Volume

1

NORSEMETER FRICTION AS

A Primer on Modern Runway Surface Friction Measurement

NORSEMETER COURTESY PUBLICATION

A Primer on Modern Runway Surface Friction Measurement

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Preface and Acknowledgments

In recent years, a better understanding has been gained of the friction phenomena related to pneumatic tires slipping and sliding on a runway surface. Norsemeter is devoted to transforming this understanding into useful products for those who depend on friction characteristics information in their work.

A major contribution to the increased understanding has been the international cooperative efforts lead by the World Road Association (PIARC), whose headquarters is in Paris, France. This booklet makes several references to the International PIARC Experiment to Compare and Harmonize Texture and Skid Resistance Measurement in 1992. We wish to extend our sincerest acknowledgments to the Technical Commission C1 of the World Road Association (PIARC) for their achievements and contribution to this engineering field.

Norsemeter was a participant in the above experiment and has since been active in applying some of the findings in the experiment to our products. We are bringing to market a friction and texture measuring device named RUNAR (RUNway Analyzer & Recorder). This device works on the principles of a variable slip measurement technique. It has a high content of PIARC recommendations as product features.

For the airport industry, Norsemeter is committed to develop and provide leading edge products for runway braking condition reporting, exploiting the most recent knowledge and technology in the area. In 1996 a series of RUNAR prototypes were tested. We are extremely grateful for the opportunity extended to us by Transport Canada to perform testing under many different weather conditions at the Jack Garland Airport in North Bay, Ontario. We are proud to be associated with the sincere efforts of Transport Canada to introduce and validate the highest quality and most cost effective measuring schemes and equipment for winter runway friction reporting. We are honored that the RUNAR device will participate in the Joint Winter Runway Friction Measurement Program under the leadership of Transport Canada, National Aeronautics and Space Administration, Federal Aviation Administration and the National Research Council Canada.

This booklet is intended to give technical background information on some of the new developments regarding friction measurements in the context of a friction process between a surface and a tire. It is the surface part in this process which traditionally has been the preoccupation of aviation administrations, airport owners, operators and users. This material is primarily put together for such an audience with emphasis on the surface characteristics. Aircraft tires are not discussed.

That is not to say that the airmen, airline operators and aircraft manufacturers have less interest in the runway friction. It is just that we have less to say at this time on the more complex subject of assessing wheel braking distances of the many different types of aircraft, because much work has still to be done in that area.

General and direct correlation of ground-vehicle friction measurement devices with aircraft braking action have not yet been found[1], although some limited cases of correlation have been established. New tools and new understanding has created impetus for significant advances in this area.

The reader should consult the Norsemeter product descriptive literature such as the *RUNAR Owner's Manual* for more particular information about the device.

This booklet is the sole responsibility of Norsemeter and does not imply endorsements by the parties named herein.

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[1] U.S. Department of Transportation, Federal Aviation Administration, Advisory Circular No. 150/5320-12B

A Summary

This booklet presents basic and advanced technical background information for the Norsemeter products in four parts.

In part one it discusses basic mechanics of the measurement of the resistive force in the contact patch between a braked pneumatically tired wheel and a surface. The tired wheel is moving in a rectilinear direction. Lateral forces are not discussed.

The resistive force is used as a measure of the capability for a given pair of tire and surface to stop a vehicle on wheels. The interaction between tire and surface is called a friction process involving several parameters determining the braking capabilities of a vehicle on a surface.

The friction process involving pneumatic tires differ from the well known friction in the contact area between solid bodies with opposing motions. This difference is explained by looking at the braking friction process for a conventional locking wheel brake, an Anti-locking Braking System (ABS) and the Johnsen Peak Braking System[i] .

Major parameters that influence the friction process are discussed, including slip speed, texture and contaminants.

In part two, current practices of making use of friction information for diverse needs are briefly discussed. Some uncertainties of friction measurement practices are reported.

To predict the friction properties of only the surface part of the friction process has been of particular interest to pavement engineers. Several measurement approaches and many different devices have been manufactured to measure surface frictional properties. Unfortunately, the measured values have been device specific, making comparisons across devices cumbersome and some times impossible.

A brief survey of the current knowledge and practice of friction measurements for aviation use is presented with material from the International Civil Aviation Organization (ICAO), the Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA).

Part three deals with new developments. In 1995 the international body of the road community, the World Road Association (PIARC), proposed the use of an universal yardstick for surface friction measurement called the International Friction Index, IFI. This booklet discusses the concept and some applications of this new contribution to mobility engineering and advocates its use in aviation.

Another important new addition to tire-surface engineering grew out of the PIARC International Experiment 1992. It is the Rado[ii] Unified Friction Model which offers a unified theory for the friction process and robust techniques for its measurement using variable speed of a pneumatically tired wheel.

This booklet discusses these new accomplishments with the use of Norsemeter variable slip speed measurement devices, including calibration procedures to achieve the IFI parameters and correlation to other friction measuring devices mentioned in the ICAO literature.

The unique features of the variable slip measuring technique as a single source for obtaining the International Friction Index parameters are explained throughout part four.

Some approaches to using IFI for regulation and monitoring purposes in aviation are described, including application for maintenance of surfaces and information for ground operation of aircraft.

Sample model parameters for common ICAO surface condition friction levels are developed and discussed.

A Runway and Aircraft Friction Index is proposed based on the new models.

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Part 1

Friction Fundamentals

The Tire-to-Runway Surface Friction Process

In this document we deal with the interaction between a pneumatic tire and a runway surface during wheel braking of the vehicle. A braking action exerted on the tire by the wheel brake causes resistive forces in the tire-surface contact area to halt the vehicle.

A Few Basics

A measure of the resistive forces to movement between two opposing object surfaces is traditionally called a friction coefficient. We often use the Greek letter μ as its one letter denotation.

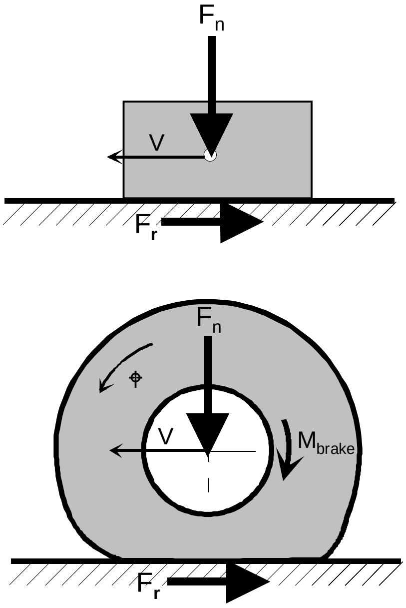

Figure 1 - Free body diagrams of a sliding block and a braked wheel.

For many pairs of moving opposing objects, the friction coefficient according to Euler is a relationship between the opposing normal force, F_n, in the contact area and the parallel resistive force, F_r,

$$\mu = F_r/F_n \qquad (1)$$

Or rearranged, the resistive force can be expressed as a function of a friction coefficient and the normal opposing forces,

$$F_r = \mu \times F_n \qquad (2)$$

The equation (2) is the form used to evaluate braking properties of the opposing object pair. We measure μ and predict how much resistive force, F_r, that may be attained when we have a known normal force, F_n. The braking or stopping distances which friction can support for a vehicle is a major factor in evaluating safe ground operations of moving transportation equipment. That is the major reason why we measure it.

Unfortunately, μ is not a constant. When the two opposing objects are a rubber like material and a runway surface, μ is influenced strongly by several factors. That is why we need to look at the interaction between a tire and a runway surface as a friction process, implying that μ is a variable output. We often use the term friction number for this output. If it is obtained by a braking measuring process, we call it a braking slip friction number as long as the wheel is rotating or braking slide number when the wheel is not rotating.

Major influencing factors are the tire geometry and carcass design, rubber compound of the tread, traveling speed of the vehicle, relative speed between the two opposing objects, the minute surface structures of the interfacing contact areas (texture), tire inflation pressure, presence and form of contamination (water, ice, pollutants), ambient temperature, etc.

For the friction process between a rolling pneumatically tired wheel circumference and a runway surface, the relative speed between the two opposing objects is commonly known as slip speed. At free rolling wheel there is practically no slip, i.e. the slip speed is zero. When the wheel is locked, the slip speed is equal to the traveling speed of the vehicle.

The following mathematical relationships for slip speed are used in this booklet,

$$s = v - v_p = v - \omega \cdot r = v - \omega \cdot \frac{C}{2 \cdot \pi} \qquad (3)$$

where

s = slip speed,

v= vehicle speed,

v_p = average peripheral speed of the tire in the contact patch,

ω = angular velocity of the wheel,

r = average radius from wheel center to surface contact area,

C = tire circumference measured with steel tape at the prescribed inflation pressure and normal load.

A locked wheel state is often referred to as a 100 percent slip ratio and the free rolling state is a zero percent slip ratio. The following mathematical relationships for slip ratio are used in this booklet,

$$\lambda = \frac{v - v_p}{v} \cdot 100 = \frac{s}{v} \cdot 100\,\% \qquad (4)$$

where

λ = slip ratio in percent,

v= vehicle speed,

v_p = average peripheral speed of the tire in the contact patch,

s = slip speed.

A Look at the Braking Friction Process

Since the major reason for measuring friction is predicting safe braking, lets look at how μ varies during longitudinal braking maneuvers.

We look at three scenarios. One is the conventional locking brake, which is also the same as an ABS brake with a failing ABS function, illustrated in Figure 2. The other is a functional anti-locking braking system in Figure 4. The third is the proposed Johnsen Peak Braking System in Figure 6.

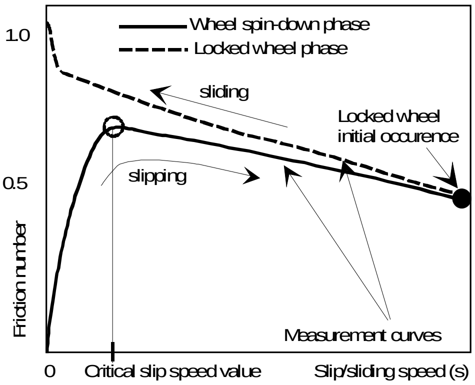

Figure 2 - Friction number graph for a locking brake.

In Figure 2 we see that in the first phase of conventional braking, the wheel rotation is gradually reduced from free rolling to a locked state. We may call this a wheel spin-down phase and the tire is now slipping. The corresponding friction number during the spin-down draws a line running from origo to the black bullet. We note that the line has a maximum point at the open circle mark, as it turns its upward direction to a downward direction to the right. This occurs at what is commonly called the critical slip speed value.

When the wheel maintains its locked state, the vehicle will reduce its speed further until it comes to a complete stop. The slip speed changes to a sliding speed, equal to vehicle speed, when the wheel locks up. During the sliding time, the friction number continues to draw a curve back the same way and upward to the left, ending in another maximum friction value associated with what is often called stiction or static friction.

The wheel spin-down phase is of short duration compared to the second phase, as can be seen in Figure 3. The two curve segments join at the maximum slip speed in a given braking process. For a wide range of slip speeds, the two curve segments are practically parallel or the same.

The discussion so far has been including the slip and sliding speeds. We get another feel for the braking surface friction process by looking at how it develops over the time during which the vehicle comes to a complete stop. It is shown in Figure 3.

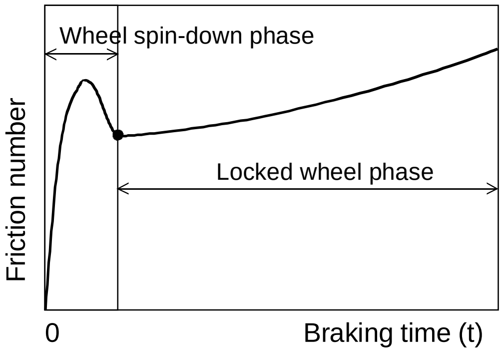

Figure 3 - Friction number graph over braking time for maximum braking with locked wheel..

The dip of the friction number from maximum value to the lower locked wheel value is undesirable from a braking efficiency, and therefore, an operational safety point of view. One severe property of the pneumatic wheel in the locked wheel phase is that it cannot contribute to steering, which requires a minimum wheel spin. Vehicles have therefore in recent years been equipped with braking systems that ensure some wheel spin in order to always provide directional control capability.

