CORRELATION OF SELF-WETTING FRICTION-MEASURING DEVICES

By:

Gerard van Es (principal author)*
(National Aerospace Laboratory NLR)

Ad van Leest
(CROW Technology Centre for Transport and Infrastructure)

Jeannot Fafié
(Road and Hydraulic Engineering Division, Department of Transportation)

Ronald Van der Vegte
(Amsterdam Schiphol Airport)

Harry Van Dijk
(Dutch Civil Aviation Authority)

Christ van Gurp & M. Moeniel
(Dutch Road Research Laboratories KOAC-NPC)

*P.O. BOX 90502
1006 BM Amsterdam
The Netherlands
vanes@nlr.nl

PRESENTED FOR THE
2004 FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE
Atlantic City, New Jersey, USA

April 2004

INTRODUCTION

Airfield runways must provide adequate friction between an aircraft tire and the wet surface for the safe operation of aircraft during landing and in the event of a rejected takeoff. Runway friction measurements are made to detect any deterioration of the skid resistance and to determine if there is a need for maintenance action. A large number of different friction-measuring devices are available for this purpose. These friction-measuring devices have different operating modes, different tires, and are tested with a wide range of tire inflation pressures. Furthermore, there are many variables that affect the measured friction values. Due to these facts, attempts to find a simple correlation of the measurement outputs of one device against that of another have not been successful. Several attempts have been made in the past to correlate the results of the different friction-measuring devices using more advanced methods (Van Es and Giesberts [1]). Unfortunately, only limited success was achieved with these methods. One of the major problems is that of the many variables that affect the measured friction values, only a limited number can be controlled during a test. The uncontrolled variables will contribute to the random uncertainty in the output of a friction-measuring device. The influence of this random uncertainty on the results is not taken into account in the methods developed in the past.

In 2002, a Dutch working group on runway friction (under supervision of the CROW Technology Centre for Transport and Infrastructure) started to examine the problem of correlating friction-measuring devices from a runway maintenance perspective. The working group reviewed the important literature and projects regarding wet runway friction with special focus on friction-measuring devices. Furthermore, the working group examined the potential of an advanced statistical method to correlate the output of friction-measuring devices that operate in a self-wetting mode. This new method takes the random uncertainty in the output of a friction-measuring device in to account. This was missing in all previously developed methods.

This paper presents and discusses some of the important achievements of the working group. In particular, the advanced statistical method to correlate the output of friction-measuring devices is presented and discussed in this paper.

The objective of this paper is to give an insight into a new approach to correlate the output of friction-measuring devices that operate in a self-wetting mode, which is important when the results from different runway maintenance surveys are compared.

