLANK-P / *SANS SCULPTURE-P* / LISO-P	100	40, 60, 90
D7B	PETRA (D)	VARIABLE SLIP / *GLISS. VAR.* / BLOQUEO PARCIAL VARIABLE	PATTERN / *AVEC SCULPTURE* / CON DIBUJO	0-100%	30, 60, 90
D8	GRIPTESTER (UK)	FIXED SLIP / *GLISS. LONG.* / BLOQUEO PARCIAL FIJO	BLANK / *SANS SCULPTURE* / LISO	14.5	5, 30, 65, 90

(*) **For side force devices the equivalent slip is given followed by the yaw angle in parenthesis.**
(*) *Pour les mesures de SFC, le taux de glissement correspond à l'angle d'envirage donné entre parenthèses.*
(*) Para los equipos de rueda oblicua, el grado de deslizamiento equivalente figura seguido por el ángulo de deriva entre paréntesis

RIBBED-P = PIARC ribbed tire
BLANK-P = PIARC smooth tire
RIBBED-A = ASTM ribbed tire (E-501)
BLANK-A = ASTM smooth tire (E-524)
PATTERN = Tires with various tread patterns

NERVURE-P = pneu nervu'r AIPCR
SANS SCULPTURE-P = pneu lisse AIPCR
NERVURE-A = pneu nervuré ASTM (E-501)
SANS SCULPTURE-A = pneu lisse ASTM (E-524)
AVEC SCULPTURE = pneus comportant diverses sculptures de bande de roulement

ESTRIADO-P = neumático estriado AIPCR
LISO-P = neumático liso AIPCR
ESTRIADO-A = neumático estriado ASTM (E-501)
LISO-A = neumático liso ASTM (E-524)
CON DIBUJO = neumático con diferentes dibujos

Table A.2 Texture measurement devices taking part in the PIARC trials

TABLE 2. LIST OF TEXTURE EQUIPMENT
TABLEAU 2. LISTE DU MATERIEL DE MESURE DE TEXTURE
TABLA 2. LISTA DE EQUIPOS DE MEDIDA DE TEXTURA

DEVICE ID *IDENTIFICATION* IDENTIFICACIÓN	DEVICE NAME *DENOMINATION (PAYS)* DENOMINACIÓN (PAÍS)	TYPE *TYPE DE MESURE* TIPO DE MEDIDA	SPEED *VITESSE* VELOCIDAD (km/h)
A1	FHWA TEXTURE VAN (US)	RMS	30
A2	VTI MOBILE PROFILOMETER (S)	RMS, ETD, TDMA, MPD	36
A3B	ARAN (CAN)	MPD, RMS	30, 60, 80
A3E	AEPO RST (E)	MACRO-MEGATEXTURE / *MACRO-TEXTURE* / MACRO-MEGATEXTURA	30
A4	CRR MOBILE PROFILOMETER (B)	MPD, RMS	18, 36, 72
A5	CRR STATIONARY PROFILOMETER (B)	MPD, RMS	0
A8	ASTM E-965 SANDPATCH (US)	MTD	0
A12	ROSAN (US)	MTD (CALCULATED) / *MTD (CALCULEE)* / MTD (CALCULADA)	5
B8	OUTFLOW METER (CH)	OUTFLOW TIME / *TEMPS D'ECOULEMENT* / TIEMPO DE DESAGÜE	0
B11E	OUTFLOW METER (US)	OUTFLOW TIME / *TEMPS D'ECOULEMENT* / TIEMPO DE DESAGÜE	0
D2	GEOCISA SCRIM (E)	MTD (CALCULATED) / *MTD (CALCULEE)* / MTD (CALCULADA)	60
D3	RUGOLASER (F)	HSC, RA, RQ	60
D4	SUMMS (I)	MTD (CALCULATED) / *MTD (CALCULEE)* / MTD (CALCULADA)	50
D5	SCRIMTEX (UK)	MTD (CALCULATED) / *MTD (CALCULEE)* / *MTD (CALCULADA)*	50

Table A.3 Skid resistance devices taking part in the HERMES trials

Code	Device Name	Operator Organisation (Country)	Key Operating Principles*	Thumb-nail Photograph
F01	*DWW* Trailer	*DWW* Rijkswaterstaat (NL)	86% Fixed Slip. *PIARC* Radial smooth tyre at 200 kPa. 0.5 mm water film thickness.	
F02	ADHERA	*CETE* de Lyon (FR)	Locked Wheel. smooth *PIARC* tyre at 180kPa. 1.0 mm water film thickness.	
F03	SCRIM	*CEDEX* (ES)	Side Force 20º wheel angle. Avon SCRIM smooth tyre at 350 kPa. 0.5 mm water film thickness.	
F04	SCRIM	*MET* (BE)	Side Force 20º wheel angle. Avon SCRIM smooth tyre at 350 kPa. 0.5 mm water film thickness.	
F05	Grip-Tester	*MET* (BE)	15% fixed slip. 254 mm (10") dia. smooth tyre at 138 kPa. 0.5 mm water film thickness.	
F06	ROAR	*DRI* (DK)	Variable slip device run at 20% fixed slip. *ASTM* 1551 smooth tyre. 0.5 mm water film thickness.	
F07	ROAR	*DWW* Rijkswaterstaat (NL)	Variable slip device run at 86% fixed slip. *ASTM* 1551 smooth tyre. 0.5 mm water film thickness.	
F08	Odolio-graph	*BRRC* (BE)	Side Force 20º wheel angle. *PIARC ASTM* E525 88 smooth tyre **. 0.5 mm water film thickness spread by preceding tanker.	
F09	PFT	*TRL* (GB)	Locked wheel. *ASTM* E524 smooth tyre at 200 kPa. 1.0 mm water film thickness.	
F10	OSCAR	(*NPRA/NRRL*) (NO)	Variable slip device run at 18% fixed slip. *ASTM* E524 smooth tyre at 207 kPa. 0.5 mm water film thickness.	

Code	Device Name	Operator Organisation (Country)	Key Operating Principles*	Thumb-nail Photograph
F11	ROAR II	Statens Vegvesen (NO)	Variable slip device run at 18% fixed slip. *ASTM* E1551 smooth tyre. 0.5 mm water film thickness.	
F12	SRT-3	*IBDIM* (PL)	Locked wheel. Commercial patterned tyre at 200 kPa. 0.5 mm water film thickness.	
F13	SCRIM	*TRL* (UK)	Side Force 20º wheel angle. Avon SCRIM smooth tyre at 350kPa. Water flow 0.95l/s giving 0.5mm water film thickness at 50km/h and 0.25mm at 90km/h.	
F14	Odolio-graph	*MET* (BE)	Side Force 20º wheel angle. PIARC *ASTM* E525 88 smooth tyre **. 0.5 mm water film thickness spread by preceding tanker.	
F15	IMAG	*STBA* (FR)	15% Fixed slip. Smooth *PIARC* tyre. 1.0 mm water film thickness.	

Tyre pressures are given in SI units to the nearest kPa based upon information provided by the Operating Organisation *(some operators use Imperial (UK) or Metric units).* The water film thickness given here is the theoretical water film thickness at which the device normally operates when wetting the road for a test, as advised by the Operating Organisation. *(For some devices this is controlled automatically by varying the flow rate according to the test speed, for others a fixed flow rate may be used that results in a slight variation in water film thickness at different operating speeds. In most cases in the HERMES trials, apart for the first machine on the first test run, the road surface had already been wetted by preceding devices).*

** The Hermes report states "PIARC ASTM E525 88 smooth tyre" for both Odoliographs. This should probably be either "PIARC smooth tyre" or ASTM E524(!) smooth tyre"

Table A.4 Texture devices used in HERMES trials

Device Code	Name of Equipment	Nationality	Operator Organisation
T1	GREENWOOD	DK	Danish Road Institute
T2	ARAN	NL	DWW Rijkswaterstaat
T3	Rugolaser	FR	CETE de Lyon
T4	GEOCISA	ES	CEDEX
T5	HARRIS	GB	TRL
T6	ROAR	NO	Statens Vegvesen
T7	SCRIMTEX	GB	TRL
T8	Stat TX meter	BE	BRRC

Annex B: CEN TC 227 WG5 harmonisation strategy proposal

Doc. CEN/TC227/WG5 N° 176 E rev. 2005-06-01

Strategy of Working Group CEN/TC227/WG5 to develop a European Standard of test method for the dynamic measurement of road and airfields pavement skid resistance ("new prEN 13036-2")

During its meeting in Paris on 25-26 November 2004, CEN/TC 227/WG 5 discussed and defined a step-by-step strategy to develop a European Standard of test method for the dynamic measurement of pavement surface friction : the strategy was presented to CEN/TC 227/Chairman's Panel (Berlin, 3 December 2004). It was confirmed and finalized during the last meeting of WG 5 (Vienna, 12-13 May 2005)

Context

WG 5 has taken into account:

- the decision of CEN Authorities to delete prEN 13036-2 for "administrative" reasons (excessive delay between CEN Inquiry and Formal Vote stages),
- the urgent need for a test method to assess skid resistance properties of road materials as mandated by Mandate M 124 (in the first generation of European standards , that concerns Surface Dressings and Slurry Surfacings only),
- the available knowledge on skid resistance measurement – comparison of the existing European test methods and feasibility of their harmonization – as issued from the HERMES pre-normative research project conducted by FEHRL (final report to be published in Summer 2005),
- the current level of equipment of European countries with machines for measuring texture and friction (due to their investment value, they can not be easily replaced in a short term period),

Strategy

CEN/TC 227/WG 5 declares to be unable to rapidly produce an Harmonised European standard for the measurement of roads an airfields pavement surface friction by using a single dynamic method, independent of any particular device, providing consistent and reliable results: unfortunately the current definition (as issued from HERMES project) of a common scale of European friction index (EFI) appears not to be precise enough for use in defining the properties of CE marked materials.