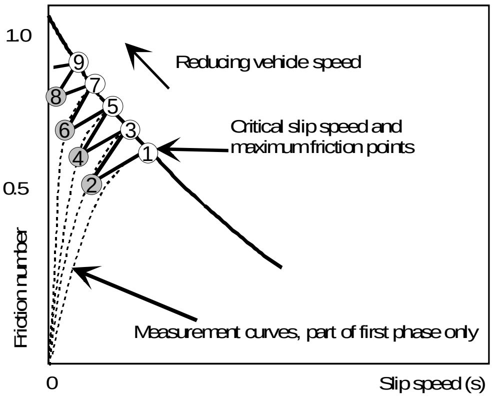

Figure 4 - Friction number graph for anti-lock brake system.

Looking at the scenario for an ABS brake in Figure 4, we note that operation generally takes place only at low slip speeds. As for a conventional brake, the friction number rises sharply in the beginning and reaches a maximum. The ABS control function notices the degradation in friction indirectly by interpreting the rate of change of the wheel rotational speed that takes place at around the critical slip speed. The ABS control logic stops the braking for a small amount of time, at points 1,3,5,..,etc, letting the wheel regain rotational speed. In this time the slip speed and the friction number decrease again before a new braking cycle is initiated at points 2,4,...etc. As the vehicle speed is reduced due to the ABS braking action, the maximum friction number increases as it travels along an exponential line upwards to the left.

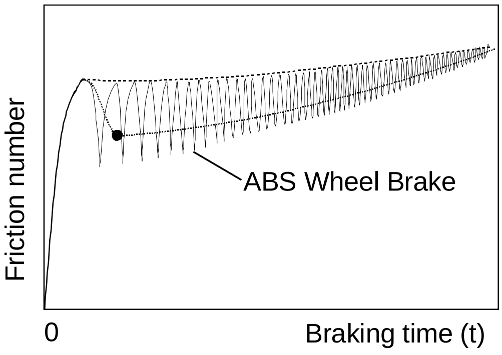

Figure 5 - Friction number graph for ABS braking and locked wheel braking.

We have assumed a wet and uniform runway surface in our scenarios.

Looking at the ABS over braking time, we get a graph like Figure 5.

Noting that the pulses have turning points at maximum friction value, the efficiency is less than maximum possible. Under many surface conditions, it approaches a mean value close to that of the locked wheel braking.

Oddvard Johnsen has proposed a braking system which stays at the peak friction value during the braking time. Figure 6 illustrates his proposal. Such a braking efficiency is the maximum attainable.

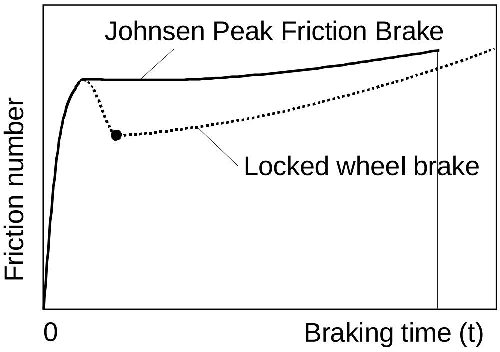

Figure 6 - Friction number graph for the Johnsen Peak Friction Braking System and locked wheel braking.

Slip Speed and Texture Dependency

We have so far studied the slip speed variable in the friction process. Another major influencing parameter is the so-called texture, i.e. the size and shape of the runway surface geometry and asperities.

The asperities penetrate the rubber giving increased area of contact for adhesion and energizes the resistive hysteresis work phenomena of rubber. As the elasticity of rubber is dependent of the strain rate, the faster these asperities hit the rolling tire circumference, the less they penetrate the rubber. Thus making smaller real contact areas available for adhesion. Smaller penetrations also yields less hysteresis energy loss which means less braking energy.

Adhesion is generally believed to have a major influence at low to moderate traveling speeds. Hysteresis becomes predominant at very high traveling speeds.

We may summarize as follows,

1. The faster a wheel spins, the less the friction will be because of reduced real contact area.
2. But also, naturally, the smaller the asperities are in absolute sizes, the less the friction will be.

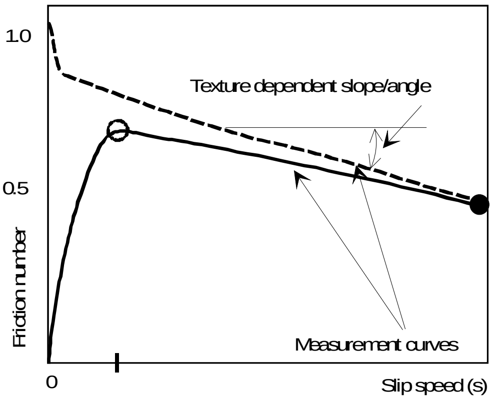

Figure 7 - Macrotexture dependency of friction.

In Figure 7 the influence of texture is depicted as a slope of the friction vs. slip speed curve. That is for simplified illustration only. When the curve is put on a logarithmic form, it takes the form of a straight line. The texture is related to the slope of this straight line. It is in fact the negative inverse of the logarithmic slope.

In general, we desire a texture that yields a minimum negative slope of the curve in order to minimize the loss of friction with increasing speed.

The role of texture has been much studied in relation to dynamic hydroplaning, i.e. a circumstance where the tire looses contact with the surface by forces from an inter-spaced layer of water in the contact area. The contamination of the pavement with water is common everywhere and always induces tire-surface conditions with loss of friction. Hydroplaning is the extreme.

The onset of hydroplaning has been experimentally shown to take place at a vehicle speed that is mostly governed by the inflation pressure of the tire. For aircraft tires the governing empirical equation predicts the hydroplaning speed in km/h to be 6.35 times the square root of the tire inflation pressure in kPa. It is valid with only a few millimeters of water depth. Once set on, the amount of water required to sustain the hydroplaning is much less, down to a fraction of a millimeter, than the water depth at initiation.

For aircraft this phenomenon is a particular safety hazard during wheel spin-up at touchdown. If sufficient amount of water is present on the surface, and it has a low hydraulic drainage capability and a poor texture which cannot break up the water film, the wheels may not spin-up for a long distance of runway due to hydroplaning. The effective landing length is reduced. There is also a risk for only partial spin-up in which case the brake control systems may interpret the major part of the runway to be more slippery than it is, resulting in a reduced effective braking supply from the wheel brakes. A longer landing length is used unnecessarily.

The properties of surface texture when the surface is wet therefore has great interest. The presence of sufficiently sharp and numerous asperities to break up a water film intervening the tire and surface is an important texture attribute for avoiding or minimizing hydroplaning. It is best measured when the surface is wet. Friction measuring devices therefore apply water ahead of the measuring wheel to bring out these properties.

Traffic and pollution deteriorate the texture by polishing it and leaving deposits of contaminants on it. The texture of a runway surface can be changed by maintenance action and it is therefore a parameter of interest to maintenance engineers. High pressure water jet systems, hammering or shot-peening machines may remove contamination layers like rubber deposits, produce texture of desired geometry and restore the quality of texture

The Tire and Surface Influences on the Friction Number

The characteristic shape of the friction slip speed curve may be explained by two major influences.

The tire has a predominant influence on the first rising part of the curve to the maximum point. The surface has a predominant influence on the curve with higher slip speeds after the maximum point.

In Figure 8 a tire influence line and a surface influence line are drawn as asymptotic border lines for the friction curve to illustrate this inherent characteristic of the friction process.

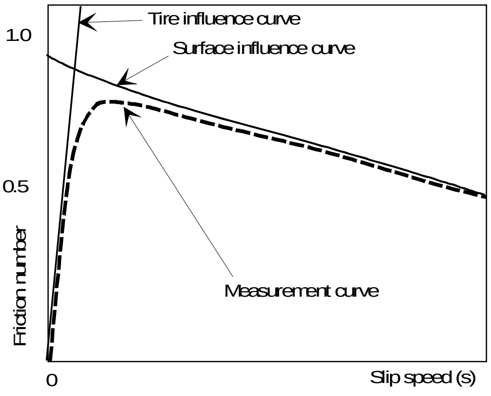

Figure 8 - Tire and surface influence lines.

For friction measurement devices that operate and yield results at low slip speeds, the friction number will carry much information stemming from the tire. Consequently, variations in tire properties will markedly influence the friction value.

For friction measurement devices that operate and yield results at higher slip speeds, or across the whole slip speed range, the friction value reported will carry mostly information stemming from the surface. For these devices the variations in tire properties are affecting the friction value less than the slow slip speed devices.

Part
2

Current Practices

The Arbitrary Friction Measures

Clearly, the friction coefficient is not a constant. Our scenario is limited to one pair of tire-surface and we have discussed dependency on slip speed only. For different pairs of tire-surface the curve takes another shape and other values. For instance, when the surface condition is dry, the curves draw higher friction values than for a wet condition of the surface. For a wet surface, the bullet often drops about 30% in friction value below the dry surface condition.

Therefore, when we measure μ it is imperative to keep as many as possible of these influencing factors constant, and/or establish the degree of influence of the most pronounced influencing factors, so as to correct for them to a common set of references by convention. For friction measurement devices, use of the same standardized measuring test tire design with the same rubber compound etc. is highly desirable.

It has been an industry problem that such common references have not been defined. Therefore, every different design of a friction measuring device has reported its own definition of the friction coefficient. Comparisons between measured values of different friction devices have been cumbersome to achieve and maintain. To use the friction coefficient as a measure in their policies and administration, many organizations have felt compelled to standardize on the use of one selected friction measuring device in order to have consistent friction data.

The World Road Association (PIARC) has acknowledged the above problems and in recent years provided some workable solutions. The first chapter in part 3 *'Harmonizing Friction Measurement Devices'* elaborates on that.

ICAO has been a major contributor to resolve this issue. A program to determine correlation between commonly used friction measuring devices was conducted following the year 1972. Correlation of the participating friction measuring devices when used on wet surfaces was found to be unacceptable.

Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA) has undertaken extensive testing of measurement test tires in recent years and has verified acceptable correlation between various continuous friction measuring devices on wetted pavement only when using carefully manufactured measurement test tires.

A program undertaken in the United States in 1989 to develop standards that would ensure tire performance and reliability on artificially wetted runways surfaces, established correlation between four continuous friction measuring devices.

A Joint FAA/NASA Runway Friction Program in 1986 established correlation between some continuous and decelerometer type friction equipment on compacted snow and ice-covered surfaces.

Recently, Transport Canada has initiated an international five year winter test program together with National Aeronautics and Space Administration (NASA), Federal Aviation Administration (FAA), the National Research Council Canada (NRC) and others. The objectives are to provide guidance to pilots and civil aviation authorities on how information on contaminated runways can be used for assessing aircraft performance. Norsemeter is proud to be one of the first industry representatives to be invited to perform in a pilot to that program. A joint Transport Canada/Norsemeter winter condition correlation program between RUNAR and other friction measuring devices was conducted in North Bay, Ontario, in 1996[iii].

In the aviation industry, a common calibrated scale of friction has not been established. For pavement maintenance purposes, surface condition levels have been regulated using the reported friction value of each participating device in the correlation programs. For operational purposes, the maintenance scheme is often seen applied for lack of better tools, pending further research to validate correlation between ground friction measuring devices and aircraft braking.

The correlation of ground-vehicle friction measurements with aircraft braking performance is limited. An extensive survey was done in Scandinavia in the 1970's in which airline pilot braking reports were correlated with ground friction devices on winter contaminated runways. For wet pavements and for certain snow- and ice-covered runways, the National Aeronautics and Space Administration (NASA) has developed and published correlation procedures for a limited types of aircraft and ground-vehicles. Further research and development is ongoing.

Many End-Uses of Friction Information

The principal reason for measuring friction is to collect information to predict braking performance of vehicles. When braking control schemes vary widely, as demonstrated in our simplified scenarios in figure 2 to 6, it is a problem to decide which representative friction value to use in our predictions. Clearly, we cannot regard friction numbers as materials constants which would imply interest for only one fixed number.