REVIEW OF PREVIOUS CORRELATION STUDIES

In this section, a brief overview is presented of some correlation studies of friction-measuring devices. The simplest way to correlation different friction-measuring devices is by directly comparing the output of two devices. Examples of such approaches are reported by Merritt [2] and Anon. [3]. The important conclusion made in these early studies is that there is no consistent or precise correlation between the output of the various friction-measuring devices. Despite these results, still even today studies are conducted in which the output of two different devices are compared directly. In 1983, Horne and Buhlmann [4] developed a method from the combined viscous-dynamic hydroplaning theory (also known as the 3-zone concept of Gough). This method used empirical data to derive coefficients from friction tests, which characterised the surface macro- and microtexture. These are then used to predict the braking friction coefficient for other tire braking operating modes. Compared to the earlier studies this method was advanced and looked very promising. Unfortunately, it lacked any consideration for uncertainties in the friction measurements. This was one of the reasons for its limited success. In the period from 1992 to 1995, the PIARC Technical Committee on Surface Characteristics carried out a study to compare and harmonise measuring methods for determining the friction and texture of pavement surfaces (Wambold [5]). Numerous tests were conducted during this study on a large number of surfaces using different types of self-wetting friction devices. One of the main results of the PIARC study was the introduction of the International Friction Index (IFI). This index should allow for the harmonising of friction measurement with different equipment to a common calibrated index. Although the IFI index made it to an ASTM standard, the practical results of the method were not very encouraging (see Van Es and Giesberts [1]). The surface microtexture can be as important as the macrotexture regarding the friction characteristics on a wet surface (Van Es and Giesberts [1]). Since there is no method available for measuring the microtexture of a surface directly only the surface macrotexture is correlated to the friction in the IFI method. The British Pendulum Tester BPT is sometimes considered a measuring method for the microtexture. However, the size and shape of the surface macrotexture can affect the BPT results and therefore it is likely that the BPT does not measure the microtexture correctly (Van Es and Giesberts [1]). In addition to these shortcomings, the IFI method does not consider the uncertainties in the friction measurements. These are the main reasons of the limited success of the IFI method. In 1997, the Engineering Sciences Data Unit (ESDU) Company developed a method for representing and relating the braking performances of aircraft and ground-test machines in wet conditions (Balkwill and Mitchell [6], [7]). This ESDU method is essentially statistical. The method was successfully applied for correlating the braking performances of aircraft and friction-measuring devices in natural wet runway conditions. The method was also successful in correlating friction-measuring devices among each other in natural wet runway conditions. Unlike all previous developed methods, the ESDU method does account for the uncertainties in the friction measurements in a systematic way. However, the usefulness of this method for correlating different friction-measuring devices that operate in a self-wetting mode was not investigated by ESDU. Because the ESDU method looked very promising in correlating self-wetting friction-measuring devices, the working group on runway friction decided to evaluate the method. The remainder of this paper will discuss the results of this evaluation study.

ADVANCED METHOD FOR CORRELATING FRICTION-MEASURING DEVICES

BACKGROUND OF THE ESDU METHOD

The relevant conditions of a runway friction measurement will vary to some degree from one test to another and can even vary within the same test. In most cases it is impossible to determine even what all of the relevant conditions actually are, let alone control them. These unpredictable and uncontrollable effects are called random uncertainties. These uncertainties should not be mistaken for so-called systematic errors. Systematic errors are a systematic uncertainty in the output meaning that it should be possible to determine the source of the error and filter or subtract it from the output. This cannot be done with random uncertainties in the output, as these errors cannot be determined. The ESDU Company developed a statistical method for relating the braking performances of aircraft and friction-measuring devices in wet conditions (Balkwill and DJ. Mitchell [6], [7]). The ESDU method has the clear advantage above the other developed methods that it accounts for random uncertainty in the measurements. The method has been successfully applied for correlating the braking performances of aircraft and friction-measuring devices in natural wet runway conditions. The method was also successful in correlating friction-measuring devices among each other in natural wet runway conditions. Friction-measuring devices used for runway friction maintenance purposes are normally operated in a self-wetting mode. So far, the ESDU method was only applied to analyse correlations between friction-measuring devices that were tested on natural wetted surfaces. There are no real limitations known to the ESDU method that could restrict its use on friction-measuring devices that operate in a self-wetting mode. However, the method of water application when using a self-wetting friction-measuring device prevents any influence of the runway natural drainage characteristics. This could result in the fact that the ESDU method cannot be used for self-wetting friction-measuring devices. A study was therefore conducted to evaluate if the ESDU approach can be used to correlate the output of friction-measuring devices that are operated in a self-wetting mode. The results of this study are reported by Van Es [8] and will be discussed later in this paper.

DESCRIPTION OF THE ESDU METHOD

In this section, only a brief description of the ESDU method is given. A more detailed and complete description of the method is provided in Balkwill and Mitchell [6], [7].