The following progressive (step-by-step) strategy is proposed.

i) In the short term (from now to 3 or 5 years)

a) *For the assessment of mandated skid resistance properties of Surface Dressings and Slurry Surfacings*

The assessment method should be based on:

- the specifications and measurement of proxy characteristics dealing with skid resistance properties : maximum size, shape and angularity of aggregates for initial and durable level of skid resistance, and PSV of aggregates for the durability of skid resistance,
- the measurement of the macrotexture MPD according to EN ISO 13473-1 of the product in place on the road

> Note 1 : dynamic in situ friction measurements are not required at this stage (for slurry surfacings or microsurfacings with fine granularity the friction measurement according to EN 13036-4 should be usefully considered)
> Note 2 : among the three standardized test methods (EN ISO 13473-1, EN 13036-1, EN 13036-3) to assess pavement surface macrotexture, it appears desirable that MPD index (Mean Profile Depth) calculated from texture profile measurements will be the reference value due to its relevance and its metrological confidence (previously, the MTD index – Mean Texture Depth – by the Patch Test method was the reference value). For FPC procedures, MTD index can be still used (with a recommendation to substitute MPD progressively).

As a consequence of such proposal, the current draft of Annex G of prEN 12271 prepared by CEN/TC227/WG2 (out to CEN Enquiry currently) has to be deleted and replaced by appropriate text. By the same way, the project of new answer of TC 227 to mandate M 124 (doc. CEN/TC 227 N° 0727 rev.2) has to be deleted or modified , at least in the part related to skid resistance properties of surface treatments : any reference to the use of dynamic friction measurement has to be deleted, at least in the short term.

b) *For the other applications (including road surveys)*

CEN/TC227/WG5 will prepare a draft of Experimental standard based on:

- the measurement of macrotexture MPD according to EN ISO 13473-1,
- the measurement of EFI according to the current results of the HERMES research project and based on the use of the existing measuring equipment in service in Europe calibrated versus a floating reference,
- the development of a set of harmonized operation and Quality Assurance procedures (with a status of Technical Specifications) to be applied to each family of friction measuring equipment.

ii) In the mid term (from 3 or 5 years to 10 years)

For any application, including the assessment of mandated properties:

CEN/TC227/WG5 will prepare a draft of Harmonized standard based on :

- the measurement of macrotexture MPD according to EN ISO 13473-1,
- and the measurement of a "new" EFI, defined according to the calibration of data provided by the existing equipment in service in Europe versus an elected reference device and reference surfaces (objectives and scope of a new pre-normative research project to be requested by CEN/TC227 and conducted by FEHRL (?)),
- the development of harmonized Quality Assurance procedures to be applied to the measuring equipment.

iii) In the longer term (over 10 years)

For any application, including the assessment of mandated properties:

CEN/TC227/WG5 will prepare a draft of Harmonized standard based on :

- the measurement of macrotexture MPD according to EN ISO 13473-1,
- the measurement of a friction index with a common and single European measuring equipment (which remains to be defined and designed),
- QA procedures to be applied to the equipment.

Drafted by M. Boulet, convener of CEN/TC227/WG5

Annex C Requirements for a future reference method (i.e. device + conditions) for tyre/road friction measurements.

The HERMES project investigated the preferable requirements for a possible "reference device" (and its operating conditions) as an alternative to the practice in which the “grand average” of all devices provides a floating reference. This Annex describes and discusses these requirements.

C.1 What is a reference device?

This device would, in the future, possibly take over the role of the calibration process in the proposed European standard (prEN 13036-2:2003) by providing a direct reference, rather than the practice adopted in HERMES in which the “grand average” of all devices provides a floating reference. Groups of different combinations of devices can meet at different places at regular intervals for calibration purposes. In the long term, a fleet of devices of this type could possibly replace the many different devices now in used in Europe.

In approaching its objective, the HERMES working group proposed that the “reference device” should be a friction device to which any device currently in use could be compared.

C.2 Repeatability and reproducibility

Good repeatability and reproducibility are desired for the reference friction measurement device. Exactly how good repeatability and reproducibility are really required, depends on the use that is going to be made of the results. This may well differ between e.g. winter operation of runways and roads, network monitoring and management, acceptance testing.

Many countries that have an existing fleet of one or more device configurations in use, will want the reference device configuration to achieve at least the same repeatability and reproducibility as their current fleet. This would probably mean a required repeatability of less than about 0.05 (in friction coefficient units, $\sigma_r \leq 0.02$) and a reproducibility of less than about 0.08 (in friction coefficient units, $\sigma_R \leq 0.03$).

It cannot yet be defined what values are achievable. The actual spatial and temporal variability of the road surface and its friction characteristics impose limits on the possible repeatability and reproducibility of friction measurements.
Achievable values might be derived from the repeatability and reproducibility values stated in the CEN Technical Specifications for twelve device types. However, a rough view of the HERMES repeatability data (average repeatability 0.07) seems to suggest that:

- either there were a number of devices in HERMES with much worse repeatability than the above mentioned values
- or the TS-devices may have performed less repeatable in HERMES than stated in the Technical Specifications

A more detailed analysis of the HERMES repeatability data seems necessary to resolve this.

C.3 Review of suggested requirements from the HERMES experiment

One objective of the HERMES project was to develop a specification for a single friction and texture measurement device. It was decided that, before drawing up a specification, it would help if there was a proper understanding of the needs within Europe and to see whether it was possible to conduct all friction tests with a single device. To this end, the HERMES working group sent a questionnaire to all FEHRL members. The questionnaire identified the main potential areas of use for the device (excluding accident investigation, which in this context was regarded as a special case of the research category) and asked respondents to indicate which principles and key parameter ranges they thought would best meet their needs. In the latter case, the respondents were asked to “agree” or “disagree” with the proposal that the device should use the feature concerned. A question was included as to whether simultaneous measurements of surface texture would be required.

Twelve replies were received and syntheses of the results of this enquiry have led to nine requirements and a list of recommended uses; these are briefly discussed in the following sections.

Recommended uses

In different countries, the measurements may be made for various purposes:

- On new works to check the quality level of the work;
- In surveys of skid-resistance characteristics of in-service roads to assist in identifying areas requiring treatment and to prioritise maintenance works;
- On airfield surfaces in real conditions, to give the information about runway condition to the pilots before landing;
- For accident investigation;
- For research (for example, developing new friction models, assessing the behaviour of new types of wearing courses, testing the influence of different parameters on skid resistance, etc.).
- For type approval of pavement materials or pavement products, like high-grip thin surfacings.

Continuous measurements

The primary purpose of the reference device is to provide a means of calibrating other devices, with the secondary potential to become a routine tool. In that regard, it would need to be capable of continuous surveys. In either case, the device should be able to carry out repeated tests on long sections of road without serious rapid deterioration of the test tyre.

Measurement principle

Because this was to be a reference device, in order to minimise concerns over possible adverse effects such as transverse deformation of the tyre during a test and the uneven tyre wear that can occur using an angled wheel, it was decided that inline braking should be used. To meet the continuous measurement requirement, a locked-wheel system would not be suitable and therefore the basic operating principle of the device should use inline controlled slip.

Normal operating speeds

Three normal operating speeds are proposed: 40, 60 and 80 km/h. This range of speeds will assist safe operation on most types of road, for example: 40 km/h for urban roads, 60 km/h on main roads and 80 km/h on motorways. This also provides a range of speeds for comparative tests with other devices for calibration purposes. Clearly, for research use, other speeds may also need to be used.

Use of several different slip ratios to provide a constant slip speed

The HERMES report (Descornet et al 2006) states: "For calibrating other devices, the reference device should, ideally, record its measurements directly at the reference slip speed of 30 km/h. This value was chosen in HERMES to minimise the (im)precision (repeatability and reproducibility) of the European Friction Index (EFI). However, since the device will need to operate at different speeds in practice, this imposes a special requirement on its operation. In order to achieve a constant slip speed, the actual speed of the test wheel will need to be measured and compared with the vehicle speed so that the slip ratio can be varied depending upon the vehicle speed:

- A test speed of 40 km/h requires a slip ratio of 75%;
- A test speed of 60 km/h requires a slip ratio of 50%;
- A test speed of 80 km/h requires a slip ratio of 37.5%."

The text above seems to suggest that the slip ratio should be fully variable and automatically speed-controlled. Thus, not only could different slip ratios be chosen for different target operating speeds, but also could the slip ratio be continually adapted to correct for small deviations from the target speed. However, the proposed specifications in Annex L of the HERMES report (see Annex D of this report) do not explicitly state such full variability.
The specifications mention (section 7.7): "The device should be able to vary and control the slip ratio such that the tire slides over the surface at the same slip speed for the 3 chosen nominal test speeds (40, 60 and 80 km/h)). For this purpose, three different slip ratios are required." Section 7.2 mentions "These brake conditions can be reached either with a normal well-controlled brake, or with another mechanical or hydraulic system, which allows a constant chosen slip ratio of the test wheel to be maintained."

So the specifications only require three different speed ratios, although the mention of a brake suggests a larger variability. It would probably be more practical to construct a number of preset slip ratios by means of a gear box. Small variations in operating speed would then influence the results, but this could be acceptable within limits.

Of course, a fully variable speed-controlled system would have some advantages, but the HERMES experiment found that such systems may have problems keeping the slip ratio constant when confronted with varying levels of skid resistance (even when speed remains constant) (Descornet et al 2006)

Static vertical load

For the reference device, a value of 3000 N was chosen because it was more representative of the average load of a normal quarter passenger car. Because the actual momentary vertical load on the tyre can deviate from the static value, due to vehicle dynamics, the vertical load should be measured as frequently as the horizontal load.

Dynamic vertical load

Even with damping on the test wheel suspension, roughness or unevenness of the road can induce variations in the vertical load applied to the test wheel. Additionally, the response of the vehicle suspension relative to the test wheel (when entering, leaving or negotiating a curve, for example) may also have an effect on the dynamic load. For this reason, the reference device should continuously measure the vertical load and use this value when converting frictional force to coefficient of friction.