The friction numbers to pull out of the friction process are those that are most suitable for the user of the information. There are many different users of friction information and they deal with predicting braking performance for different objectives and diverse needs. Here are some examples listed,

- Pavement contractors may use friction information for product development or documentation of pavement quality.
- Maintenance engineers monitor the deterioration of the pavement over time span of years for planning resurfacing or retexturing. They have a tradition for the use of the texture information from the friction process.
- Maintenance crews of winter runways may measure friction to aid in deciding whether, and where, to apply de-icer and/or abrasives on the runway surface, when slippery.
- Traffic accident investigators measure the surface of an accident scene to estimate the driving conditions. Note that ABS brakes do not leave the same skid marks as locking brakes do to aid in estimating vehicle speeds.
- Flight dispatchers use runway friction numbers to estimate the maximum loading of an aircraft for takeoff.
- Airmen request friction information before takeoff and landing to plan the aircraft braking procedure.
- Airport operators use friction information to decide whether to close or open a runway under adverse weather conditions.
- Tire manufacturers and vehicle manufacturers need to assess the friction level of proving ground surfaces when doing product testing.
- Racing car teams may measure the raceway friction to select optimized tires for the prevailing driving conditions.

We note from the above list of purposes that by measuring and reporting the same, single, common friction number for all, this may be insufficient and not carrying all the information which could enhance the different applications of friction values to its fullest extent.

Many different friction measuring devices are in use. The friction values they have chosen to report are many different ones and have given rise to much confusion.

For runway and runway purposes, the focus is on the surface frictional characteristics rather than the tire-surface interaction or tire characteristics part. The surface part of the friction can be measured with a standardized tire, whose properties are kept as constant as possible, while assessing the runway surface as the only variable. The American Society of Testing Materials has several standards defining tires for friction measurements[3] to this end.

For automotive applications the focus is on the actual friction process including the actual full-scale tire and vehicle. Surface frictional characteristics are also important for referencing proving conditions.

Modeling actual friction processes of braking vehicles by using smaller scale friction measuring devices is very complex. The braking force information developed by a single tire in a friction measuring device is applied towards a multiple wheel landing gear of a much larger and different vehicle, having different braking mechanisms and braking controls. Friction measuring devices do not include an operator input. Even so, one popular approach is to run correlation measurements between the full-scale vehicle/tire and a friction measuring device on the same surfaces and derive specific correlation equations between the vehicle and the measuring device.

Due to the interactive nature of the friction process between the tire and the surface, true friction values can only be obtained by full-scale measurements between the objects. It could be achieved by having friction measuring devices placed in situ of vehicle brakes.

ICAO Estimated Braking Action on Ice and Compacted Snow

As friction values vary less with surface condition and speed on many ice and compacted snow surfaces, a practice has evolved to use a single value as an indication of estimated braking action for those surface conditions. For runways covered with ice and/or compacted snow, a five grade scale of friction has been developed as shown in the table below. It is taken from the ICAO Annex 14 to the Convention on International Civil Aviation, Volume I.

Measured Coefficient	**Estimated Braking Action on Ice and Compacted Snow**	**Code**
0.40 and above	Good	5
0.39 to 0.36	Medium to good	4
0.35 to 0.30	Medium	3
0.29 to 0.26	Medium to poor	2
0.25 and below	Poor	1

Table 1 - Estimated braking action in 5 grades.

A problem with using such a scale of friction is that it is has no calibration reference. The actual friction numbers reported by a particular friction measuring device is specific for that device only, related to its design, construction and measuring tire used. One can therefore not assume that the tabulated values are valid for a particular device.

The Federal Aviation Administration (FAA) and National Aeronautics and Space Administration (NASA) conducted correlation test between four types of continuous friction measuring devices and two types of decelerometer friction measuring devices in 1986 which illustrate this point (see reference 6). A correlation graph is shown below. It is redrawn from ICAO Airport Services Manual, Part 2.

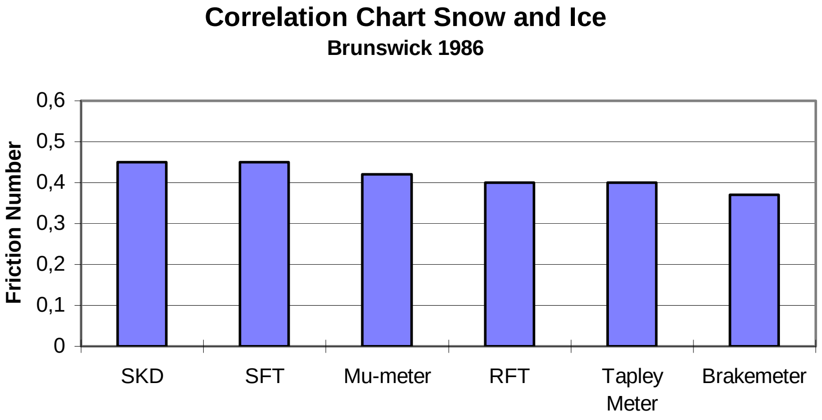

Figure 9 - Correlation between friction devices on compacted snow- and ice-covered runways from Brunswick,1986.

A friction number value of 0.45 reported by the Skiddometer (SKD) and Surface Friction Tester (SFT) corresponds to a value of 0.40 reported by the Runway Friction Tester (RFT). The variance in friction numbers reported was 0.10.

From the joint Transport Canada/Norsemeter winter runway survey program in 1996 the following correlation between participating devices have been worked out (see reference 7). The variance in friction numbers reported was 0.21. The devices participating were Surface Friction Tester (SFT), Electronic Runway Friction Decelerometer (ERD) and Runway Analyzer & Recorder (RUNAR). The RUNAR reported a peak friction number and a friction number at 60 km/h slip speed. The average critical slip ratio was found to be in excess of 30 percent.

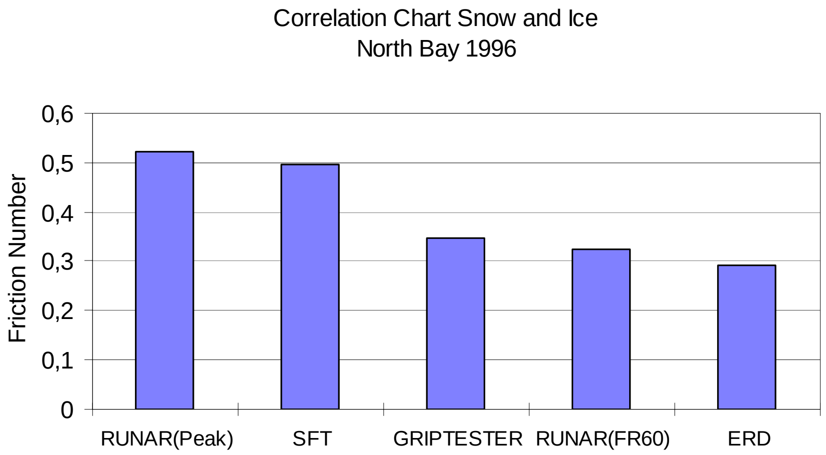

Figure 10 - Correlation between friction devices on snow- and ice-covered runways from North Bay, 1996.

ICAO Runway Surface Condition Levels

For a wet paved runway, where the speed dependency of friction is highly noticeable, a maintenance scheme may be based on a set of friction values. An ICAO guidance includes a set of three friction values - a maintenance friction level at which maintenance action should be initiated, a minimum friction level when users of the runways should be informed that the runway may be slippery when wet, and thirdly, a design minimum friction level for a new or resurfaced runway surface. The guidance values are shown in the table below. It is based on Table A-1 in ICAO Annex 14 to the Convention on International Civil Aviation, Volume I.

Friction device	**Test speed (km/h)**	**New/resurfaced Design Objective Level DOL**	**Initiate Maintenance Level - IML**	**Minimum Friction Level - MFL**
Mu-meter	65	0.72	0.52	0.42
Mu-meter	95	0.66	0.38	0.26
Skiddometer	65	0.82	0.60	0.50
Skiddometer	95	0.74	0.47	0.34
Surface Friction Tester	65	0.82	0.60	0.50
Surface Friction Tester	95	0.74	0.47	0.34
Runway Friction Tester	65	0.82	0.60	0.50
Runway Friction Tester	95	0.74	0.54	0.41
TATRA	65	0.76	0.57	0.48
TATRA	95	0.67	0.52	0.42
GRIPTESTER	65	0.74	0.53	0.43
GRIPTESTER	95	0.64	0.36	0.24

Table 2 - Runway Surface Condition Levels in device specific units.

Again, the friction values tabulated are specific for that device only, related to its design, construction and measuring tire used. The table will grow with the introduction of new models of friction measuring devices. Even the named friction devices will undergo evolutionary changes of model features that may affect the output values.

There is no administration in place to update the table on a regular basis that would accommodate new entries and model changes of existing entries.

A common scale of friction would simplify the regulation and relieve the process of re-editing, printing and distribution when new devices are marketed. Imagine replacing the table with one row of values in terms of a non-proprietary friction index!

Part 3

New Developments

Harmonizing Friction Measurement Devices

In 1992 a major international experiment was conducted using a wide selection of public road sections and airfield runways in Belgium and Spain. All the different friction and texture measurement devices of the world were invited to participate. 41 devices took part in establishing a rich database of friction and texture measurements.

From analysis performed on this database, PIARC has found a way to harmonize measurement results from existing friction measurement devices. Measured values from one device can be transformed to the value of another device by including a separate texture measurement of the same surface in the transform equation.

A Calibration Reference for Measuring Friction

PIARC also has proposed to make the average measurement value of all participating devices in the experiment a standard reference for friction. This average is called a Golden Value. It makes it possible for the first time in history to calibrate friction measuring devices to a universally accepted, commonly established, non-proprietary scale of friction.

The Golden Value can be established for a surface by any participating device in the PIARC international experiment, as calibration factors have been published for each of them. Other devices can then be calibrated by measuring the same 'golden' surfaces.

In essence, the Golden Value solves most of the problems of influence from the design of the measuring device on reporting friction.

PIARC has proposed to report the friction value at a relative speed of 60 km/h between tire and pavement and name it the Friction Number, F60. At this high slip speed the harmonization of different friction measuring devices is of the highest and commendable quality. The reporting speed and harmonizing speed are the same.

Harmonizing vs. Reporting Needs of Slip Speed References

The value of 60 km/h may empirically also be justified to reflect an average friction value for a maximum hard braking maneuver with a locked wheel state on public roads.

However, organizations are expected to set their own reporting speed references. The most important feature with the 60 km/h reference is that is the commendable point for harmonizing friction measures between different devices.

For airfields, for instance, the reported Friction Number could be set at some lower slip speed. Designing for landing gears of aircraft with ABS braking maneuvers that do not exceed a slip ratio of 10 %, a reporting slip speed could be set as low as 15 km/h assuming wheel braking is used with 150 km/h as a mean value. However, the slip speed value at which transformation of friction values between different devices shall always be 60 km/h.

Safety Aspects of Macrotexture

As a measure on how strongly the friction number depends on the relative speed, the gradient of the friction values estimated from friction values below and above 60 km/h shall also be reported according to PIARC. This gradient is named the Speed Number, S_p, and is reported in the range 1 - 500 km/h.

The PIARC experiment strongly confirmed other research that the Speed Number is a measure of the texture influence of the surfaces on friction.

When measured by a blank treaded tire, it is a measure of the runway surface texture with structure elements commonly called macrotexture, i.e. sizes from 0.5 mm to 50 mm in extension.

Macrotexture is in focus as a major contributor to friction safety characteristics for several reasons. The most well known reason is the hydraulic drainage capability that macrotexture has for wet pavements during or immediately after a rainfall. This capability will minimize the risk for hydroplaning. Another reason is that the wear or polishing of macrotexture can be interpreted from the Speed Number as it changes value over time for a section of road.

A pronounced peak shape or a steep negative slope of the friction - slip speed curve is considered dangerous. The normal driver will experience an unexpected loss in braking power when the brake pedal is pushed to its maximum, and the braking power is not at its maximum.

A smallest possible negative slope or even a flat shape of the friction - slip speed curve beyond the peak is therefore desired.

With conventional wheel brakes the peak is the starting point for an instability region. The resistive force changes direction at the peak and quickly retards the wheel rotation to a locked state. The wheel exploits the lesser resistance to lock up. A release of the brake pedal is required to remedy the situation and bring the wheel back into rolling - before the peak.

A good tire design will act to minimize the effects described above. The interaction between a commercial aircraft tire and runway surface constitutes another friction process than the interaction between a friction measuring device and the same surface. We limit ourselves to friction measuring devices with standardized test tires for the examination of the surface contribution to deceleration efforts in this booklet.