It is assumed that the output measured by a friction-measuring device can be represented as a coefficient of friction μ, which is a function of ground speed V, inflation pressure p, surface macro texture d, and the surface contaminant density ρ. The friction coefficient μ is whatever a friction-measuring device records (e.g. friction measured in a locked-wheel, prescribed slip, optimum slip, or yawed wheel condition). It is further assumed that the tire-ground contact area on a wetted surface is divided into three zones. From this 3-zone concept the following equation can be derived for the coefficient of friction of a braked tire on a wet surface:

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

In which μ_{datum} is coefficient of friction at zero ground speed on a dry surface and β an empirical variable. The datum coefficient of friction μ_{datum} is a function of tire pressure, tire tread material, and braking slip ratio. Tire tread pattern and runway texture have no significant influence on μ_{datum}. Experimental data have shown that the influence of ground speed on the *dry* runway friction coefficient is usually small. Therefore, the datum coefficient of friction can be estimated from friction measurements made on a dry surface at low speeds.

With a sufficient comprehensive data set for a friction-measuring device, each value of β can be combined with the corresponding macro texture d of the tested wetted surface. A variable κ (runway interaction parameter) is defined as

$$\kappa = \sqrt{\beta d} \qquad (2)$$

The introduction of the runway interaction parameter into the method was driven by the desire to have a parameter that accounts for the effect of runway texture so that for a range of wet surfaces the parameter is independent of the runway texture.

In the development of the method, care was taken that the values of the runway interaction parameter are normally distributed. It is for this reason that the runway interaction parameter is defined as in Eq. 2 and not in any other form. Note that random uncertainties often tend to follow a normal or Gaussian distribution. The runway interaction parameter should conform to a normal distribution given by

$$\kappa = \overline{\kappa} + z\,\sigma[\kappa] \qquad (3)$$

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

For each analysed friction-measuring device, values of κ should be derived from a series of tests on surfaces with a wide range of representative macro textures. It has to been shown that these values of κ can be represented by a normal distribution. Several goodness-of-fit tests are available for this purpose. However, for small sample sizes (say less than 20 data points) preference is normally given to the Anderson-Darling test for normality. For larger samples the Kolmogorov-Smirnov test can be used. Note that it is not possible with random samples smaller than 8 points to distinguish between samples that originate from a normal distribution and those from a non-normal distribution.

The values of $\overline{\kappa}$, $\sigma[\kappa]$, and μ_{datum} form the *friction database* for a particular friction-measuring device. These values are unique for a particular type of friction-measuring device with a given tire type and inflation pressure. The friction database cannot be used for another friction measuring device unless it is of the same type and has the same tire type and tire inflation pressure.

To use the friction database it must also be shown that for every combination of friction-measuring device (for which parallel test data are available), the values of κ are normally correlated. The values of κ of two devices A and B are *normally correlated* when there is a linear relation of the form

$$\frac{(\kappa_A - \overline{\kappa}_A)}{\sigma[\kappa_A]} = r\,\frac{(\kappa_B - \overline{\kappa}_B)}{\sigma[\kappa_B]} \qquad (4)$$

With the values of κ for each device A and B being normally distributed. If a correlation according to Eq. 4 exists and the correlation coefficient r is tested to be significant, then the values of κ of two devices A and B are normally correlated. The significance of the correlation can be tested using the Spearman rank order correlation method. A normal correlation implies that the transfer of probabilities at all levels is appropriate, which is essential for correlating the results of different friction-measuring devices. For those future cases where parallel test data are not available, it has to be assumed that a friction-measuring device is normally correlated with any other device. This assumption does not rule out the condition that the runway interaction parameter should be normally distributed.

When a friction database has been established the measured friction coefficient of a particular friction-measuring device from the database can be correlated with any other friction-measuring device listed in the database. A schematic overview of this correlation process is given in Figure 1.