Water film thickness

The reference device will make measurements on a wet road and it should carry its own water supply to wet the road just in front of the test wheel.

The theoretical water film thickness can be defined as the water depth obtained on a perfectly flat, smooth and waterproof surface. The actual water film thickness will depend on the surface to which it is applied and will be affected by the texture and porosity of the surface as well as the way in which it is applied. Other practical issues such as air currents (both from side winds and the vehicle slipstream) may also influence the actual application of water. A value of 0.5 mm was chosen since it is already widely used by current European devices. It is also a value that should give a reasonable operating range for the reference device.

Test tyre

It was decided that the device should use a tyre that was similar to a normal passenger car tyre under worst conditions, i.e., with a smooth tread so that the device would test the road surface characteristic and not the wear level of the tyre. The chosen tyre is that recommended by PIARC Committee C1 which specifies, in addition to the smooth tread, other characteristics such as compound, size (similar to a normal passenger car tyre), inflation pressure, hardness/resilience and storage conditions. Research has shown that the reproducibility of test tyre characteristics has a large influence on the reproducibility of the friction measurement values.

Other parameters to be measured or controlled

Clearly, the horizontal force must be measured during the test, as must the distance travelled. The operating speed should be measured and recorded (the speed is also needed in order to determine and control the slip ratio).

In order to ensure that the measurements at different speeds reflect any the variations along the road, the sampling interval (i.e. the period over which instantaneous values of the forces

are aggregated in order to provide a sample) should be based on the travelled distance and not on elapsed time. It was decided that a sample value should be obtained at least every 100 mm (i.e. a sampling frequency of up to 220 Hz at 80 km/h).
To suppress “noise” due to vibrations, the horizontal and vertical force samples will be averaged over 10 m before calculating the coefficient of friction.

HERMES proposes that the reference device should also measure macrotexture and mega texture in the line of friction measurement, according to ISO 13473-1 and 13473-5 respectively. When the reference device measures at a slip speed of 30 km/h, these measurements are not strictly necessary, as there is no need of macrotexture input for slip speed conversion. Still, these measurements are recommended, both for research purposes and to check the macrotexture measurements of the devices to be calibrated against the reference. (Macrotexture mismatch between reference device and the other device may more often result from different positions on the pavement than from measurement errors, but still would indicate calibration challenges.)

C.4 Likely candidates to become the European reference device

There are several candidate device types that seem to be most likely to become the European reference device (in alphabetical order):

- IMAG (because the IMAG is the reference device for the IRFI, and therefore choosing the IMAG would harmonise measurements for roads and airports) (15% slip ratio)
- HERMES reference device proposal (because of historic support), like e.g. implemented in RoadSTAR
- RoadSTAR in its standard configuration at 18% slip ratio (because it matches the HERMES proposal, except for the three different slip ratios)
- SCRIM (because of present widespread use)

However, it is possible that another device type (either existing or still to be developed) will be adopted, for whatever reasons (e.g. technical or political).

C.5 Discussion

Because of differing traffic situations in practice, skid resistance measurement should be possible at two speeds or speed ranges at least ("low" e.g. 40 km/h for urban situations and tight curves, "high" e.g. 80 km/h for highways). How should these different measuring speeds be dealt with in harmonisation? There are three main options.

- adopt different scales for different speeds (i.e. partial harmonisation in stead of full harmonisation),
- use different slip ratios for different speeds (HERMES-proposal), or
- use some sort of “speed correction" (e.g. HERMES Sp-factor or others)

One of the striking features of the HERMES proposal for the reference device is its variable slip ratio. This enables the device to measure at the reference slip speed of 30 km/h, while operating at other speeds to merge with traffic. This is expected to eliminate the need for conversion formulas for different operating speeds. However, it is not yet proven that a constant slip speed would yield a constant measurement value for the friction coefficient at different operating speeds. Given the information in section 6.9 this may even be doubted.

If the friction coefficient would be influenced by both slip ratio and operating speed separately, and not by slip speed alone, there would be no real need for a variable slip ratio[10].
If a single slip ratio would be chosen, this could significantly simplify the reference device, and eliminate the problems associated with adjusting and controlling the slip ratio.

It could be that a variable slip ratio for the reference device would be useful during the transition period, to better be able to correlate local devices to the reference, but could be altered to a fixed slip ratio when the transition period is over.

Regarding the choice of a fixed slip ratio, Figure 7.2 suggests that one of two main options has to be chosen:

1. aim for the peak friction force (i.e. at a slip ratio of about 12-18%), with the advantage that variations in operating speed do not significantly influence the results, but that variations in slip ratio may have significant influence. Additional advantage is that modern non-blocking braking systems (ABS) often operate around this peak, so the device becomes more representative of the (future) practical situation. However, this is a "best case" regarding friction coefficient and braking distance, whereas safety considerations might urge to use a "worst case" value, especially while not all vehicles have ABS.
2. keep well away from the peak friction force (i.e. at slip ratios above ca. 30%), making the device less sensitive to variations in slip ratio, but more sensitive to variations in operating speed. Variations in slip ratio may occur due to wear of the measurement tyre, or due to inaccuracies or retarded response of servo-controlled variable slip systems.

Figure 7.2 also suggests that slip ratio between 0 and 12%, and between 18 and 30% should be avoided, as these are too sensitive for small deviations of slip ratio.

[10] Such a variable slip ratio still would be very helpful for research purposes, and maybe for intermediate steps in calibration of different types of friction measurement devices to a common reference scale.

Annex D: Proposed specification for a reference device (Annex L of HERMES report)

CEN TC 227
Date : 2004-04

prEN 13036-2a

CEN **TC 227**
Secrétariat: DIN

Road and airfield surface characteristics — Test methods — Part 2: Procedure for determination of skid resistance of a pavement surface using a reference device (LFC)

Caractéristiques de surface des routes et aéroports — Méthodes d'essai — Partie 2 : Procédure pour déterminer l'adhérence d'une surface de chaussée en utilisant un appareil de référence (CFL)

Oberflächeneigenschaften von Straßen und Flugplätzen — Prüfverfahren — Teil 2: Verfahren zur Messung der Griffigkeit

ICS :
Descripteurs :
Type de document : Norme européenne
Sous-type de document :
Stade du document :
Langue du document : E

1 Foreword

This European Standard has been prepared by Technical Committee *CEN* TC 227 *WG*5 Surface Characteristics and accepted by a vote on [Insert date] by a simple majority.

2 Introduction

The skid resistance of a surface is determined by considering the friction measurement carried out using one reference device, and a measurement of surface texture also carried out using one of a number of permitted procedures. The skid resistance may be reported as either a friction measurement or as a combination of friction and texture measurements.

3 Scope

3.1 This test method covers the measurement of skid resistance of paved surface using a standard reference test tyre as describe in Annex A.

3.2 This test method utilizes a measurement representing the steady-state friction force on a braked test wheel as it is dragged over a wetted pavement surface under controlled load and at a controlled speed while its major plane is parallel to its direction of motion and perpendicular to the pavement.

3.3 The value measured represents the frictional properties obtained with the equipment and procedures stated herein. The values are intended for use in evaluating the skid resistance of a pavement and more precisely the micro texture level of the pavement surface, or the polishing state of the trafficked wheel paths. To estimate the micro texture of a pavement surface it is necessary to evaluate the friction at low slip speed (under 40 km/h slip speed). For a longitudinal braking force system this low slip speed level could be reached either with a low *slip ratio* associated with a low operating speed, either a high *slip ratio* associated with a normal or high operating speed. To estimate also the macro texture of the pavement surface a laser system is used. This system is placed just before the test wheel in order to be able to measure macro texture on dry surface (we need to wet the surface for the skid resistance measurement) and on the same path as the friction measurement. This standard doesn't describe the macro texture measurement because this measurement and the devices, which are used for this measurement, are well described in other standards (EN *ISO* 13473-1, *ISO* 13473-2, *ISO* 13473-3).

3.4 The test method and the apparatus describe in this standard could be the ones used by and as a reference device which could be used at short term as a reference for the other existing devices and at more long term as the only one method and device. The proposed specifications do not correspond to any existing device.

4 Normative references

This European standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies.

EN *ISO* 13473-1, *Characterization of pavement texture using surface profiles — Part 1: Determination of Mean Profile Depth.*

EN 13036-1, *Road and airfield surface pavement characteristics — Test methods — Part 1: Measurement of pavement surface macro texture depth using a volumetric patch technique.*

EN 13036-2, *Road and airfield surface pavement characteristics — Test methods — Part 2: Procedure for determination of skid resistance of a pavement surface.*
EN 13036-3, *Road and airfield surface pavement characteristics — Test methods — Part 3 Measurement of pavement surface horizontal drainability.*
ISO 13473-2, *Characterization of pavement texture using surface profiles — Part 2: Terminology and basic requirements related to pavement texture profile analysis.*
ISO 13473-3*, Characterization of pavement texture using surface profiles — Part 3: Specifications and classification of profilometers.*

5 Terms and definitions

For the purposes of this European standard, the following terms and definitions apply.

5.1 friction
resistance to relative motion between two bodies in contact. The frictional force is the force, acting tangentially in the contact area, which is measured by a friction-measuring device.
The results from the friction-measuring device are commonly known as a device coefficient or friction value.

5.2 braking force coefficient
ratio between the longitudinal frictional force and the load on the test tyre. This coefficient is without dimension.

5.3 skid resistance
property of the trafficked surface that develops friction between a moving tyre and the pavement surface
There are numerous factors, which contribute to skid resistance, in particular:
The physical properties of specific friction measuring devices - the contact pressure, contact area, tread pattern and rubber composition of the tyre, or slider in the case of some test devices.
The slip speed of the tyre/slider over the surface and the vehicle speed,
Surface conditions, i.e. wet or dry, clean or contaminated surface, as well as air and water temperature.
The surface texture characteristics of the road surface i.e. the micro texture and macro texture of the surface.