The International Friction Index

The PIARC concept of Friction Number and Speed Number is called the International Friction Index (IFI). The index is composed of two numbers, The Friction Number, F60, and the Speed Number, S_p. Both numbers are predictions of values of the Golden Curve by a measuring device.

Since F60 and S_p on the Golden Curve are the calibrated values of friction, any friction measuring device will have to be calibrated to this reference curve.

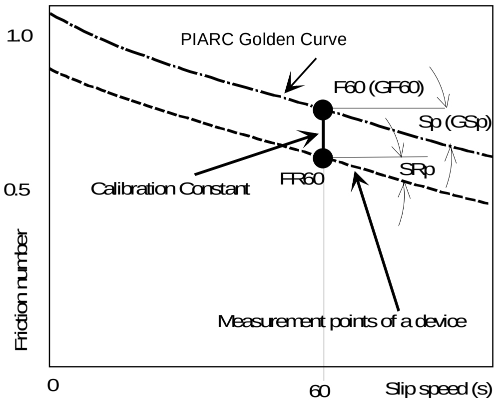

Figure 11 - The PIARC Friction Model.

The IFI is based on a mathematical model of the friction process called the PIARC Friction Model. In essence, it applies to the second phase of our braking scenario in Figure 2. It models the Golden friction coefficient as a function of slip speed and macrotexture.

If *s* is the slip speed, S_p is the Golden Speed Number and μ_s is the friction value at some arbitrarily chosen slip speed *S*, the Friction number curve may be written as follows

$$\mu(s) = \mu_S \cdot e^{-\frac{s-S}{S_p}} \qquad (5)$$

If we choose 60 km/h slip speed reference for the value of S, the equation may be written as

$$\mu(s) = F60 \cdot e^{\frac{60-s}{S_p}} \qquad (6)$$

Having measured Sp and the friction value F60 at 60 km/h, we can estimate the Golden friction value at any other slip speed by plugging in a chosen value for s.

The Speed Number for the runway surface may be measured by a specialized device for texture measurements. We can also obtain S_p by running minimum two measurement runs of the surface with each run at a different slip speed at the same vehicle speed. Some friction measuring devices - like the Norsemeter products - measure both friction force and macrotexture in the same measurement.

The Rado Unified Friction Model

The PIARC Friction Model basically deals with the locked wheel phase of our braking scenario in Figure 2. It also may be applied to the second part of the first phase where the curve is pointing to the right and runs downward. It does not apply to the initial curve segment when the friction number rises sharply to a maximum value.

With the advent of ABS brake functions, it is also of great interest to model the initial curve segment of the first phase of our braking scenario in Figure 2 and 4.

For estimating braking action with ABS brakes, the maximum friction value, when the wheel is still rolling with low slip ratios, is relevant. Under such conditions the tire will work to give the vehicle a requested change of direction, as well as perform braking. In the locked wheel state, the tire is unable to contribute to change of direction requested by a driver.

There is a need for a friction model which complements the PIARC Friction Model for above reasons. Such a friction model has been established by Zoltan Rado from analyses of the PIARC database. Moreover, a mathematical model for the behavior of the maximum friction value has been accomplished. In fact, the Rado Unified Friction Model may be viewed as incorporating the PIARC Friction Model in the wheel spin-down phase above the critical slip speed.

It is on the form

$$\mu(s) = \mu_{\max} \cdot e^{-\left(\frac{\ln\left(\frac{s}{S_{\max}}\right)}{\hat{C}}\right)^2} \qquad (7)$$

In this relation (7) μ_{max} is the maximum friction value, and S_{max} is the corresponding slip speed, also known as the critical slip speed.

C^ is a shape factor which is closely related to the speed constant in the PIARC model.

The transformation equation at 60 km/h slip speed is

$$S_p = \frac{\hat{C}^2 \cdot 60}{2 \cdot \ln\left(\frac{60}{S_{\max}}\right)} \qquad (8)$$

The Rado Model also treats μ_{max} as a function of surface and tire properties, measuring speed and slip speed.

A family of Rado friction number curves for 3 measuring speeds and a Rado maximum friction curve are shown in Figure 12.

Variable Slip Measuring Technique

The Rado Friction Model lends itself to determining the actual friction curve for a braking process from free rolling to a locked wheel state.

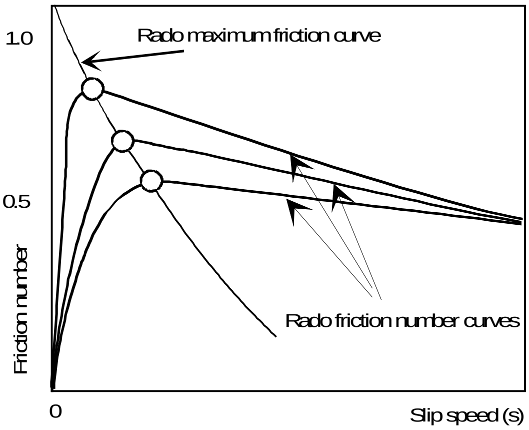

Figure 12 - The Rado Friction Model in graphic presentation.

The Norsemeter friction measuring devices utilize what is called a variable slip measuring technique.

The technique is characterized by doing controlled wheel braking on the measuring tire while keeping a constant traveling speed. The measuring wheel is braked gradually from free rolling to locked state through the range of available slip speed.

By sampling hundreds of friction values at known slip speeds, a friction number curve is fitted to the acquired data points using the mathematics of the Rado Friction Model. The equation for the friction number curve is determined. An equation for the maximum friction values is also derived.

Having the equations, friction values can be estimated[iv] and presented for any slip- and sliding speeds, as well as different traveling speeds under the same environmental conditions.

Therefore, the Rado Friction Model applied in a variable slip measuring device can directly report the IFI, both the Friction Number, F60, and the corresponding Speed Number, Sp. In this model, Sp is the derivative of the curve at the F60 point, when it is transformed to a logarithmic form.

Figure 13 depicts both the Rado and PIARC friction models.

FR60 and SRp are the real measured values by the device before applying calibration factors for the prediction of the Golden Values.

Maximum friction values can be predicted for the measured surface stripe at all other traveling speeds for the same tire using this model.

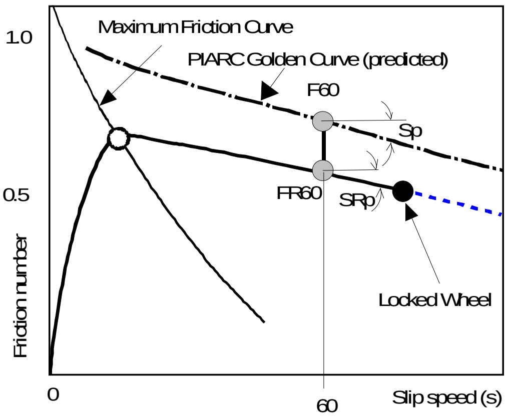

Figure 13 - The PIARC and Rado Friction Models.

Due to the variable slip technique, the PIARC Friction Model can be established directly, as well. The PIARC Model equation (5) can be fitted to the data above the critical slip speed or the second part of the Rado Model curve can be used directly. Having the equations, the friction values can be estimated for all slip speeds and traveling speeds.

For instance, the friction number at a selected 14% slip ratio may be reported along with the maximum friction number and the IFI device pair of parameters.

The 14% slip ratio is a common ratio for fixed slip friction measuring devices.

The capability to report a friction number at a selected slip ratio is important for users that have maintenance or operational schemes historically based on fixed slip measuring devices. Values from fixed slip devices may be compared with the values obtained by the variable slip device directly. For fixed slip devices that are calibrated to the PIARC Golden standard, harmonization of the Friction Number F60 is also available.

The combination of the Rado Friction Model and the variable slip measuring technique provides a modern and powerful tool for studying and monitoring friction processes between a tire and runway surface. It is a synthesis of product development at Norsemeter and the research of PIARC and its supporters.

The capability described above is standard in the OSCAR, ROAR and RUNAR friction measuring devices made by Norsemeter. Operations of friction measuring is made easier, more efficient and safer with such capabilities. The richness in reported friction process parameters is unique.

Here are some striking points:

- Measurements taken at one speed can be estimated for other speeds. For instance, measurements may take place at a safe traveling speed and be estimated for higher speeds.
- Measurements taken at different speeds can all be estimated and reported for the same reference speed. Useful for ruling purposes.
- The same device can measure friction and macrotexture from the same measurement data.

- The same device can serve the needs of pavement maintenance engineers, transportation operators, vehicle operators, vehicle accident investigators and others.

FrictionPrints™v

The speed and texture dependencies may be well illustrated by the family of friction number - slip speed curves for one set of surface - tire interaction during braking. This set of curves shows one curve for every constant vehicle speed one may choose to investigate. See Figure 14.

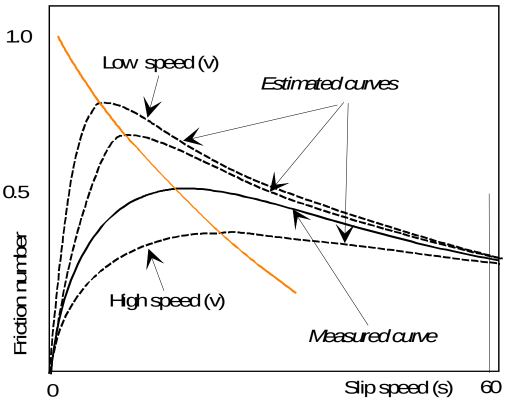

Figure 14 - A sample FrictionPrint for wet pavement.

The Rado Friction Model:

$$\mu(v,s)=\mu_{max}(v)\cdot e^{-\left(\frac{\ln\left(\frac{s}{S_{max}}\right)}{\hat{C}(v)}\right)^2}$$

A simplification of the Rado Friction Model to one independent variable x:

$$f(x)=A\cdot e^{-\left(\frac{\ln\left(\frac{x}{B}\right)}{C}\right)^2}$$

Figure 15 - Simplified mathematical model of friction curve.

Since the set of curves represents a unique set of graphics for each variable slip measurement taken of the surface, its uniqueness may be thought of as representing identification information much like that of fingerprints of a human finger. Thus, the designation FrictionPrint™ .

With application of the Rado Unified Friction Model on the measured surface friction data, we are able to define the set of curves mathematically. In essence, one variable slip measurement constitutes the identification of one the curves in the FrictionPrint, namely the one at the vehicle measuring speed.

Having the mathematical parameters determined, a whole family of curves for the same tire - surface pair may be constructed.

In Figure 15 we find that the equation f(x) can be used to draw one curve for all values of x once the parameters A, B and C (treated as constants) are determined.

These three parameters are outputs in the Norsemeter measurement processing software. The A parameter is the maximum friction number, B is the critical slip speed and C is the shape factor. Thus, the measured curve has been turned into an equation.

Measuring Cycle

The variable slip measuring cycle can be applied repeatedly in a pulsing measuring manner, so as to determine the friction equation for surface segments from 3 to 30 meters in length depending on the traveling speed of the measuring device. See Figure 16.

When a segment is not sufficiently homogeneous for the quality of the curve fitting, the measurement will be discarded.

Friction numbers can be reported single or as a statistically estimated friction level for a section of runway.

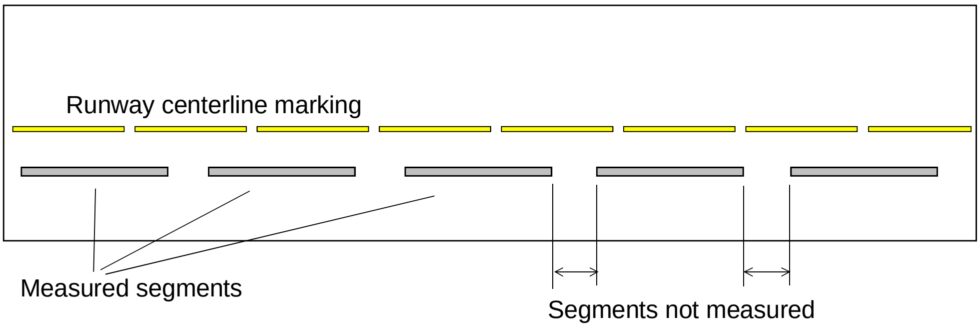

Figure 16 - Measured segments in continuous mode.