EVALUATION OF THE ESDU METHOD

In this section a summary of the results of the study reported by Van Es [8] is presented. Existing test data that were obtained during an international experiment organised by the Permanent International Association of Road Congresses PIARC (Wambold [5]) were used to evaluate to potential of the ESDU method. The PIARC experiment involved 41 friction and texture measuring devices that were operated on 58 locations in Spain and Belgium. Friction tests were typically conducted at three ground speeds (30, 60, and 90 km/h). The surfaces on which friction tests were conducted varied from airfields, public roads, and racetracks. After a close examination of these surfaces, it was concluded that not all surfaces are representative for airfield runways and therefore only a subset of data from the PIARC experiments was used for the evaluation study. Furthermore, the complete data set was biased towards low macrotextures. The selected surfaces had a more even spread in macrotexture. Finally, 30 surfaces were selected for the study. These surfaces had harsh microtextures and a range of macrotexture depths representative of airfields.

The evaluation study was limited to the analysis of four different friction-measuring devices used in the PIARC experiment. These devices are listed in Table 1. All these friction-measuring devices were operated in a self-wetting mode that placed a sheet of water of 0.5 mm thick in front of the tire. Note that analysis of experimental test data of friction-measuring devices equipped with low-pressure tires showed that the friction coefficient is essentially independent of the water film depth for thickness ranging from 0.5 mm to 1.0 mm (see Van Es [8]).

Table 1. Analysed friction-measuring devices*.

Device name	**Slip**	**Tire type**	**Tire inflation pressure kN/m^2**
BV-11	15%	Trelleborg T49 4.00-8	140
GripTester	18%	McCreary	138
ASTM E-274 TRAILER	100%	ASTM E-524	165
DWW Trailer	86%	PIARC 165R15 Smooth	200
IMAG	15%	PIARC Smooth	150

**The authors do not endorse products or manufacturers. Trade or manufacturers' names appear in this report only because they are essential to its objectives.*

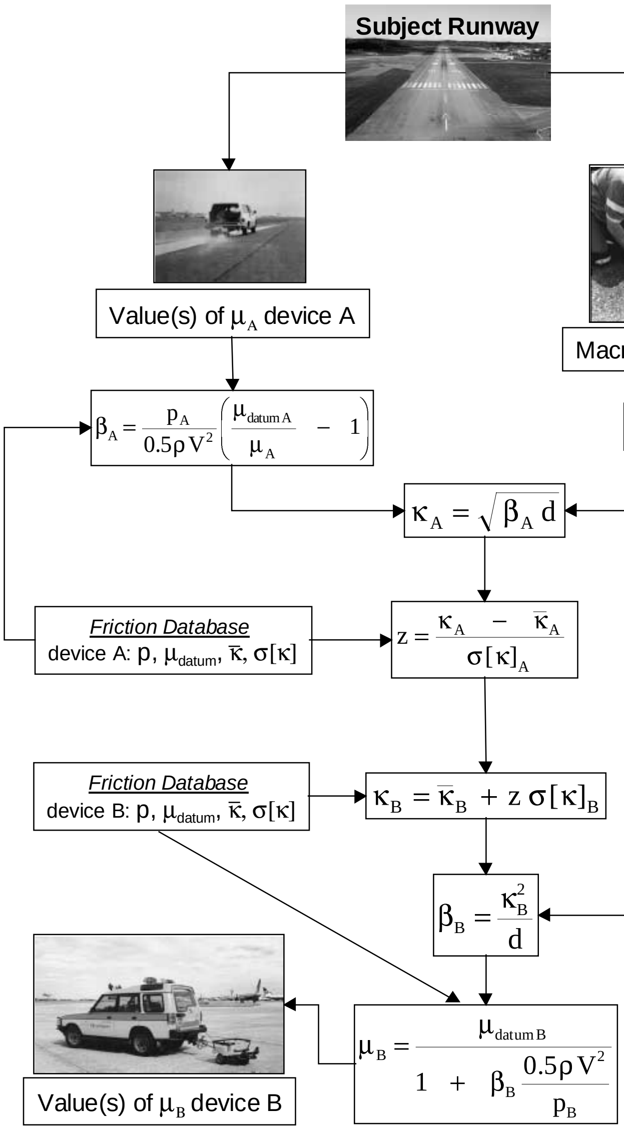

Figure 1. Schematic overview of the correlation process between friction measuring device A and B.