5.4 skid resistance index (*SRI*)
objective estimate of skid resistance, which is independent of the friction-measuring device, used as defined in EN 13036-2.
NOTE The *SRI* is intended to facilitate objective comparison of surfaces, and is based on friction and macro texture measurements and subsequent calculations. The friction measured with a particular device is combined with corresponding macro texture data as well as pre-determined device-related constants representing most devices used in Europe, normalized to a certain fixed slip speed, to calculate the *SRI* (see Annex B of EN 13036-2).

5.5 micro texture
deviation of a pavement surface from a true planar surface with characteristic dimensions along the surface of less than 0.5 mm, corresponding to texture wavelengths with one-third-octave bands with up to 0.5 mm of centre wavelengths.
NOTE 1 Peak to peak amplitudes normally vary in the range 0.001 mm to 0.5 mm.

NOTE 2 Micro texture is a primary component in skid resistance at slow speeds. Those devices that utilize a relatively low slip speed measure primarily the component of friction affected by micro texture.

5.6 macro texture
deviation of a pavement surface from a true planar surface with characteristic dimensions along the surface of 0.5 mm to 50 mm, corresponding to texture wavelengths with one-third-octave bands including the range 0.63 mm to 50 mm of centre wavelengths.
NOTE 1 Peak to peak amplitudes normally vary in the range 0.1 mm to 20 mm.
NOTE 2 Macro texture is a major factor influencing skid resistance at high speeds but it also has an effect at low speeds.

5.7 mean profile depth
descriptor of macro texture, obtained from a texture profile measurement as defined in EN *ISO* 13473-1.

5.8 mean texture depth
result of the volumetric measurement of macro texture in accordance with EN 13036-1.

5.9 estimated texture depth
value obtained when a transformation equation is used to estimate the Mean Texture Depth from Mean Profile Depth as described in EN *ISO* 13473-1.

5.10 calibration
periodic adjustment of the offset, gain and linearity of the output of a measurement method so that all the calibrated devices of a particular type deliver the same value within a known and accepted range of uncertainty, when measuring in identical conditions within given boundaries or range of parameters.
NOTE The method of calibration of the reference device is given in paragraph 7.

5.11 operating speed
speed at which the device traverses the surface.

5.12 slip speed
relative speed between the tyre and the travelled surface in the contact area.

5.13 slip ratio
quotient of the slip speed divided by the operating speed.

5.14 wheel path
parts of the pavement surface where the majority of vehicle wheel passes are concentrated.

6 Summary of the test method

6.1 The test apparatus consists of one or more test wheels that either are incorporated into an automotive vehicle, or form part of a suitable trailer towed by a vehicle. It must be built in such way as to be able to measure the friction coefficient on the right or on the left side of the vehicle. This requirement could be achieved with one test wheel that can be moved easily from one side to the other of the vehicle or trailer, or by two test wheels one mounted on each side of the vehicle. In the latter case, the two test wheels shall be capable of operation either together or separately. The apparatus contains a transducer, instrumentation, a water supply and proper dispensing system, and, if needed, actuation controls for the test wheel brake. The test wheel is equipped with a standard pavement test tyre. See Annex A for tyre references.

6.2 The test apparatus is brought to the desired test speed. Water is delivered ahead of the test tyre and if needed the braking system is actuated to retard the test wheel so that the wheel an tyre rotate with the defined *slip ratio*. The resulting friction force acting between the test tyre and the pavement surface (or some other quantity that is directly related to this force) and the speed of the test vehicle are recorded with the aid of suitable instruments. It is necessary that all the sensors used for the measurement work with the same response time. If there is more than one test wheel, it is also necessary that the sampling interval used be based on a defined, constant, measured length.

6.3 The skid resistance of the paved surface is determined from the resulting force or torque record and reported as friction coefficient (FC) which is determined from the force required to slide the braked wheel (longitudinal braking force measurement), at a stated speed, divided by the effective wheel load and multiplied by 100.

7 Apparatus

Listed below are the minimum requirements to provide a good repeatability and reproducibility of the device:

7.1 Vehicle- the vehicle shall be capable of maintaining any specified test speed in the range 40 to 80 km/h to +/- 2 km/h during a test on a level pavement having a friction coefficient of 0.80.

7.2 Braking system- The test wheel shall be equipped with a suitable brake. The brake system shall be capable of retarding the wheel under the conditions specified in 7.1 and maintaining the required braked-wheel condition throughout the test. These brake conditions can be reached either with a normal well-controlled brake, or with another mechanical or hydraulic system, which allows a constant chosen *slip ratio* of the test wheel to be maintained.

7.3 Static wheel load- The apparatus shall be of such a design as to provide an equal static load of 3000 N +/- 45 N to each test wheel.

7.4 Dynamic wheel load- During the test the apparatus shall be able to measure the vertical load within +/- 1% and with the same time response as the other measurements made during the test.

7.5 Tyre and Rim- The test tyre shall be of a normal passenger car size, smooth and one of the standard tyres for the pavement test as specified in Annex A. As indicated in this annex, it shall be mounted on a suitable rim. Since all rims do not have the same offset from the hub, replacement rims must be of the same offset to ensure consistent alignment of the tire with the water path. In any case the rim offset shall not be more than 8 mm.

Note: The rim offset is the distance between the rim's centre line and its mounting surface. The following diagram shows why it is important to retain proper offset when a rim is changed: a tire which is not centred properly affects driveability (negative roll radius changes), bearing load, rubbing on the struts or wheel arches, etc.

Cross sectional view of a rim:

```
     Centre Plane
|\____+____/|
|_____.____ |  Street Side of Rim
      .  //
      . //
      . ||  Mounting Face
      . ||
     >--< Rim Offset
```

7.6 Test speeds. In order to be able to measure the friction level of different networks, the apparatus shall be able to operate at each of the three following test speeds: 40 km/h, 60 km/h and 80 km/h (see also 10.5).

7.7 *Slip ratio*-
The device should be able to vary and control the *slip ratio* such that the tire slides over the surface at the same slip speed for the 3 chosen nominal test speeds (see paragraph 7.6). For this purpose, three different *slip ratios* are required. For the purposes of this standard, the common slip speed shall be 30 km/h, the slip speed value indicated as the reference speed for the *SRI* calculation. Therefore:

- for a test speed of 40 km/h it is necessary to apply a *slip ratio* of 75%,
- for a test speed of 60 km/h it is necessary to apply a *slip ratio* of 50%,
- for a test speed of 80 km/h it is necessary to apply a *slip ratio* of 37.5%.

The friction coefficients obtained on the same surface when using each of these three test speeds will not necessarily be equivalent. However, the apparatus, after calibration and calculation of its *"A"* and *"B"* values, will be able to calculate the *SRI* value for each of these test speeds and these *SRI* values shall be equivalent (see paragraph 5.3).

7.8 Instrumentation:

7.8.1 General requirements for measuring system- The instrumentation system shall conform to the following overall requirements at ambient temperatures between 4 °C and 40 °C.
Overall system accuracy of 1.5% (for example at 900 N, applied calibration force of the system output shall be determinable within +/- 14 N).
The exposed portions of the system shall tolerate 100% relative humidity (rain or spray) and all other adverse conditions, such as dust, shock, and vibrations, which may be encountered in normal test operations.

7.8.2 Force-measuring transducer- A tyre force-measuring transducer shall be of such design as to measure the force generated at the tyre-road interface with minimum inertial effects. It is recommended that the transducer should provide an output directly proportional to force, with hysteresis less than 1% of the applied load, non linearity less than 1% of the applied load up to the maximum expected loading, and sensitivity to any expected cross-axis loading or torque loading less than 1% of the applied load. The force transducer shall be mounted in such manner as to experience less than 1 deg angular rotation with respect to its measuring plane at the maximum expected loading.

7.8.3 Torque-measuring transducer- A torque transducer provides an output directly proportional to torque, with hysteresis less than 1% of the applied load and nonlinearity up to the maximum expected loading less than 1% of the applied load. It should have sensitivity to any cross-axis loading less than 1% of the applied load.

7.8.4 Additional transducers- A force transducer for measuring quantities such as vertical load, etc., shall meet the recommendations stated in 7.8.2.

7.8.5 Vehicle speed-measuring transducers- Transducers such as free-rolling wheel coupled tachometers shall provide speed resolution and accuracy of +/- 1.5% of the indicated speed or +/- 0.8 km/h whichever is greater. Output shall be directly viewable by the driver and shall be simultaneously recorded.

7.9 Signal conditioning and recorder system:

7.9.1 Minimum sampling interval- The minimum sampling interval both for vertical and horizontal force applied to the test wheel should be less than 12 cm.

7.9.2 Transducers that measure parameters sensitive to inertial loading shall be designed or located in such manner as to minimize this effect. If the foregoing is not practical, data correction must be made for these effects if they exceed 2% of actual data during expected operation. All signal conditioning and recording equipment shall provide linear output and shall allow data reading resolution to meet the requirements of 7.8.1. All systems, except the smoothing filter recommended in 7.9.3, shall provide a minimum bandwidth of at least 0 Hz to 20 Hz (flat within +/-1%).

7.9.3 It is recommended that on the channels of vertical and horizontal loads, an electronic low pass filter be installed in the signal conditioning circuit preceding the electronic divider and integration calculation FC (see paragraph 12).

7.9.4 Tyre friction force or torque and any additional desired inputs, such as vertical load, wheel speed, etc., shall be recorded in phase (+/- 5° over a bandwidth of 0 Hz to 20 Hz). Vehicle speed shall also be recorded. All signals shall be referenced to a common time base.