Extended Use of IFI

IFI is defined by PIARC for bare, wetted pavements. When a friction measuring device that is calibrated to the IFI, it is a calibration only to one out of many possible surface conditions, namely wetted pavement with a 0.5 millimeter water film thickness. One would most probably also use a device which is calibrated to this wet pavement condition to measure surfaces with other contaminants.

The friction scale for wet pavement would then serve as the baseline for a common scale for evaluating other surfaces, simply because the device is set up with that scale of friction and it is not feasible to change the scale or calibrate to other surface conditions.

To avoid confusion with reported friction values from a device which not only measures IFI for bare, wet surfaces, but also friction numbers for many other surface types and conditions with the same instrumentation, it seems feasible to introduce an extended IFI designation to cover measurements taken on other than bare, wet pavement surface conditions.

For each consistent and reproducible surface condition one might envisage another set of golden values for that surface condition. When no such golden scale exists, it is not possible to translate friction values from one device type to another using the PIARC harmonizing approach. It also means that the relationship to macrotexture similar to that found in the PIARC Golden Curve is unknown for other surface conditions.

Golden values for other than wetted pavements have not yet been produced as far as we know. Dry, bare pavements are a candidate, but another approach may be feasible in that case. It is described in a next paragraph headed *'Dry Measurements'*.

For winter contamination a general difficulty is to describe the contaminant and produce/reproduce the same contaminant consistently. It is therefore difficult to do another 'PIARC experiment' on such surface conditions for establishing a new golden curve from a sufficiently large population of different friction measurement devices.

Devices like RUNAR are sensitive to slip speed regardless of surface conditions. The operator must therefore note when the surface is right for naming the friction value a valid IFI according to its definition valid for wet pavement only. However, it seems feasible to use the scale of IFI also for other surface conditions. This is an extended use of IFI.

The Norsemeter variable slip devices are designed for measuring under winter conditions involving dry segments of runway surface. Then, the use of water may be unsafe at temperatures near or below freezing and detrimental to the measuring work, as it would create a new surface condition with slush and/or ice.

Dry Measurements

Under non-freezing conditions, measurements of friction are traditionally done with a water film sprayed onto the surface ahead of the measuring tire. The film is standardized to be a constant 0.5 mm or 1.0 mm in nominal thickness regardless of traveling speed.

Water has been added to the measurement method to deliberately obtain a measure of macrotexture. The water also protects the tire from excessive heat and wear.

With fixed slip devices the tires are constantly braking, and therefore subjected to wear all the time during a measurement mission.

For variable slip devices, the tires are operating in braking modes down to fractions of a second and rolling freely between brake cycles. These devices lend themselves therefore to measuring without water as far as protecting the tire is concerned.

This capability has opened up for new applications of friction measuring. In regions of the world where ice formation on the runways may be a safety hazard, the variable slip device may essentially be put to work as an ice detector. This is particularly useful when surfaces are badly visible like in the darkness of night. Visual assessment of the surface is then difficult and unreliable. On measuring missions when freezing may occur, the device will have to be operated in a dry mode.

Friction numbers obtained from a dry measuring mode are generally higher than the wet mode numbers for a surface. Since the device can operate in both modes, correlation of measured values dry vs. wet are conveniently established. For many conditions this correlation may be used as a transforming equation from dry to wet numbers. This is a way to estimate IFI also from dry mode measurements.

The following relationships for friction and texture have been found between wet and dry conditions using RUNAR devices with ASTM E-1551 tires on some black top surfaces:

$FR60_{wet} = 0.309 \bullet FR60_{dry} + 0.2688$ with $R = 0.97$ (9)

and

$SR_{pwet} = 0.2867 \bullet SR_{pdry} + 68.963$ with $R = 0.84$. (10)

R is a coefficient of correlation expressing how much of the variation in the wet values that can be explained by the dry values.

Calibration of Friction Measurement Devices to IFI

For all participating friction and texture measuring devices in the PIARC International Experiment 1992, calibration constants to the Golden standard have been worked out by PIARC and published (see reference 1).

The calibration scheme for friction is based on doing a linear regression at 60 km/h slip speed between the Golden value and the value measured by a device.

For the friction part, the calibration constants are *A*, *B* and *C* in the equation

$F60 = A + B \bullet FR60 + C \bullet Tx$ (11)

where FR60 is the measured value by the device.

It has been shown that for variable slip devices using blank treaded ASTM test tires that C = 0.

The calibration factors of the texture part are similarly *a* and *b* in the equation

$S_p = a + b \bullet SR_p$ (12)

where SR_p is the measured texture value by the device.

Calibration is achieved by

1. doing measurements on wetted pavements with a friction measuring device and a texture measuring device that participated in the said PIARC experiment to establish Golden values for the surfaces,

2. doing measurement of an uncalibrated device on the same surfaces under the same conditions to establish the device values for the surfaces.

3. Then, from comparing the two set of values across several friction levels, a set of secondary calibration constants A,B,C,a and b can be derived for the uncalibrated device(s).

Calibration of Variable Slip Devices

The OSCAR variable slip device, owned by the Norwegian Directorate of Public Roads, participated in the PIARC Experiment. For ROAR and RUNAR variable slip devices, Norsemeter has performed secondary calibration with OSCAR according to the procedure generally outlined above.

For OSCAR the following calibration constants to PIARC Golden values have been published:

$F60 = -0.0000074 + 1.000022 \bullet FR60$ with $R = 0.83$. (13)

FR60 is the measured value by OSCAR for 60 km/h slip speed.

> We note that OSCAR practically measures F60 directly since the calibration factors are so close to zero and 1.

R is the coefficient of correlation expressing that 83 percent of the variation in the golden F60 can be explained by FR60.

From secondary calibration runs between OSCAR and RUNAR the following secondary calibration constants have been established:

$FR60_{OSCAR} = 0.0189 + 0.7 \bullet FR60_{RUNAR}$ with $R = 0.98$. (14)

$FR60_{RUNAR}$ is the measured value by RUNAR for 60 km/h slip speed, and $FR60_{OSCAR}$ is the corresponding value measured by OSCAR.

Since both devices also measure macrotexture, calibration relationships are established in the same manner for texture. SR_{pOSCAR} are measured values of Speed Number for OSCAR and SR_{pRUNAR} are the same for RUNAR.

$S_p = -125.909 + 1.482922 \bullet SR_{pOSCAR}$ with $R = 0.83$. (15)

$SR_{pOSCAR} = 11.048 + 0.7433 \bullet SR_{pRUNAR}$ with $R = 0.95$. (16)

By elimination of $FR60_{OSCAR}$ in equations (13) and (14) the following predictions of the IFI Friction Number F60 by RUNAR is established:

$$F60 = 0.0189 + 0.7 \bullet FR60_{RUNAR} \quad (17)$$

i.e. the calibration constants are A = 0.0189 and B= 0.7.

Similarly for equations (15) and (16), the prediction of IFI Speed Number Sp by RUNAR is established:

$$S_p = -109.5257 + 1.102256 \bullet SR_{pRUNAR} \quad (18)$$

i.e. the calibration constants are a = -109.5257 and b = 1.102256.

Calibration of Fixed Slip Devices

By design the fixed slip friction measurement devices are limited to a fixed slip ratio during measurement. Typically, they yield results in the low slip speed range < 20 km/h. They normally cannot be operated with a slip speed of 60 km/h at which the calibration scheme discussed previously for variable slip devices is used.

A workable approach is as follows.

On a surface we measure a friction number at 10 km/h slip speed with a fixed slip device.

On the same surface we measure IFI (F60, S_p) with a variable slip device.

For further explanation of the calibration scheme, look at Figure 17.

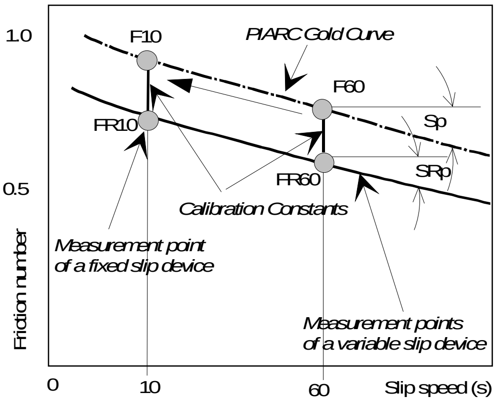

Figure 17 - Calibration of a fixed slip device.

With the variable slip device we identified the point FR60 and SRp. With the calibration constant for IFI of this device, we estimate F60 and S_p.

The logarithmic form of the PIARC Golden Curve is a straight line. S_p is a value for the slope of this line. We can, therefore, estimate the F10 value when knowing F60 and S_p. Having found F10, the unknown calibration constant between F10 and FR10 can be calculated, as we have measured FR10.

Fixed slip devices can also report IFI(F60) when calibrated. However, a separate texture measurement is required in order to establish the Speed Number of the surface S_p at F10 (predicted GF10). Then, knowing the ordinate and abscissa of F10 and the slope of the curve, we can estimate F60 (predicted GF60).

Part

4

New Applications

Using IFI for Surface Maintenance Intervention Levels

For quality management of runways, a promising new tool for setting intervention levels based on minimum target Friction Number and the Speed Number is available. Thus, both the speed and the texture dependencies of friction are incorporated as quantified parameters in the construction and maintenance of runways. The numbers are device independent.

For different classes of runway conditions, different sets of IFI may be set as minimum standard targets. A sample set are derived in the following sections and examples are shown in the section 'ICAO Surface Condition Level in Terms of the PIARC Model Parameters'.

Intervention charts based on intervention work equations are useful complements to the index parameter numbers. Such charts can be worked out for reported friction numbers that are harmonized to IFI, and for reported friction values that are device specific, provided the calibration constants for the device are known.

See the later section 'Sample Intervention Work Equations and Chart' for how to derive the work equations for harmonized reporting. The following chart in Figure 18 is based on device specific reporting for RUNAR.

With graphical representations of intervention work equations, we can visualize the evaluation of the texture and speed influences on surface friction. The graph provides us with a guide to what corrective maintenance action that would have effect for a given runway survey.

To discuss texture influences, a set of intervention values are chosen. The minimum target friction number shall be 0.3 at 90 km/h slip speed. The minimum texture requirement is chosen at 200 km/h and is shown as a vertical line.

From the graph for this scenario, we see that four quadrants are depicting different road surface conditions.

The upper right quadrant, labeled Roman I, holds all values with a satisfactory road quality.

The upper left quadrant, labeled roman II, holds all values where the Friction Number is satisfactory, but the texture Speed Number is unacceptable. Macrotexture could be improved.

The lower right quadrant, labeled Roman IV, holds all values where the Friction Number is unsatisfactory, yet the Speed Number (macrotexture) is good.

The lower left quadrant, labeled Roman III, holds all values that are unacceptable.

- When measured values fall in quadrant I, it indicates that no maintenance work on the pavement is necessary.
- When measured values fall in quadrant II, it indicates that macrotexture should be improved.
- When measured values fall in quadrant IV, it indicates that the pavement microtexture should be improved.
- When measured values fall in quadrant III, it indicates that the pavement should be resurfaced of higher quality.

Reported measurement values maybe plotted into the chart for illustration. Two measurements are shown as bullets no.1 and no.2. In this example, the uncalibrated values of the measuring device relative to IFI are used. They are denoted FR60 and SR_p as opposed to F60 and S_p as calibrated denotation.

From RUNAR we have obtained the following values:

Measurement no.1: FR60 = 0.37 and SR_p = 153.

Measurement no.2: FR60 = 0.67 and SR_p = 342.

Measurement no.2 indicates a satisfactory pavement.