During the PIARC experiment the macrotexture was measured using the traditional volumetric technique (sand patch) and by profilometers. The volumetric technique is relatively simple to perform, but its results are operator dependent and therefore not very reproducible. The result of this method is a mean texture depth MTD. In the PIARC experiments glass spheres were used in accordance with ASTM Method E-965. The results from profilometers are less operator dependent and have a better reproducibility. The result of a profilometer is a mean profile depth MPD. Several different types of profilometers were used in the PIARC experiment. For only one type of profilometer (the CRR Stationary profilometer) MPD data were available which were processed according to ISO standard 13473-2. Since this is the current standard, only the results from the CRR Stationary profilometer were used in the evaluation.

Since the evaluation study looked at self-wetting devices, any influence of the runway natural drainage characteristics should come from the runway texture. It is therefore important to have a set of test data on surfaces that a have macrotexture depth variation that should preferably be normally distributed or be close to a normal distribution. If this is indeed the case the likelihood of finding a normal distributed runway interaction parameter κ will increase. In Figure 2 the distribution of the macrotexture depth measured with the CRR Stationary profilometer is shown. The square root of the macrotexture depth is shown here rather than the macrotexture depth itself because in the equation for the runway interaction parameter the macrotexture depth appears as a square root.

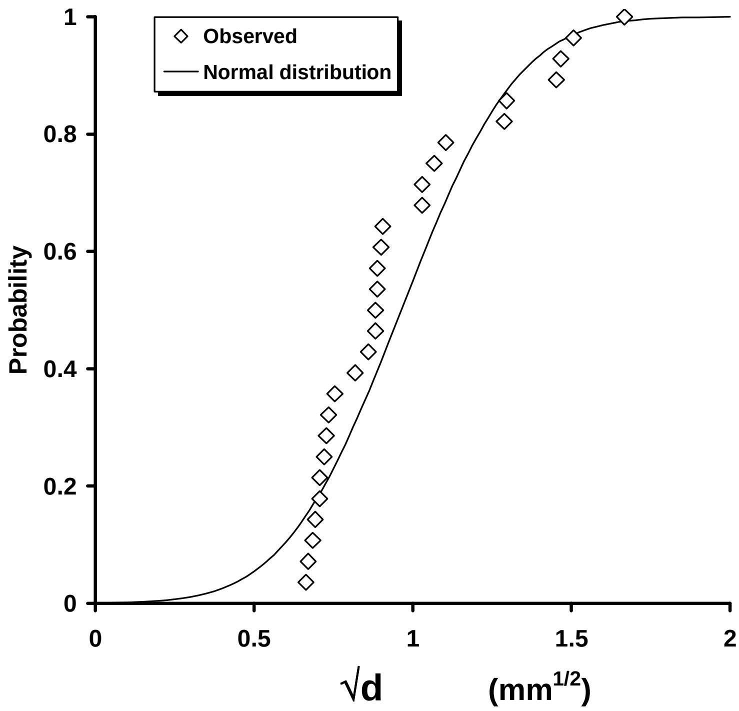

Figure 2. Distribution of the mean profile depth of the PIARC data set.

For each friction-measuring device listed in Table 1 and surface combination, values for the empirical variable β (as given by Eq. 1) were determined by a linear regression of the test data. The value of β was then combined with the corresponding macro texture (MTD or MPD) of the tested surface to obtain the runway interaction parameter κ. Normality of the distribution of the runway interaction parameter was then tested using the Kolmogorov-Smirnov test. From the analyses it followed that the runway interaction parameter for all friction-measuring devices listed in Table 1 is normally distributed at the 2% significance level, regardless of the method used to determine the macrotexture depth. Note that except for the DWW trailer all devices had in fact a significance level of 5% or higher. In Figure 3 an example is shown of the distribution of the runway interaction parameter for the GripTester.