7.9.5 A signal to electrical noise ratio of at least 20 to 1 is desirable on all recorded channels.

7.10 Pavement wetting system:

7.10.1 A special nozzle shall supply the water being applied to the pavement ahead of the test tyre. The quantity of water applied at each operating speed shall be such to provide a constant theoretical water film thickness of 0.5 mm (+/- 10%). The water layer shall be at least 25 mm wider than the test tire tread and applied so the tyre is centrally located between the edges. The volume of water per millimetre of wetted width shall be directly proportional to the test speed.

Note: the water film thickness is described as “theoretical” because it is the thickness that would be obtained if the road surface was perfectly dense, smooth and horizontal. The real water film thickness depends upon the surface on which it is applied. For example, the water film will be affected by the magnitude and form of the macro texture and, especially on porous surfaces, the porosity of the surface.

7.10.2 The nozzle configuration and position shall ensure that the water jets shall face directly toward the test tyre, pointed toward the pavement at an angle of 20° to 30°. The water shall strike the pavement 200 mm to 450 mm ahead of the vertical axes through the centreline of the test wheel. The nozzle shall be 25 mm above the pavement or the minimum height required to clear obstacles that the tester is expected to encounter, but in no case more than 100 mm above the pavement.

7.10.3 Water used for testing shall be fresh, reasonably clean and have no chemicals such as wetting agents or detergents added.

8 Safety

Appropriate safety measures shall be in place to maintain a safe working area in accordance with regulations, including measures to control traffic as necessary.
All equipment should be operated safely and fitted with safety equipment in accordance with the relevant procedures and regulations.
NOTE The wetting of surfaces can have an effect on other users of the site and every effort should be made to ensure that they do not have to make any sudden changes in speed or direction.

9 Calibration

9.1 Speed- Calibrate the test vehicle speed indicator at the test speed by determining the time for traversing at constant speed a reasonably level and straight, accurately measured pavement of a length appropriate for the method of timing. Load the test vehicle to its normal operating weight for this calibration. Record speed variations during a traverse with the skid-test system. Make a minimum of three runs at each test speed to complete the calibration. Other methods of equivalent accuracy may be used.

9.2 Skid resistance force- Place the test wheel of the assembled unit, with its own instrumentation, on a suitable calibration platform, which has been calibrated, and load vertically to the test load. Measure the test wheel load within +/- 0.5% accuracy whenever the transducer is calibrated.

Level the transducers both longitudinally and laterally, such that the tractive force sensitive axis is horizontal. This can be accomplished by minimizing the tractive force output for large variations in vertical load. The system should be approximately level during the procedure. The calibration platform shall utilize minimum friction bearings and have an accuracy of +/- 0.5% of the applied load and a hysteresis of +/- 0.25% of the applied load up to the maximum expected loading. Take care to ensure that the applied load and the transducer sensitive axis are in the same vertical line. Perform the tractive force calibration incrementally to not less than 3000 N.

10 General

10.1 Test preparation- Condition new test tyres by using them at or near their rated load and inflation pressure on the test vehicle at normal test speed on at least 5 km measurement section before they are used for real test purposes. Prior to each series of tests warm up the tyre by putting it in contact with the pavement during at least 500 m. Inspect the tyre for flat spots, damage, or other irregularities that may affect test results, and replace if it has been damaged or is worn beyond the wear line. Check the test-wheel load (if adjustable) and adjust, if necessary, prior to each test series to within the value specified in 7.3. Set the test tyre inflation pressure at the ambient temperature just before the 500 m warm-up (see Annex A for the value of the test tyre inflation pressure).

10.2 Test section- Test sections shall be defined as section of road with the same administrative reference. The beginning and the end of the section shall be referred with kilometric points or with well-defined events located near the road. Take skid resistance measurements only on pavements that are free of obvious contamination.

10.3 Skid resistance of a test section- The skid resistance of a test section is reported on a special document with one value each 10 m. The average of the measurements obtained on the section can be used as a representative value of the test section if the pavement is enough homogeneous.

10.4 Lateral position of the test vehicle- In order to evaluate the skid resistance of the more trafficked area of the tested lane of one road, the test vehicle have to drive in order to put its operating test wheel on the right side (on the left side in UK) of the measured lane. If the device has two tests wheels (see 6.1) it will be possible to measure the skid resistance on the two wheel paths of the road section to be analysed.

10.5 Test speed- The device shall use one of 3 standard test speeds appropriate to the type of road being tested (see paragraph 7.6): 40 km/h on urban roads, 60 km/h on secondary and main roads and 80 km/h on highways. Where the legal maximum speed is less than 60 km/h the test may have to be conducted at 40 km/h. Where the legal speed is considerably in excess of 60 km/h, test may be made at 80 km/h. Maintain test speeds within +/- 2 km/h.

10.6 The test speed and the type of tyre are to be cited when quoting the friction coefficient obtained. Water supply before the test wheel shall start before application of the test wheel brake.

11 Procedure

11.1 Bring the apparatus to the desired test conditions (speed, *slip ratio*, etc) and deliver the correct water flow to the pavement ahead of the test tyre.

11.2 At the beginning of the test section start the recording of the measured parameters (skid resistance, speed, load on test wheel, etc)

11.3 At the end of the section, stop the recording of the measured parameters. The water delivery may be terminated automatically as soon as the brake has been released.

12 Calculation

12.1 The instrumentation system incorporates automatic dynamic friction coefficient computation equipment. For each successive 10 m of road tested, the average of the horizontal traction force is automatically divided by the average of the dynamic vertical load in real time. The resultant braking force coefficient *BFC* is recorded in real time.

13 Report

13.1 Field report - The field report for each section shall contain data on the following items
13.1.1 Location and identification of test sections,
13.1.2 Date and time of day,
13.1.3 Weather conditions: principally temperature, cloud cover, and wind,
13.1.4 Lane and wheel-path tested,
13.1.5 Friction Coefficient, speed of test, *slip ratio* and test tyre type,
13.1.6 Number of tests or test length already made with the test tyre used,
13.2 Summary report- The summary report shall include, for each test section, data on the following items insofar as they are pertinent to the variables or combinations of variables under investigation:
13.2.1 Location and identification of test sections,
13.2.2 Number of lanes and presence of lane separators,
13.2.3 Grade and alignment,
13.2.4 Pavement type, mix design of surface course, condition, and aggregate type (specific source, if available),
13.2.5 Age of pavement,
13.2.6 Average daily traffic (all vehicles and % of heavy vehicles),
13.2.7 Posted speed limit,
13.2.8 Date and time of day,
13.2.9 Weather conditions,
13.2.10 Lane and wheel-path tested,
13.2.11 Average, high, and low skid number for the test section and speed at which the tests were made. (If values are reported that were not used in computing the average, this fact shall be recorded),
13.2.12 An histogram of the friction coefficients, and
13.2.13 Plot of speed gradient data (if obtained),
13.2.14 The main characteristics of the apparatus.

14 Precision and Bias

14.1 The acceptable precision of *BFC* units can be stated in the form of repeatability. As there is no significant correlation between standard deviation and arithmetic mean of sets of test values, it appears that standard deviations are applicable to this test method regardless of the average locked wheel sliding friction of the surface. An acceptable standard deviation shall be of 2 *BFC* units.
14.2 This value will be determined at each of the three test speeds on the basis of at least 36 individual skids, 12 on each of three pads.

Annex A: Specifications for a reference test tyre (normative):
(see the document from *PIARC C1* committee)

Annex E: Data from the annual NASA Tire/Runway Friction workshop

Table 1 History of F60 for NASA Friction Workshop test sites, based on Dynamic Friction Tester data at 20 km/h (DFT20) (Wambold et al. 2004)

SITE	1993	1994	1996	1997	1998	1999	2001	2002	2003
A	0.27	0.27	0.23		0.24	0.23	0.26	0.31	0.32
B	0.46	0.47	0.29		0.41	0.41	0.53	0.47	0.48
C			0.34		0.44	0.4	0.51	0.47	0.30
D	0.37	0.35	0.27		0.26	0.29	0.26	0.32	
E	0.46	0.45	0.35		0.37	0.42	0.48	0.49	0.50
F	0.51				0.44	0.47	0.55	0.55	0.540
K	0.26				0.19	0.21	0.17	0.18	
K0					0.35	0.35	0.36	0.32	
P	0.08						0.08		0.08
S0	0.28				0.25				
S1	0.41	0.4	0.34	0.33	0.35	0.37		0.35	0.37
S2	0.48	0.41	0.36	0.33	0.34	0.37		0.38	0.41
S3	0.56	0.47	0.43	0.41	0.46	0.46		0.43	0.47
S4		0.61	0.46	0.5	0.54	0.53		0.5	0.54
S5			0.5	0.44	0.52	0.49		0.42	0.42
S6				0.48	0.51		0.46	0.5	

NOTE F60=0.0811+.732[DFT20/exp(40/Sp)]
1995 - no data
2000 - no DFTester data

Table 2 History of Sp for NASA Friction Workshop test sites, first based on Mean Texture Depth (MTD, "sand patch"), from 2000 on Mean Profile Depth (MPD) (Wambold et al. 2004)

		1994	1996	1997	1998	1999	2000	2001	2002	2003
A	47.6	52.3	46.3		41.8	41.8	53.2	42.2	58.2	53.5
B	206	206	95.2		172	195	238	280	187	161.7
C			118		210	213	257	244	213	54.1
D	81.2	68.3	56.6		52	56.6	67.9	48.8	62.1	
E	131	109	98.6		103	129	166	139	175	131.8
F	198				188	192	225	201	207	193.8
K	45.8				42.9	40.7	58.2	44.4	39.9	
K0					70.2	63.4	67.3	69.8	55.4	
P	6.6					2.4		1.2		1.9
S0	49.4				45.2					
S1	70.8	68.2	62.3	53.2	71.3	63.4	70.2		62.6	60.2
S2	98.3	66.7	71.3	60	67.9	67.9	88.7		72.6	77.6
S3	169	106	116	108	105	109	121		98.1	101.2
S4		260	133	235	262	249	241		197	256.2
S5			162	95.2	137	123	118		80.4	72.4
S6				125	107		155	94.2	114	