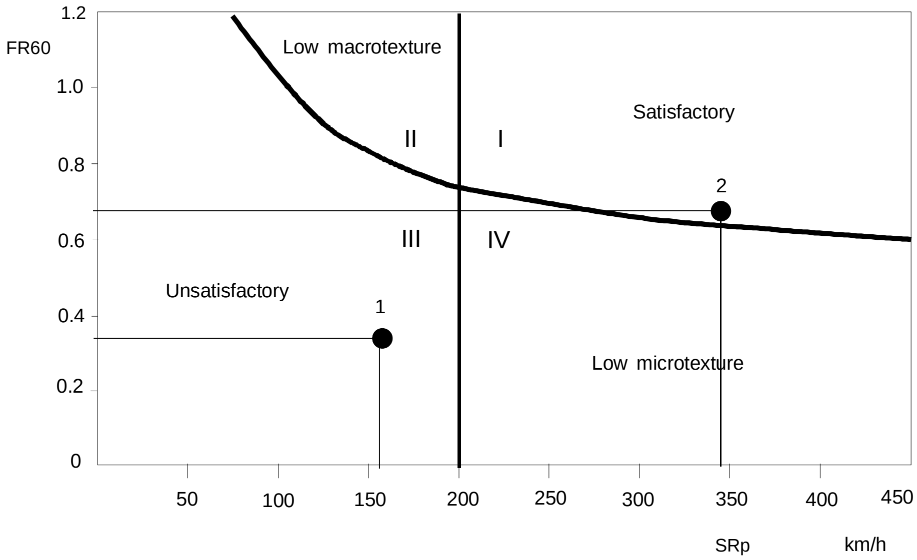

Figure 18 - IFI intervention chart for a class of runways with the intervention values of Friction Number 0.3 at 90 km/h slip speed and a Speed Number of 200 km/h. Axis indicate uncalibrated RUNAR measurements.

The Norsemeter measuring devices have the capability to carry out the logic testing for the measured values against the intervention limits and report the results. The reporting may be simplified to a binary 'Acceptable' or 'Not Acceptable' relative to the regulated work equation.

Using IFI for Operational Intervention Levels

The well known minimum friction level applicable to wet pavement required by ICAO is referenced in Table 2. When the friction falls below the values tabulated for the device, information is promulgated to airport users that the runway may be slippery when wet.

The friction levels are stated per friction device at two speeds, 65 and 95 km/h. At the lower speed the friction numbers range from 0.42 to 0.50 across devices. At the higher speed the range is from 0.24 to 0.42.

By calibrating the friction devices to IFI, only one friction number will suffice. The reported friction number would be the same for any of the harmonized devices.

The table states two friction numbers at different speeds for each device. It is an indication of the slope of a friction versus speed which is a measure of macrotexture. So is the IFI Speed Number. The set of two values of friction at two different speeds may be replaced with a single IFI speed number.

The variable slip devices like RUNAR produces the speed number in one survey. The reported slip speed reference for the speed number may be 65 km/h, although the IFI is harmonized across friction measuring devices at 60 km/h slip speed.

Fixed slip devices should be used together with a separate texture measurement device to obtain the speed number. See the following section *'The Risk of Measuring False Texture Using a Fixed Slip Device Only'.*

For all users and providers of friction information, the minimum friction level expressed in IFI would be a set of one friction number and one speed number. The interpretation would be so simple that an informed user needs only to know the runway IFI to determine whether the runway should be regarded as slippery when wet.

The task of transforming surface condition levels currently promulgated by leading aviation community sources to IFI parameters remains to be done. A sample theoretically derived set of values are presented in the section *'ICAO Surface Condition Level in Terms of the PIARC Model Parameters'.*

On snow- and ice covered runways, the braking action is considered less dependent on surface, speed, tire and device specifics. Table 1 on estimated braking action for compacted snow- and ice covered runways is therefore tabulated without reference to specific friction devices. Differences across devices are indeed present, although they may typically constitute 0.03 to 0.08 friction numbers[vi] on those surfaces. In a friction number measuring range 0.25 to 0.40, that is a variance of 10 to 20 percent equivalent of a full code range, which is 0.05.

Clearly, there is a need for a common scale of friction apllicable for winter contaminated surfaces and IFI is useful for this purpose also.

The application of the Friction Number can be done in the same way that other proprietary wet pavement friction scales are transferred to winter contaminated runways. The Speed Number adds a new dimension of texture equivalency to the contaminated surface. It is useful for the administering of abrasives onto the ice covered runway to improve braking action. In principle, the tool described in a previous section regarding surface maintenance on wet pavement indices may be well suited for winter maintenance as well. However, more research is needed to verify its usefulness.

One particular interesting aspect for winter contaminated runways, is the frictional characteristics that occur with some amount of loose material on the surface when the friction number increases with increasing slip speed. The Rado Unified Friction Model senses such tire-surface interaction behavior and accentuates frictional properties that may have been difficult to assess in the past. The IFI tool may have to be complemented by Rado Model parameters (critical slip speed and shape factor) to fully make use of variable slip techniques on contaminated surfaces. Already, limited research[vii] shows that there is a pronounced peak friction value also on winter contaminated surfaces with the critical slip speed considerably higher than most fixed slip devices are built to register. On such surfaces they measure too conservatively.

The Risk of Measuring False Texture Using a Fixed Slip Device Only

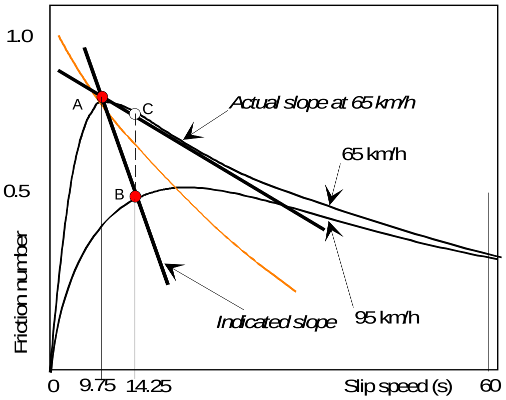

Figure 19 - False texture prediction with fixed slip technique.

The scenario for this illustration is a fixed slip measuring device which performs two runs at 65 and 95 km/h respectively, on the same wetted pavement. The slip ratio is fixed at 15 percent. Therefore, the slip at 65 km/h is 9.75 km/h and at 95 km/h it is 14.25 km/h.

In the first run at 65 km/h the device reported a value at point A. We assume this was at the peak friction value. In the next run the friction number reported was the value at B. It is a common mistake to assume this is point C. But at higher vehicle speeds, the friction curve is flatter and the peak moves to the right. The true friction curve is therefore another and is shown as the lower of the two. A peak friction curve has been drawn as a guide.

When deducting the slope from points A and B to find a measure of texture (refer to equation (19)), the indicated slope is far from the one we look for. It is more like the one denoted actual slope.

For this reason, a fixed slip device should be used together with a texture measurement device to obtain the speed number, rather than running the risk of falsely reporting the slope interpreted from two speeds.

A Sample Transform of ICAO Surface Condition Levels to IFI Models

Can we transform earlier practices to the new developments? What do the PIARC and Rado Models look like when applied to aviation regulations and airport authority monitoring practices?

To give answers to above questions, we will use the Table A-1 in ICAO Annex 14, Volume I. It is partially reproduced here as Table 2. Our demonstration is for illustration only of new models. Access to the more detailed source data for the Table A-1 is necessary for an actual transformation. But in principle, the transform may be done as outlined in the following.

The table defines three surface condition levels.

DOL - Design Objective Level for new or resurfaced runway pavements, IML - Intervention Maintenance Level when maintenance action should be taken to improve the surface or resurface it,

MFL - Minimum Friction Level for informing pilots, flight dispatchers and other users that the runway may be slippery when wet.

For each of these condition levels, the table has two friction numbers, one each at 65 km/h and 95 km/h vehicle speed, for six particular devices. The devices are all continuous fixed slip type machines with known slip ratios. We will use the values for slip ratio for each machine as stated in ICAO Airport Services Manual, Part 2. Hence, we can convert the quoted vehicle speeds to slip speeds.

Next, we calculate the average friction number for each condition level at each vehicle speed and calculate the average slip speed for the devices at the low vehicle speed 65 km/h and the high vehicle speed 95 km/h. The outcome of these calculations are shown in the Table 3 below.

Condition level	Slip speed at 65 km/h	Friction number at 65 km/h	Slip speed at 95 km/h	Friction number at 95 km/h	Average slip ratio in %
DOL	8.67	0.78	12.67	0.70	13.33
IML	8.67	0.57	12.67	0.46	13.33
MFL	8.67	0.47	12.67	0.34	13.33

Table 3 - Average ICAO Surface Condition Levels with a slip speed variable.

The results so far enables us to construct the graph in Figure 20.

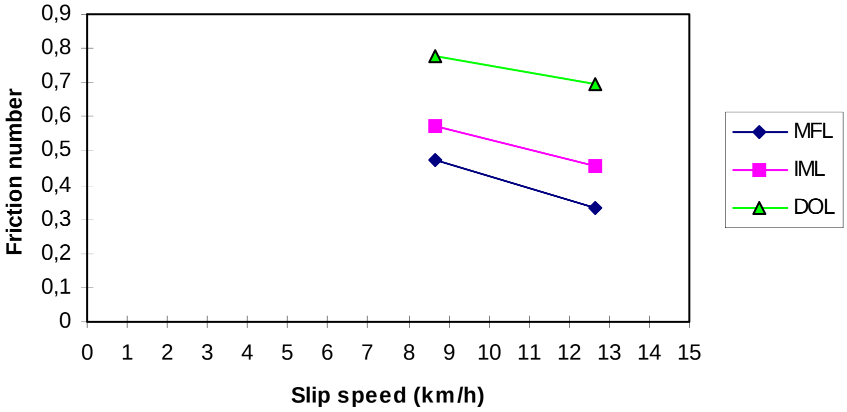

Figure 20 - Surface Condition Levels with a slip speed variable.

We now have the data for two points in the graph for each condition level to calculate the slopes of the curve segments. The slopes are key to deriving the macrotexture measure. In the PIARC Model the Speed Number is defined as the negative inverse of the slope on a log-normal form.

$$\frac{\ln\mu_1 - \ln\mu_2}{s_1 - s_2} = -\frac{1}{S_p} \quad (19)$$

The reader should be warned that this application of equation (19) may give erroneous results when the data points are close, they are both in the peak friction region and the slip speed curve for each measuring speed differ much in shape. This is discussed in the previous section and illustrated in Figure 19. It emphasizes the value of measuring over a wider slip speed range than offered by fixed low slip speed devices.

We still think this exercise is instructive to demonstrate the use of new tools. The results of this calculation is shown in Figure 21. They are denoted SR_p instead of S_p to indicate that the values are not calibrated to the IFI calibration reference.

For each condition level the speed numbers are calculated using (19) as follows,

DOL - SR_p= 36.17 km/h,
IML - SR_p= 18.04 km/h,
MFL - SR_p= 11.69 km/h.

Recalling that the IFI Speed Number is

$$S_p = a + b \cdot Tx \quad (12)$$

For Tx equal to 1 mm, and the IFI calibration factors for sand patch a= -11.59813 and b= 113.63243,

$$S_p = -11.59813 + 113.63243 \cdot 1 = 102.03\ (\text{km/h}) \quad (20)$$

These are all extremely low values for describing a good surface. One reason for this may be an invalid use of the equation (19) on the low slip speed device data available.

In ICAO Airport Services Manual, Part 2, a design level of minimum 1 mm average texture depth is recommended. That corresponds to a Speed Number of 102 km/h, when estimating it on basis of the **a** and **b** calibration constants for sand patch method from PIARC. See boxed text for the calculations.

Computations of texture measures based on Table 3 yield only about one third (36 km/h vs. 102 km/h) the value of the average texture depth requirement. This seems to be a discrepancy within the same document from an authoritative source on the subject and should be looked at. The application of new knowledge brought this discrepancy into the open.

The PIARC Model is an exponential equation. With the use of a spreadsheet software, the curve segments are then extrapolated, assuming the intercept value for zero slip speed to be in the range of 0.80 to 0.90. The resulting curves are shown on the next graph.

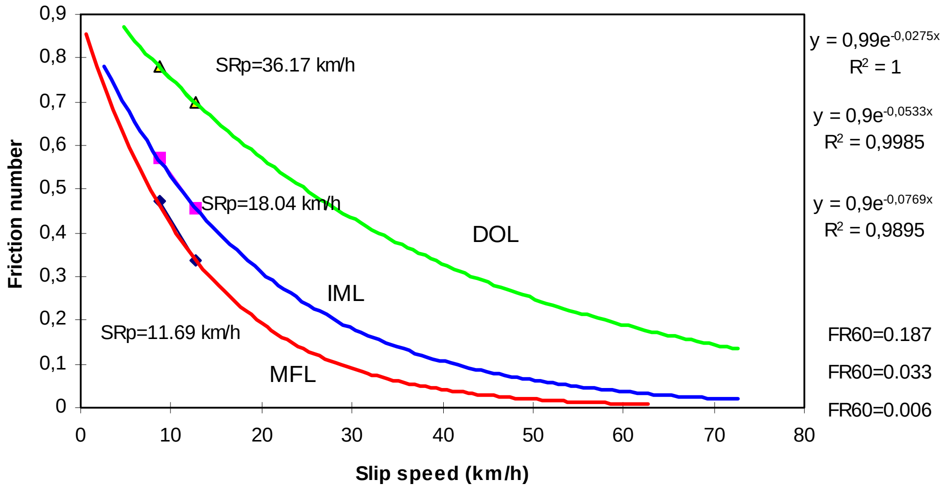

Figure 21 - Surface Condition Level data extrapolated.