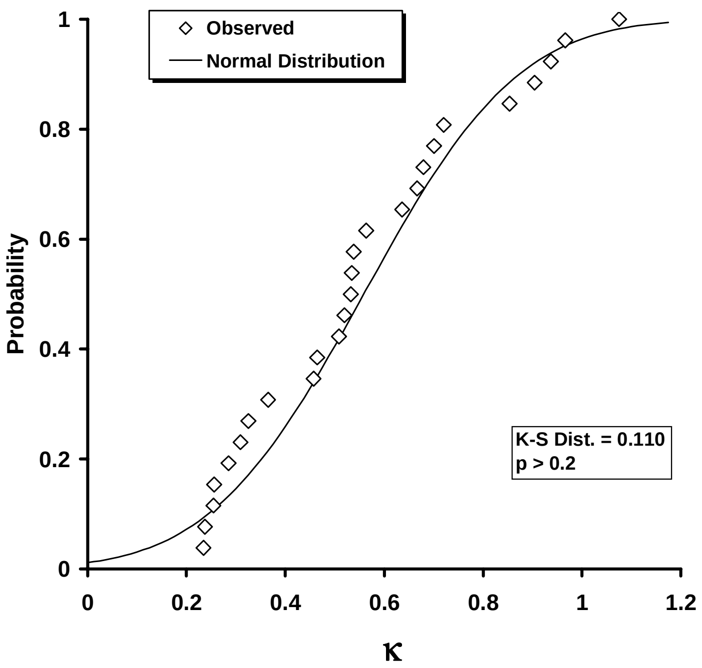

Figure 3. Distribution of κ for the GripTester based on mean texture depth.

It must be shown that for every combination of friction-measuring device (for which parallel test data are available), the values of the runway interaction parameter κ are normally correlated. The values of κ of all four analysed friction-measuring devices from the PIARC experiment were correlated according to Eq. 4. The significance of the correlation was tested using the Spearman rank order correlation method. The analysis showed that the values of κ for each of the four friction-measuring devices, for which parallel test data were available, are normally correlated with those from every other device. All pairs of variables had positive correlation coefficients higher than 0.87 and P values below 0.0001 indicating very significant relationships between all pairs of variables. Figure 4 gives an example of a correlation between two devices.

The friction database for the four analysed friction-measuring devices operating in a self-wetting mode is given in Table 2. The influence of the macrotexture measurement method on the values of $\overline{\kappa}$ and $\sigma[\kappa]$ of a particular friction-measuring device is clearly visible from the data in the friction database. It must be noted that this particular friction database has been derived solely for the purpose to evaluate the ESDU method. The objective of the evaluation study was not to derive the friction database for any particular self-wetting friction-measuring device that could be used as a standard.

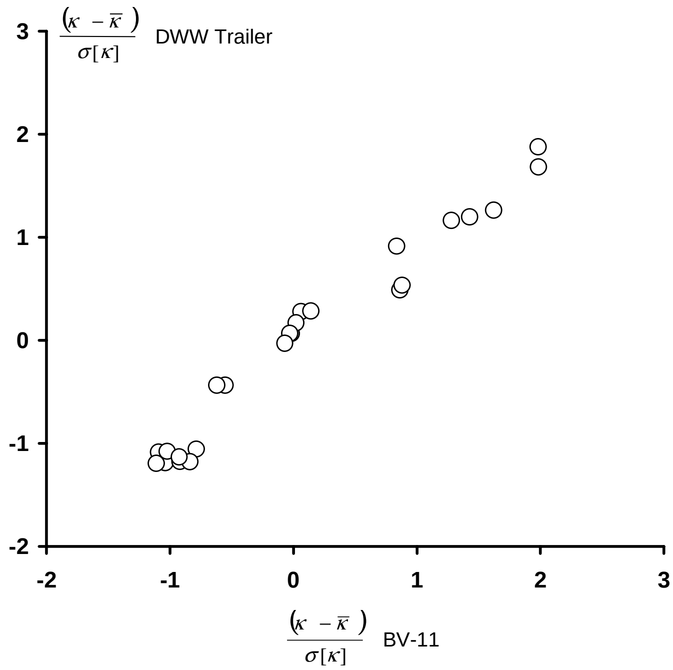

Figure 4. Correlation between DWW Trailer and BV-11 (based on mean profile depth results).