NOTE 1993-1999 Sp derived from MTD where Sp=113.6MTD-11.69
2000-2002 Sp derived from CTMeter where Sp=110.72MPD-1.02

Annex F: The ESDU model

The mathematical descriptions below of the relevant ESDU models, together with the notation and the numerical values of constants are copied from Balkwill (2003)

MATHEMATICAL MODELS

Rolling Resistance Cases

Case	**Description and Equation**
Rolling *on* any paved runway $s = 0$	Plausible empirical relation describes data from tests on single wheels and on a complete aircraft.
	$\mu_{ROLL} = \left(\zeta_0 + \zeta_1 V^2/2g\right)\left(\dfrac{Z^{1/3}}{p/p_a}\right)$
Decelerating force on single tyre rolling *through* fluid $s = 0$	Systematic tests on single tyres conducted in United States and United Kingdom form the basis of an empirical model. Model matches data from tests done on full-scale aircraft for whole of ground speed range in water and in slush.
	$G_1 = G_T + G_C$ $G_T = \left(\sigma\rho V^2/2\right)\times\left(d\sqrt{Z/p}\right)C_D$ $G_C = \gamma_0 w D\sigma d\sqrt{pZ}\ln\left[1/\sigma\right]$ $C_D = \xi_0\left(\dfrac{1+\sin\left[\theta\right]}{2}\right)+\xi_1\left(\dfrac{\cos\left[\theta\right]}{2}\right)^4+\xi_2\left(\dfrac{1-\sin\left[\theta\right]}{2}\right)\left(\dfrac{\cos\left[\theta\right]}{2}\right)^2$ $\theta = \tan^{-1}\left[1-q/p\right] : \xi_0 = \xi_{01}\left(w/D\right)^2 : \xi_1 = \xi_{11}D^{3/4}\left(\xi_{12}+d/w\right)\left(D/w\right)$ $\xi_2 = \dfrac{\xi_{21}}{w\left\{\xi_{22}\left(1-\left(\dfrac{D}{\xi_{23}}\right)^2\right)+\dfrac{d}{w}\right\}} : \xi_2 \geq 0 : q = \dfrac{1}{2}\sigma\rho V^2$

Braking on Wet Runway

Case	Description and Equation
Pressure under tyre running on wet runway for all values of s	Footprint assumed to conform to "*three-zone*" model. Slip speed of footprint determines kinetic pressure under tyre. Pressure in zone 1 is kinetic pressure. That in zone 2 described by empirical equation that fits data measured *under* rib of tyre on smooth surface. Pressure in zone 3 is inflation pressure in *absolute measure*.
	$v = sV$: $p = p_i + p_a$: $q = \rho v^2/2$ $\varphi = \dfrac{\sin[q/p]}{\sin[q/p] + \cos[q/p]}$ $q_v = q + a_0 p \varphi^{m_1} (1-\varphi)^{m_2}$
Full skid on wet runway $s = 1$	Coefficient of braking friction in full skid on dry runway is modified empirically to fit several sets of measurements on single tyres collected at both NASA Langley and the Road Research Laboratory in United Kingdom.
	$\mu_{SKID\ WET} = \dfrac{\mu_{REF}}{\left(1+\left(\eta_0 + \eta_1 \dfrac{V^2}{2g}\right)\dfrac{p/p_a}{Z^{1/3}}\right)} \dfrac{(1-\varphi_0\, q/p)}{(1+\varphi_1\, q_v/p_a)}$ $\ln\left[\dfrac{\left(1-e^{(-d/d_0)}\right)}{\mathrm{E}[\varphi_1]}\right] = \varphi_{12}\left(1-e^{(-d_{tex}/d_{tex0})}\right)\left(\ln\left[\dfrac{1}{1-Z/pwD}\right]\right)^n$ $n = \varphi_{10}\left(1+\varphi_{11}\ln\left[d_{tex}/d_{tex_0}\right]\right)$
Braking on wet runway[2] $0 < s < 1$	Coefficient of braking friction in full skid on wet runway is modified empirically to fit measured data collected at Road Research Laboratory and NASA on single tyre.[3] Slip speed of footprint determines kinetic energy absorbed by tyre and kinetic pressure under tyre.
	$\mu_{SLIP\ WET} = \dfrac{\mu_{REF}\left(1-e^{\eta_2 s}\right)}{\left(1+\left(\eta_0 + \eta_1 \dfrac{v^2}{2g}\right)\dfrac{p/p_a}{Z^{1/3}}\right)} \dfrac{(1-\varphi_0\, q/p)}{(1+\varphi_1\, q_v/p)}$ $\eta_2 = \left\{1+\eta_{20}\left(\dfrac{q/p_a}{1+q/p_a}\right)\right\}\left\{\dfrac{\eta_{21}}{(1+q/p_a)}\right\}$, $\varphi_0 = \dfrac{2/\pi}{(1+d_{tex}/d)}$

2 Note that values of μ_{max} follow from the equation given here. It is the maximum value of $\mu_{SLIP\ WET}$ for a given set of values of independent variables.

3 Kinetic pressure used in calculating the exponent η_2 is calculated at the axle translation speed. There is no variation in the exponent for a dry runway because the density of the contaminant is zero: thus, kinetic pressure is zero.

Numerical values of constants – British and Metric Units

	British		Metric	
Symbol	**Value**	**Unit**	**Value**	**Unit**
a_0	3.138		3.138	
d_0	3.333×10^{-4}	ft	1.016×10^{-4}	m
d_{tex_0}	1.95×10^{-4}	ft	5.9436×10^{-5}	m
$C_{u\ REF}$	5.6×10^{4}	lbf/ft^2	2.6813×10^{6}	N/m^2
$G_{s\ REF}$	7.305×10^{7}	lbf/ft^2	3.4977×10^{9}	N/m^2
m_1	0.4		0.4	
m_2	2.4		2.4	
γ_0	0.2	ft^{-2}	2.15278	m^{-2}
$\mathrm{E}[\mu_{REF\ ICE\ 1}]$	0.36		0.36	
$\mathrm{E}[\mu_{REF\ ICE\ 2}]$	0.25		0.25	
ζ_0	0.0062	lbf$^{-1/3}$	3.7699×10^{-3}	N$^{-1/3}$
ζ_1	2.31×10^{-5}	ft^{-1} lbf$^{-1/3}$	4.60824×10^{-5}	m^{-1} N$^{-1/3}$
η_0	0.416	lbf$^{1/3}$	0.6842	N$^{1/3}$
η_1	0.019	lbf$^{1/3}$ft^{-1}	0.1025	N$^{1/3}$m^{-1}
η_{20}	2.5		2.5	
η_{21}	-12		-12	
σ_{ICE}	0.92		0.92	
$\sigma[\mu_{REF\ ICE}]$	0.084		0.084	
φ_{10}	-0.0282		-0.0282	
φ_{11}	3.9		3.9	
φ_{12}	1.9		1.9	
ξ_{01}	13.11		13.11	
ξ_{11}	1.93	ft$^{-3/4}$	4.7049	m$^{-3/4}$
ξ_{12}	0.16		0.16	
ξ_{21}	0.463	ft	0.1411	m
ξ_{22}			0.8	
ξ_{23}	3.75	ft	1.143	m

NOTATION

A list of the general notation for the whole document is presented in this part. Many of the symbols are used in their standard sense. However, an attempt has been made to eliminate complexity. To this end, superscripts have been avoided and subscripts have been used in what is hoped is a clear and natural way.

One significant departure from common usage has been adopted. Symbols succeeded by square brackets are used to indicate that the quantity within the brackets is operated upon by the symbol that precedes the bracket. For example, the string $\ln[x]$ is to be interpreted as the natural logarithm of the variable x. Again, the string $P[z < z_0] = 0.95$ is to be interpreted as the probability that $z < z_0$ is 95%.

Symbol	Description	British Units[1]	Metric Units
a	half maximum length of footprint	ft	m
a_0	empirically determined constant		
A	total area of cross-section of inlet stream tubes	ft^2	m^2
A^*	statistic for Anderson-Darling test		
A_F	area of footprint	ft^2	m^2
b	half maximum width of footprint (Section 4)	ft	m
b	characteristic speed (Section 5)	ft/s	m/s
C_D	drag coefficient due to fluid displacement by single tyre		
C_G	decelerating force coefficient for tyre rolling in clay		
C_L	lift coefficient		
C_u	shear strength of medium	lbf/ft^2	N/m^2
$C_{u\,REF}$	reference value of shear strength of snow	lbf/ft^2	N/m^2
C_Z	normal force coefficient for tyre rolling in clay		
d	depth of fluid contaminant or other medium	ft	m
d_0	reference depth fluid contaminant or other medium	ft	m
d_{tex}	depth of macro-texture of runway	ft	m
d_{tex_0}	reference depth of macro-texture of runway	ft	m

[1] Consistent, British, units are used throughout this document. However, the model presented is empirical and some equations contain dimensional constants. Care must therefore be exercised when converting to other systems of units.