We can now predict the friction number for much higher speeds. Values at 60 km/h are shown on the graph. A further indication that the current values for intervention levels ought to be looked at is the observation that the IML and MFL friction numbers at 60 km/h are so low that such values are normally associated with ice skating sports.

At this point we can apply the PIARC Model equation (5), as we have the speed numbers calculated, and we have pairs of friction number, μ_1, and slip speed, s_1, to put into the equation. We choose the low speed pairs at the 65 km/h vehicle speed. This gives us an equation for each surface condition level where slip speed, s, is the only variable.

$$\mu(s) = \mu_1 \cdot e^{-\frac{s-s_1}{SR_p}} \qquad (21)$$

We may generate a curve for all values of slip speed for each surface condition level. The resulting curves are shown in Figure 22.

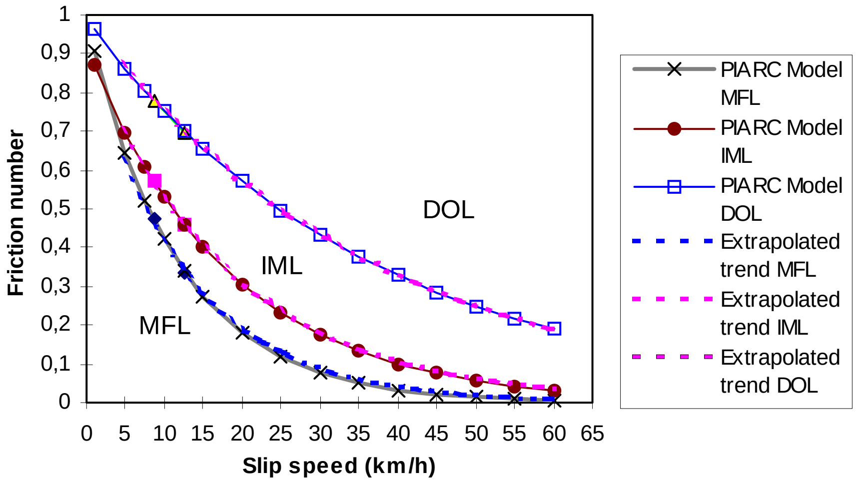

Figure 22 - Surface Condition Levels in PIARC Model graph.

We note that curves fall right on top of the extrapolations we did with another method earlier.

ICAO Surface Condition Level in Terms of the PIARC Model Parameters

At this point, we can describe each surface condition level in terms of the PIARC Model as a friction number at a chosen slip speed and a speed number constant. We choose 15 km/h slip speed as our reference. Either by calculation using the PIARC Model equation or from reading the graph, we get for each of the surface condition levels,

DOL	-	$IFI_{15}(0.655,36.17)$	or practically, $IFI_{15}(0.66,36)$
IML	-	$IFI_{15}(0.401,18.04)$	or practically, $IFI_{15}(0.40,18)$
MFL	-	$IFI_{15}(0.274,11.69)$	or practically, $IFI_{15}(0.27,12)$.

One surface condition level is thus expressed by two numbers instead of a table of data. By requiring that friction devices be harmonized, we also get device independent regulation. That is management simplified.

Note.

Harmonizing and calibration to PIARC Golden curve of friction measuring devices are to be done at 60 km/h slip. We have in our demonstration taken averages of reported values without such harmonization and the friction numbers are not calibrated to the PIARC reference.

ICAO Surface Condition Level in Terms of the Rado Model Parameters

The Rado Model (5) uses three parameters - a maximum friction number, μ_{max}, the corresponding slip speed, S_{max}, and a shape factor, C^.

For our demonstration, we assume that the maximum friction number is the average friction number for the 65 km/h vehicle speed. The average slip speed at 65 km/h vehicle speed is then also assumed being the S_{max}.

A transform equation between the PIARC speed number and the shape factor was given earlier (8). We now have all parameters to calculate $\mu(s)$ for all values of s.

The next graph is showing the Rado Model, PIARC Model and the extrapolated curves all in one illustration.

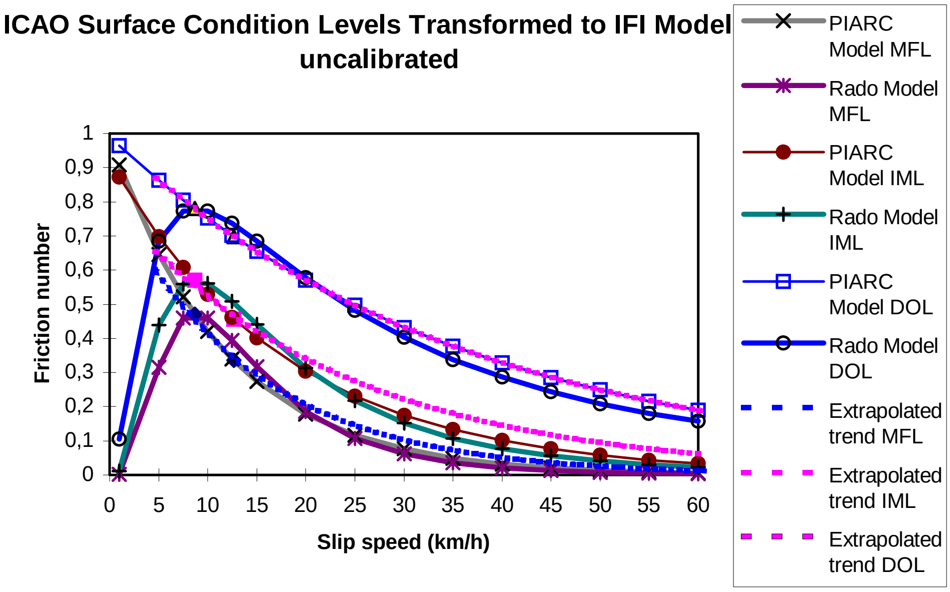

Figure 23 - ICAO Surface Condition Levels transformed to IFI models.

The Rado parameters are tabulated below.

Surface Condition Level	μ_{max}	S_{max}	C^
DOL	0.78	8.67	1.53
IML	0.57	8.67	1.08
MFL	0.47	8.67	0.87

Table 4 - ICAO Surface Condition Levels transformed to the Rado Model.

The values tabulated are the maximum friction parameters and the shape factor. The maximum is the most desired value for rule making and monitoring. We now also have the location of it in terms of slip speed. Because we are using the same tire for the measurements, the maximum friction values themselves can be predicted[viii] for different vehicle speeds of the measuring device. One measurement at a particular vehicle speed identifies one of the friction curves in the unique FrictionPrint™ for the surface condition. Refer to Figure 14.

For friction devices using variable slip measuring technique with a Rado Model interpreter, there is no question whether the peak friction is measured or not.

This ambiguity is present for fixed slip measuring techniques.

Additionally, there is a risk that the fixed slip device would wrongly report friction values on the left side of the maximum friction point. Fixed slip devices may report too low friction values when the peak friction occurs at a slip speed which is above the measuring slip speed (operating slip ratio times vehicle speed). This is particularly true for higher vehicle speeds and winter surfaces where the peak may be found at a slip ratio as high as 30 percent. Measurement point B in Figure 19 illustrates this point.

A practical significance of the Rado Model used in a variable slip device is the productivity. One loop on the runway at one speed is a sufficient survey to bring a full report on speed and texture dependency of the current runway conditions.

The Rado Model has the capability to include tire characteristics in the prediction of friction values. That makes it a promising tool for predicting aircraft tire-surface friction at all speeds, slip speeds and surface texture variables[ix]. Thus, aircraft FrictionPrints™ guides may be developed for different aircraft types on different surface conditions.

Runway and Aircraft Friction Indexes

When the friction measuring device is harmonized with the International Friction Index (IFI), the Rado Model offers an alternative tool for reporting surface condition levels. Particularly when transforming the shape factor to IFI speed number, the reporting is the most informative available for many users. We may call this index for the Rado or Runway Friction Index.

Intervention Level Type	Rado Model with Shape Factor term	Rado Model with Speed Number transform	PIARC Model with reporting slip speed 15 km/h
DOL	RFI(0.78, 8.67, 1.53)	RFI(0.78, 8.67, 36.17)	IFI_{15}(0.65,36.17)
IML	RFI(0.57, 8.67, 1.08)	RFI(0.57, 8.67, 18.04)	IFI_{15}(0.40,18.04)
MFL	RFI(0.47, 8.67, 0.87)	RFI(0.47, 8.67, 11.69)	IFI_{15}(0.27,11.69)

Table 5 - ICAO Surface Condition Levels transformed to friction indexes of Rado and PIARC.

Any of above denotations represents a unique friction curve related to the ground vehicle friction measuring device.

Provided the friction measuring device is harmonized to IFI and is using standardized test tires, the unique friction curve so identified may be used as the common base from which aircraft braking performance can be estimated. The RFI can be input to flight performance calculators engineered for each type of aircraft. Alternatively, the RFI can be transformed to an Aircraft Friction Index (AFI) for those cases where flight performance calculators are not employed or are unavailable.

The prediction of aircraft performance parameters, which may enable a landing distance estimation, needs to be engineered and tested for each type of aircraft on the different surface type and condition that it may encounter in operation.

The Aircraft Friction Index can be denoted as follows,

AFI/XXX(0.45, 7.43, 102.00)

where XXX signifies the aircraft type, for example B-737.

This index will tell what the estimated maximum braking action is, at which slip speed it occurs and how much the friction varies with the surface texture.

An operational refinement of this could be to report a predicted friction value for the spin-up at touch down, which is a value at high slip speed at nominal aircraft landing speed on the FrictionPrint™ described by AFI/XXX.

As most ground friction measuring devices apply digital computers, such reporting is minimal extra work and is only a small marginal information processing cost.

To facilitate those that think the above is too complex, the FrictionPrints™ can be translated into a five grade friction scale with similar look and feel as the well known braking action codes in Table 1.

A system overview of above proposals is shown in Figure 24. In effect, the RFI and AFI would be extensions to an already established IFI regime for pavement management objectives. The grand feature with this system is that it will bring friction measurements from different equipment through a common harmonization to present the same and calibrated numerical values of the friction process parameters for the same surface. The harmonizing system will be common across industries for most end use objectives. Yet it delivers the friction process parameters to the users in the flavor they can best make use of.

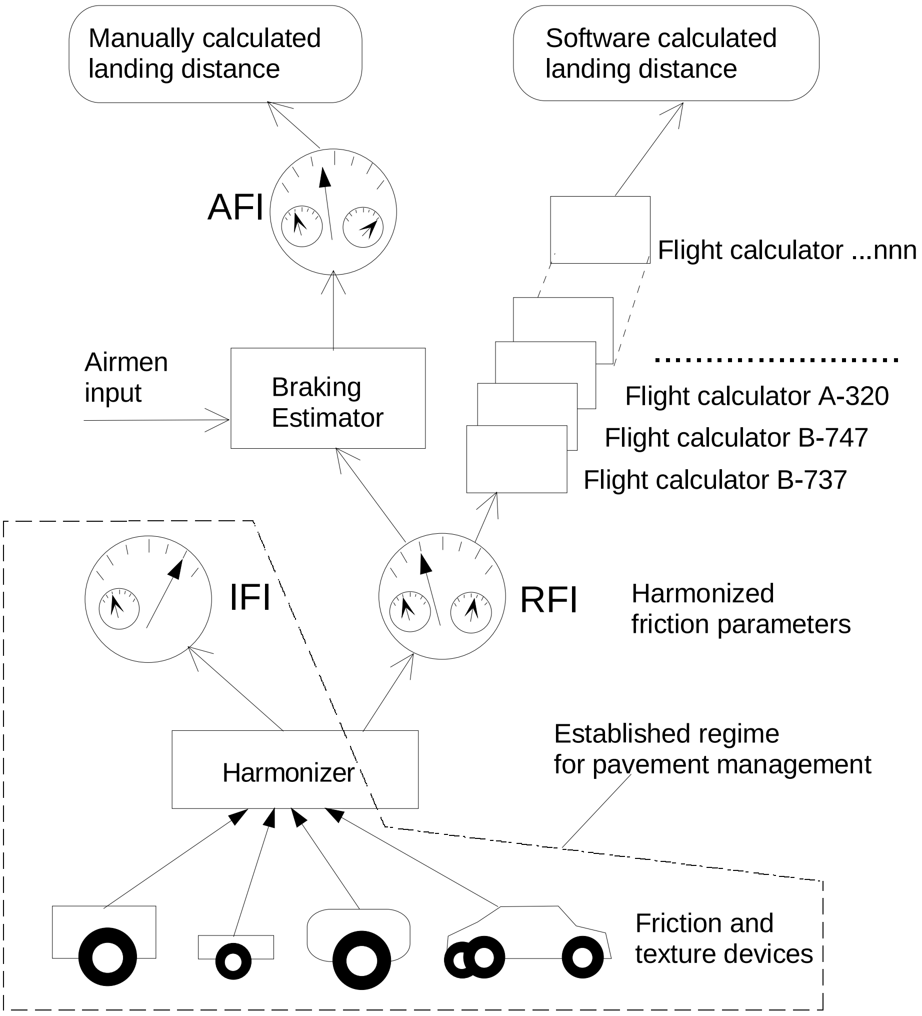

Figure 24 - A system diagram for harmonizing friction process parameters.