Symbol	Description	British Units[1]	Metric Units
D	aerodynamic force parallel with air path (Appendix E)	lbf	N
D	diameter of inflated tyre (Sections 4 and 10)	ft	m
D	wheel diameter (Section 5)	ft	m
E	Young's modulus	lbf/ft^2	N/m^2
$f[\ ]$	empirical function of quantities in [ ] (Section 3)		
g	acceleration due to gravity	ft/s^2	m/s^2
G	horizontal force (Appendix D)	lbf	N
G	rolling resistance force	lbf	N
G_1	fluid drag force on single wheel	lbf	N
G_C	fluid drag force due to compression of medium	lbf	N
G_{ROLL}	rolling resistance	lbf	N
G_S	shear modulus of medium	lbf/ft^2	N/m^2
$G_{S\ REF}$	reference value of shear modulus of snow	lbf/ft^2	N/m^2
G_{SNOW}	decelerating force due to rolling through snow	lbf	N
G_T	decelerating force due to rolling through fluid	lbf	N
k	factor		
k	factor on inlet mass flow ratio (Appendix D)		
L	aerodynamic lift	lbf	N
m	mass	slug	kg
m	parameter in distribution (Appendix E)		
$\dot{m}$	air mass flow per unit time	slug/s	kg/s
m_1, m_2	empirically determined exponents		
M_{300}	engineering stress to produce strain of 300%	lbf/ft^2	N/m^2
n	number of wheels on aircraft landing gear		
n	number of wheels (Appendix D)		
n	parameter in distribution (Appendix E)		
N	speed number		
p	tyre inflation pressure, absolute	lbf/ft^2	N/m^2
p_a	atmospheric pressure	lbf/ft^2	N/m^2
p_b	mean bearing pressure under footprint	lbf/ft^2	N/m^2
p_i	tyre inflation pressure, gauge	lbf/ft^2	N/m^2
P	power	ftlbf/s	Nm/s
$P[\ ]$	probability of event in [ ]		

Symbol	Description	British Units[1]	Metric Units
q	kinetic pressure	lbf/ft^2	N/m^2
q_v	pressure in Zone 3 of footprint (Section 9)	lbf/ft^2	N/m^2
q_v	pressure in zone 2 (Sections 10 and 11)	lbf/ft^2	N/m^2
r	exponent in calculation of C_u G_S		
R	radius of inflated tyre	ft	m
R_{VOID}	void ratio		
s	slip ratio (Sections 7, 8, 11 and 12, and Appendix E)		
s	rut depth (Section 5)	ft	m
s'	transformed slip ratio		
s'_x	$100\times x$ percentage point of distribution of s'		
S	reference area	ft^2	m^2
S_F	footprint area	ft^2	m^2
S_i	area of Zone i $(i=1,2,3)$ under footprint (Section 10)	ft^2	m^2
t	Time	s	s
$\hat{T}$	transformed ground temperature		
T	temperature	C	F
$U[\ ]_{0.95}$	uncertainty associated with parameter in [ ]		
v	volume (Sections 4 and 5)		
v	translation speed of tyre footprint (Sections 7, 8, 11 and 12)	ft/s	m/s
v_0	volume of slush before contact with tyre	ft^3	m^3
v_c	compressed volume of slush	ft^3	m^3
var[ ]	variance of quantity in [ ]		
V	ground speed of vehicle (Sections 7, 8, and 12)	ft/s	m/s
V	ground speed (except Sections 7, 8, and 12)	ft/s	m/s
V_C	"critical" ground speed at which fluid drag force is maximum (customary modelling not followed here)	ft/s	m/s
V_E	equivalent airspeed	ft/s	m/s
V_T	true airspeed	ft/s	m/s
w	width of inflated tyre	ft	m
w_{max}	maximum width of inflated tyre in motion	ft	m
W	weight (Section 5)	lbf	N

Symbol	Description	British Units[1]	Metric Units
W	work done in compressing slush	ftlbf	Nm
Z	net vertical load on wheel (Section 5)	lbf	N
z	percentage point of Normal distribution		
Z	normal (to runway) load on wheel	lbf	N
Z	normal (to runway) load on undercarriage (Appendix D)	lbf	N
Z	tyre vertical load (Sections 6, 7, 8, 9, 10, 11 and 12)	lbf	N
Z_M	normal (to runway) load on one main-wheel	lbf	N
Z_N	normal (to runway) load on one nose-wheel	lbf	N
$\beta_1[m,n]$	probability density of beta distribution of the first kind		
$\mathrm{B}[m,n]$	Beta function of m and n		
γ_0	constant in definition of force to compress slush (=0.2)	ft^{-2}	m^{-2}
$\delta[\ ]$	increment of quantity in $[\ ]$		
$\Delta[\ ]$	deviation of measured value of quantity in $[\ ]$ from model		
$\bar{\Delta}$	mean value of $\Delta[\ ]$		
Δ'	standardized value of $\Delta[\ ]$		
$\hat{\Delta}$	transformed value of Δ'		
ε	runway slope	radian	radian
$\mathrm{E}[\ ]$	value of quantity in $[\ ]$ from model		
Γ_G	decelerating force function		
η_0, η_1, η_2	empirical constants for aircraft tyres		
θ	ratio of kinetic pressure and absolute inflation pressure (Section 9)		
θ	variable defined in text (except Section 9)	rad	rad
μ	coefficient of friction (Section 6)		
μ	coefficient of braking friction (Section 6)		
μ_{MAX}	maximum available coefficient of braking friction		
$\mu_{MAX\ DRY}$	maximum available coefficient of braking friction		
$\mu_{MAX\ WET}$	maximum available coefficient of braking friction in wet		
μ_0	coefficient of braking friction at $V=0$		

Symbol	Description	British Units[1]	Metric Units
μ_{REF}	reference coefficient of braking friction		
μ_{REF}	empirically derived reference coefficient of friction (Sections 6, 7, and 8)		
$\mu_{REF\ ICE}$	empirically derived reference coefficient of friction		
μ_{ROLL}	coefficient of rolling friction		
$\mu_{SKID\ DRY}$	coefficient of braking friction in full skid on dry runway (Sections 7, 8, 10 and 11)		
$\mu_{SKID\ DRY}$	coefficient of sliding friction on dry runway		
$\mu_{SKID\ ICE}$	coefficient of braking friction in full skid on icy runway		
$\mu_{SKID\ STATIC}$	coefficient of sliding friction at $V = 0$		
$\mu_{SKID\ STATIC}$	coefficient of braking friction at $V = 0$ (Sections 6 and 7)		
$\mu_{SKID\ WET}$	coefficient of sliding friction on wet runway		
$\mu_{SKID\ WET}$	coefficient of braking friction in full skid on wet runway (Sections 10 and 11)		
$\mu_{SLIP\ DRY}$	coefficient of slipping friction on dry runway		
$\mu_{SLIP\ DRY}$	coefficient of braking friction when slipping on dry runway (Sections 8 and 11)		
$\mu_{SLIP\ ICE}$	coefficient of braking friction when slipping on icy runway		
$\mu_{SLIP\ WET}$	coefficient of slipping friction on wet runway		
$\mu_{SKID\ STATIC}$	coefficient of sliding friction at $V = 0$		
M[ ]	measured value of quantity in [ ]		
ν	Poisson's ratio		
ρ	density of respective medium	slug/ft^3	kg/m^3
ρ_1	density of slush before contact with tyre	slug/ft^3	kg/m^3
ρ_c	density of slush after compression	slug/ft^3	kg/m^3
σ[ ]	standard error of quantity in [ ]		
σ	specific gravity of fluid contaminant		
$\xi_0, \xi_1, \xi_2, \xi_3$	variables used in process of modelling		
$\xi_{01}, \xi_{11}, \xi_{12}, \xi_{21}, \xi_{22}, \xi_{23}$	coefficients in model		
ζ_0	constant in definition of coefficient of rolling friction	lbf$^{1/3}$	N$^{-1/3}$

Symbol	Description	British Units[1]	Metric Units
ζ_1	constant in definition of coefficient of rolling friction	$ft^{-1}\ lbf^{-1/3}$	$m^{-1}\ N^{-1/3}$
χ^2	test statistic		
$\varphi, \varphi_0, \varphi_1, \varphi_2$	variables used in process of modelling		
$\varphi_{10}, \varphi_{11}$	constants in model		
φ_β	coefficient in correlation of decelerating force		
φ_δ	coefficient in correlation of decelerating force		
Φ	function of wheel geometry and snow properties		
λ	proportion of vertical load carried by nose undercarriage		
ω	angular velocity of wheel	rad/s	rad/s

Suffices

0	conditions in free stream
1	conditions at plane of inlet
ICE	refers to ice
ICE 1	refers to runway covered with ice or compressed snow
ICE 2	refers to runway covered with loose snow
ICE 3	refers to runway covered in glare ice
M	main wheel/undercarriage
N	nose wheel/undercarriage
SNOW	refers to snow
TOTAL	total for whole aircraft

Annex G: Repeatability and Reproducibility, some statistics with explanations

The following introduction to repeatability and reproducibility, and its related statistics, was based on Andresen et al (2001) and Rado & Radone (2003), but extended by the authors of this TYROSAFE report. A formal definition of the repeatability and reproducibility, and its determination (experimental design and statistical analysis) is given in the different parts of ISO 5725.

Definitions (Andresen et al, 2001)

average friction coefficient, **n.** - The sum of individual friction measurements, μ_i, divided by the number of measurements, n. Mathematically expressed as

$$\mu_{avg} = \frac{1}{n}\Sigma(\mu_i)$$

coefficient of variation, **n.** - an adaptation of the standard deviation used to express the variability of a set of numbers on a relative scale rather than on an absolute scale. Mathematically expressed as

$$CV = \frac{StdDev}{\mu_{avg}} \cdot 100\%$$

friction measure, **n.** - the unit of measure of a friction measurement.

friction measurement, **n.** - the measured, processed and reported value of the ratio of braking slip friction force in the tire-surface contact plane to the tire load force acting through the test wheel axis and normal to the contact plane. Mathematically expressed as

$$\mu = \frac{F_{brakingslip}}{F_{normaltireload}}$$

friction measurement device configuration, **n.** - a term used to designate the entire test system as used for any friction measurement. It includes, but not is limited to, type of device (force or torque measurements), tire type, size and inflation pressure, slip ratio, normal load and braking system control mode.

harmonization, **n.** - the transformation of the measured outputs of different devices used for measurement of a specific phenomenon so that all devices report similar values.

IRFI reference device, **n.** - a particular friction measurement device selected as a benchmark or reference. It is used to calibrate other friction devices to permit their measurements to be converted to IRFI values.

repeatability, **n.** - the ability of a measurement device to produce the same measured value when measurement runs are repeated on the same surface under the same conditions.

standard deviation, **n.** - a measure of dispersion about a mean value, calculated as the square root of the squared sum of the difference of each measured friction value relative to the arithmetic mean friction value, divided by the number of measurements less one. Mathematically expressed as

$$StdDev = \sqrt{\frac{\sum_{i=1}^{n}(\mu_i - \mu_{avg})^2}{n-1}}$$

standard error, **n.** - the standard deviation divided by the square root of the number of samples. Mathematically expressed as

$$StdErr = \frac{StdDev}{\sqrt{n}}$$

Understanding Repeatability and Reproducibility

The ability of a friction measurement device to produce the same measured value on the same surface, when measurement runs are repeated under the same conditions, is called the repeatability of the device.

The ability of several different devices of the same brand, type and configuration to report the same friction value for the same surface is called reproducibility.

Repeatability and Reproducibility are the two aspects of what is known as *precision*. For devices of which there is only one example, precision is confined to the repeatability of that device.

Methods of comparing devices with respect to their different units of measurements and correlating them to report nearly the same value are called harmonisation methods.

If different types or configurations (and/or different operating speeds) are used, but the results are harmonised (i.e. converted to a common scale, reporting nearly the same harmonised friction value for the same surface), reproducibility is the ability of the devices, combined with the harmonisation method, to report the same value for the same surface

The units of friction measurement are unique for a device and generally there is no fundamental calibration reference for friction measures. A deviation from a calibration reference is called bias. With no calibration reference available, bias cannot be established for friction measurement devices. Either a given device needs to be accepted as the reference or in some cases the average of many devices is used as the reference.

Repeatability is device specific. The repeatability measures may be used to compare the performances of different devices or to evaluate the performance history of a device.

One should always keep in mind that a friction measurement is a product of a tyre-surface interaction. The reported friction value is an indicator of the interaction process, not of the surface or the device alone. The repeatability of a device on one surface may not apply for another surface. By studying repeatability of a device for several kinds of surfaces, one may obtain typical reference measures of repeatability, but care must be exercised in using such reference values for other device-surface pairs.

When friction measurement devices make repeated runs over the same surface segment following the same wheel track as closely as possible, the average reported friction values for that segment for all runs are compared. The measure of variance across all repeated runs for a surface segment is called repeatability.

For a friction measurement device, any repeatability measurements will include some variance stemming from surface texture and surface material. This surface variance comes from the fact that the surface is not completely uniform and is subjected to wear from use and/or weathering. Also, different wheel tracks (laterally different test lines) may be measured and in some cases the measurement changes the surface. There are no methods available to separate the surface variance from the device variance. The influence of surface variance can only be reduced as much as possible by a careful set-up and execution of the experiments (careful controlling of lateral position of test lines, periodical checking of the surface for changes, etc.)

A repeatability value of a friction measurement device is obtained for one surface at a time. The repeatability value is specific for that surface. To get a more general appreciation of repeatability for a device, one must obtain repeatability measures for several different surfaces.

The concepts of repeatability versus reproducibility are illustrated in the figure below (Rado & Radone 2003). This depicts two cases (left and right) where six devices each have made a large number of measurements on the same surface.

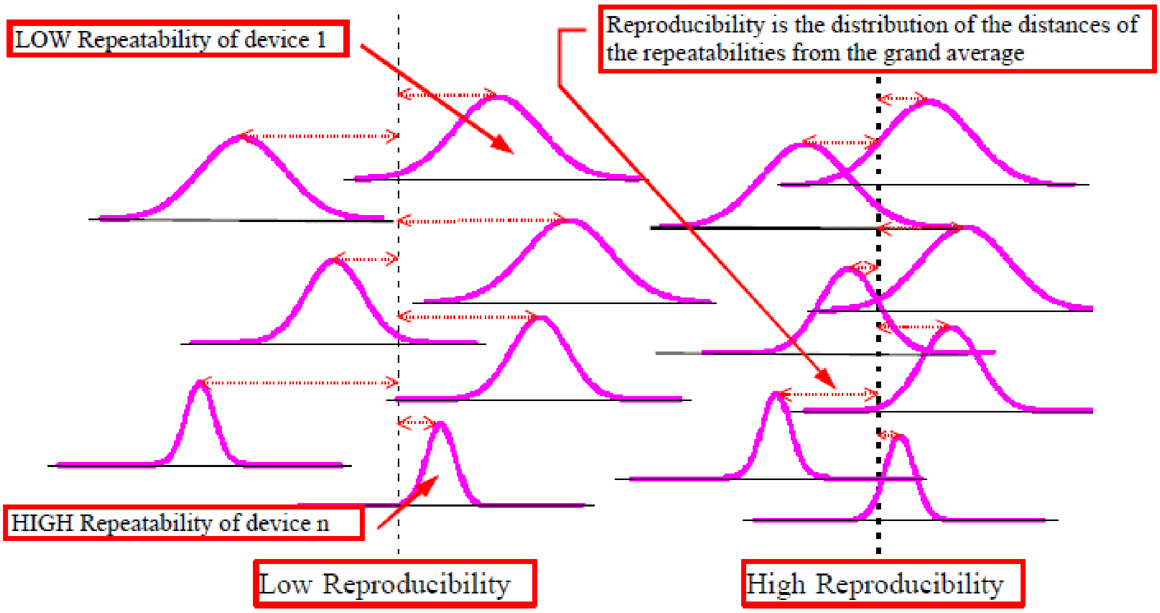
The repeatability of each device is shown by the frequency distributions of their measurement values (the bell shaped curves), when performing repeated measurements under identical conditions on the same surface. The narrower the curve, the better is the repeatability (the devices at the bottom of the graph).

The reproducibility is represented by the distribution of the distances of the repeatabilities from the grand average. The situation on the right, where the averages of the individual devices are closer to the grand average, has better reproducibility.

With respect to this figure, two things should be noted:

- The figure indicates a *good* repeatability (small variation) as "high" – devices are described as “highly repeatable”. However, as almost all statistical indicators for repeatability get numerically lower when repeatability improves, a *good* repeatability is often confusingly called "low". The same holds for the reproducibility[11].
- In formal terms, the reproducibility is not defined as the distribution of the distances of the repeatabilities from the grand average. Formal reproducibility also contains the contributing repeatabilities, as a statistical accumulation of both the variations for individual devices and the variations between the devices.

[11] A similar confusion can arise, with the use of the term “precision” when *small (low) numbers* (for repeatability or reproducibility) are good and *large (high) numbers* are poor. To add to the confusion, the expression “high precision” is also sometimes used when meaning very good accuracy.



Statistical parameters for repeatability

Repeatability (on one surface) can be characterised by several statistical parameters:

- The standard deviation (SD or StDev) of the frequency distributions of their measurement values, when performing repeated measurements under identical conditions on the same surface.
- The coefficient of variation (CV , CoV or COV) of those frequency distributions. This is the standard deviation divided by the average.
- The standard error (SE or StdErr) of those frequency distributions. This is the standard deviation divided by the square root of the number of measurements.
- The "repeatability" according to ISO 5725, equal to 2.77 times the repeatability standard deviation.

Note that in the definitions above, only measurements on *one* surface are considered. To get an impression of the repeatability on all possible surfaces, the characteristics need to be determined on many surfaces and then combined over those surfaces. The most simple method, which is often used, is to compute the average of the characteristic over all surfaces. More complex but statistically more correct procedures are also used.

The Utility of Each Statistic of Repeatability

The standard deviation is in absolute friction units of the device. It is not a function of the friction level being measured. Popularly (but statistically incorrect) stated, it is an indicator of the expected absolute difference between any one measurement value and the mean of all measurement values (under identical conditions on the same surface). This would indicate how far off from the "true" value you could expect to be when performing only one measurement. The standard deviation is an adequate statistic when evaluating one surface object at a time.

To evaluate the interactions with several surface objects, the coefficient of variation offers a normalised measure per unit of friction reported by the device. The CV is therefore better suited for a general repeatability characteristic across different surfaces and measuring speeds. Reported friction values decrease with increasing speed on wet pavement (i.e., different friction levels are reported at different speeds for the same surface object).

The standard error is a transformation of the standard deviation to reflect the number of repeated measurements. Trends of device stability may be observed, because the number of runs also implies elapsed time due to the manner in which the field tests were executed. The standard error is also helpful in comparing different cases, which have different numbers of repeat runs. Popularly (but again statistically incorrect) stated, the standard error is an indicator of the expected absolute difference between the average of a small group of measurement values and the mean of a very large number of measurement values (under identical conditions on the same surface). This would indicate how far off from the "true" value you could expect to be when performing a small number of measurement repetitions.

The "repeatability" (as 2.77 times the repeatability standard deviation), is the value that will not be exceeded by the difference between two successive measurements, with a 95% probability. Put simply (and less correctly): if the repeatability is 0.10 and you perform 101 repeats of the same measurements, 95 of the 100 difference between two successive measurements will be less than 0.10, and 5 will be higher. This indicates the differences between two measurement repetitions that you may expect to get.

Common for all the statistics is that small values indicate better performance than larger values.

When you want to assess the skid resistance from a single measurement on each pavement section (e.g. 100 m lane length), without any repetitions of the measurement, the standarad deviation or the coefficient of variation are the best indicators of haw far you are likely to be off from the "true" value (taken to be the average of a large number of repetitions of the same measurement). In this case, the "repeatability" (2.77*SD) give a too pessimistic impression of your expected "error".

Similar considerations as used above for repeatability can be applied to reproducibility.

Unfortunately, none of these statistics gives information on the power of a measurement method (be it harmonised or not) to distinguish between a "grippy" or "slippery" pavement surface. To get this information, the statistics need to be related to the range of values found with that measurement method between practical extremes of "grippy" on the one hand and "slippery" on the other.