Sample Friction Level Intervention Work Equations and Charts for Surface Maintenance

When friction measuring devices are harmonized according to the PIARC proposition, they will report measured values that are calibrated to a common scale. In the following we discuss one way of defining surface condition levels by intervention work equations and intervention charts.

We adjust any measured friction value μ_s at slip speed *s* to the 60 km/h slip speed by the PIARC Model on the form

$$F60 = \mu_s \cdot e^{\frac{s-60}{Sp}} \quad (22)$$

If we regulate that the friction μ_s shall have a certain fixed minimum value at the slip speed *s*, we can plot the F60 values for all values of Speed Numbers S_p, thus generating a boundary curve which satisfies the ruling.

Let us say that the runway surface friction μ_s shall be greater than 0.2 at 200 km/h slip speed in the touch down zone for the landing wheels to achieve a satisfactory spin-up. We can then identify all values of F60 and S_p that will satisfy that requirement by substituting these values into the equation (22) and obtain an intervention work equation as follows:

$$F60\,(S_p) = \mu_s \cdot e^{\frac{s-60}{S_p}} = 0.2 \cdot e^{\frac{200-60}{S_p}} = 0.2 \cdot e^{\frac{140}{S_p}} \quad (23)$$

We already observe from the general form of this equation that a large speed number value is desirable in order to have a low requirement for FR60.

A minimum requirement for texture also has to be chosen. We choose a Speed Number of 150 km/h.

The following graph is a plot of F60 for all values of S_p up to 400. It is an intervention chart for evaluating which pairs of measured F60 and S_p that will give us the minimum friction number 0.20 at slip speed 200 km/h.

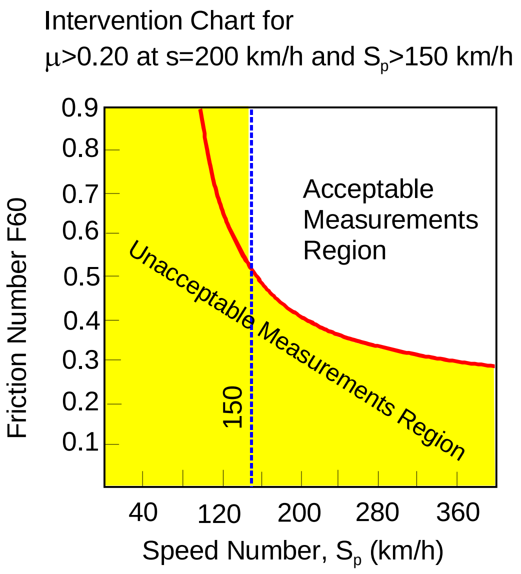

Figure 25 - Intervention chart for a touchdown zone.

An IFI friction measuring device like RUNAR will report a Friction Number F60 and a Speed Number S_p directly. The measuring speed may have been anything between 30 and 130 km/h. The friction measurement is always adjusted to a 60 km/h slip speed which is the IFI harmonizing speed.

The reported F60 friction number has to fall above the intervention boundary line in the graph, if the requirement of a minimum runway surface friction μ_s= 0.20 at 200 km/h slip speed shall be met. Since it also was a required minimum Speed Number of 150 km/h, the measured values must fall into a quadrant bounded by upper side of the friction curve and the right side of the speed number boundary line. We call this the upper right quadrant. It contains pairs of acceptable measurements.

The F60 friction number has to be at least 0.509 at the lowest allowable speed number. The 0.509 value is the intersection point with the 150 km/h speed number boundary line.

If the speed number was measured higher, the allowable reported F60 friction number could be less. With good texture we can settle for a lower friction number.

Let us look at one more example. This time we consider the middle third of a runway where anti-locking wheel brakes operate between 10 and 20 percent slip ratio and the ground speed of the aircraft is 100 km/h. We use a slip speed of 15 km/h as operational parameter. The regulated minimum friction shall be 0.25. We have the same requirement for texture with a speed number of 150 km/h. The graph for this scenario is shown below.

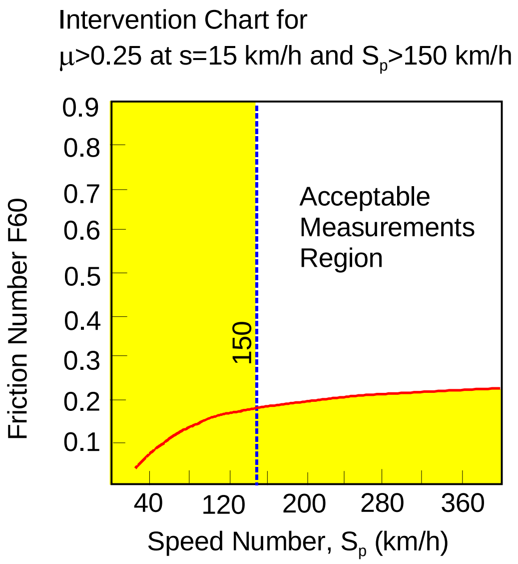

Figure 26 - Intervention chart for a middle section of runway.

The lowest permissible reported F60 friction number is 0.185, which is the friction value of the interception point with the speed number boundary line. This time the curve points down on the left side, at the lower speed numbers.

We note that in our first scenario for the wheel spin-up in the touch down zone, the reported F60 friction number had always to be higher than the required minimum friction value at the 200 km/ slip speed.

In our second scenario for the middle runway, the reported FR60 friction number may also to be a smaller value than the required minimum friction value at the 15 km/h slip speed.

This is as we would expect, since we know that friction decreases with increasing slip speed on a wet runway pavement. The FR60 friction number is by convention reported at the 60 km/h slip speed, unless specifically noted otherwise. Therefore the F60 point resides higher than the friction value at the 200 km/h slip speed and lower than the friction value at 15 km/h slip speed.

These observations may make it easier to understand the second scenario where lower F60 values are acceptable with lower S_p values (steeper curve).

Sample ICAO Intervention Charts

It can be shown that a texture measure of an average texture depth of 1 mm using the sand patch method is the equivalent of an IFI speed number of 102 km/h. From table 2 we use the average friction values for each class as follows

Condition level class	Slip speed at 65 km/h	Friction number at 65 km/h
DOL	8.67	0.78
IML	8.67	0.57
MFL	8.67	0.47

Table 6 - Friction and slip speed target intervention levels.

Using (23) for each set of minimum friction at the slip speed 8.67 km/h we get a chart as shown in Figure 27.

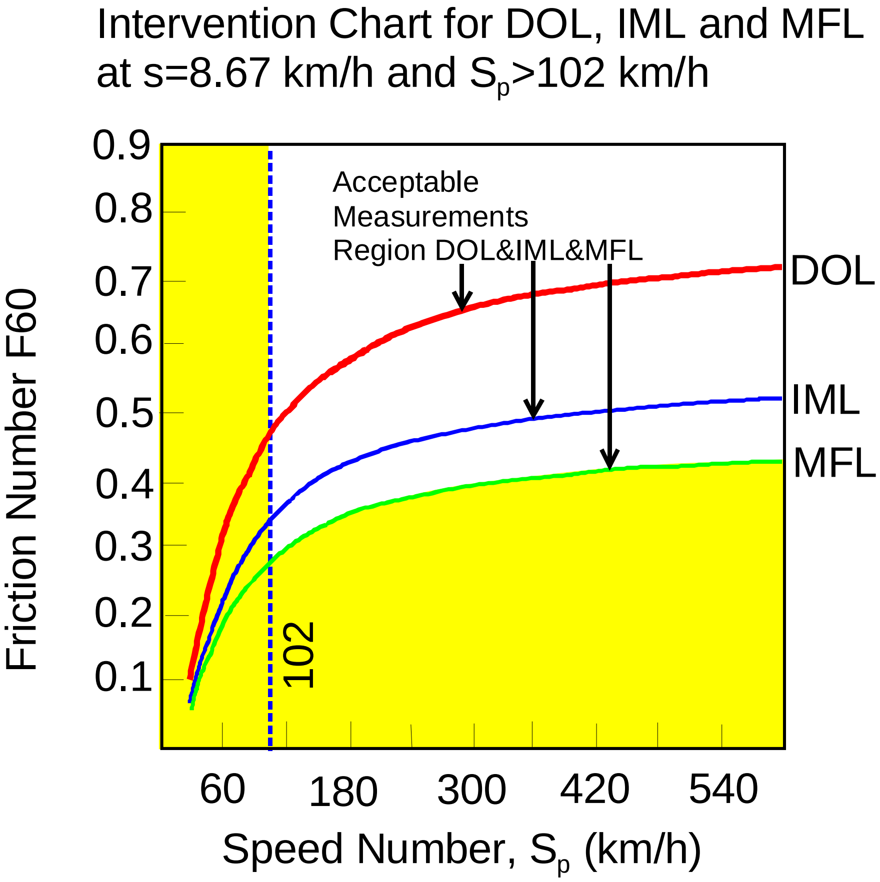

Figure 27 - Sample IFI intervention chart for a minimum IFI Speed Number of 102 km/h. Minimum friction numbers acceptable are DOL=0.78, IML=0.57 and MFL=0.47. Slip speed reference for these friction numbers is 8.67 km/h which is the average slip speed for the devices listed in Table 2 at 65 km/h traveling speed.

We note that the permissible pair of F60 and S_p values that a device can report, must fall above the curves and to the right of the 102 km/h speed number limit. The lowest acceptable F60 values are 0.472 for DOL, 0.345 for IML and 0.285 for MFL when the texture quality corresponds to a Speed Number 102 km/h. Theses friction values are the intersects with the 102 km/h speed number limit line.

An official regulatory chart would be based on a set of single harmonized friction and texture values rather than the averages from Table 2 used in the demonstration here.

Closing

The innovative Norsemeter technology is being applied to break new grounds within different fields of the transportation and mobility communities. In so doing, many issues related to standardization must be dealt with, as we are introducing new ways of measuring and organizing of common physical parameters of concern to many people worldwide.

As the pioneers progress, the Norsemeter literature will likely be extended with material from their experiences.

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[i] Invented and patented by Oddvard Johnsen, an airline pilot captain and founder of Norsemeter.

[ii] After Zoltan Rado, Hungarian engineer and mathematician from Technical University of Budapest, Ph.D. Mechanical Engineering 1994, Pennsylvania State University, U.S.A. Co-author of the PIARC Report on the International Experiment 1992.

[iii] CDRM, Inc., *Evaluation of Ground Test Friction Measuring Equipment on Runways and Taxiways under Winter Conditions*, September 1996

[iv] Patent pending

[v] Trademark of Norsemeter as.

[vi] National Aeronautics and Space Administration (NASA) Technical Paper 2917, 1990, p.43.

[vii] Joint Transport Canada/Norsemeter testing at Jack Garland Airport in North Bay, Ontario 1996.

[viii] Patent pending

[ix] Patent pending