EXAMPLE

In this section an example of the correlation process of friction-measuring devices that operate in a self-wetting mode is presented. The basic approach is illustrated in Figure 1. Assume that the following data are available for the *GripTester* on the subject runway: ground speed = 65 km/h, measured friction coefficient = 0.70, and MPD = 1.20 mm. The tire inflation pressure is 138 kN/m^2 and μ_{datum} is 1 (see friction database listed in Table 2). The empirical variable β can now be calculated from Eq. 1 as follows (assuming a water density of 1000 kg/m^3):

$$\beta = \frac{p}{0.5\rho V^2}\left(\frac{\mu_{datum}}{\mu} - 1\right) = \frac{138000}{0.5\times 1000\times(65/3.6)^2}\times\left(\frac{1}{0.70} - 1\right) = 0.364$$

With this value for β and the known value for the macrotexture depth of the subject runway the runway interaction parameter κ can be calculated from Eq. 2 as follows:

$$\kappa = \sqrt{\beta d} = \sqrt{0.364\times 1.20} = 0.661 \quad mm^{1/2}$$

Table 2. Example friction database.

Macro texture measurement method	**Device name**	**Slip**	**Tire type**	**Tire inflation pressure kN/m^2**	μ_{datum}	$\bar{\kappa}$ mm^{½}	$\sigma[\kappa]$ mm^{½}
Sand patch	BV-11	15%	Trelleborg T49 4.00-8	140	1.00	0.368	0.209
	GripTester	18%	McCreary	138	1.00	0.559	0.246
	ASTM E-274 TRAILER	100%	ASTM E-524	165	0.95	0.905	0.368
	DWW Trailer	86%	PIARC 165R15 Smooth	200	1.05	0.836	0.347
Profilometer	BV-11	15%	Trelleborg T49 4.00-8	140	1.00	0.357	0.226
	GripTester	18%	McCreary	138	1.00	0.540	0.251
	ASTM E-274 TRAILER*	100%	ASTM E-524	165	0.95	0.855	0.384
	DWW Trailer	86%	PIARC 165R15 Smooth	200	1.05	0.780	0.350

With the values of $\bar{\kappa}$ and $\sigma[\kappa]$ for the *GripTester* as given in the friction database (see Table 2) and Eq. 3, the percentage point of the normal distribution (z) can be calculated as follows:

$$z = \frac{\kappa - \bar{\kappa}}{\sigma[\kappa]} = \frac{0.661 - 0.540}{0.251} = 0.482$$

This corresponds to a probability of 1:3.1. In this example, the result of the *GripTester* will be correlated with that of the *BV-11*. With the values of $\bar{\kappa}$ and $\sigma[\kappa]$ for the *BV-11* given in the friction database (Table 2), the calculated percentage point of the normal distribution z and Eq. 3, the runway interaction parameter κ can be calculated for the *BV-11* as follows:

$$\kappa = \bar{\kappa} + z\,\sigma[\kappa] = 0.357 + 0.482 \times 0.226 = 0.466 \quad mm^{½}$$

The value of β for the *BV-11* on the subject runway can now be calculated as follows:

$$\beta = \frac{\kappa^2}{d} = \frac{0.466^2}{1.20} = 0.181$$

The above outlined process of using the friction database is further illustrated in Figure 5.

From Eq. 1, the calculated value of β, the values for tire inflation pressure and μ_{datum} for the *BV-11* (see friction database Table 2), the value of μ on the subject runway at a ground speed of 65 km/h can be calculated as follows:

$$\mu = \frac{\mu_{datum}}{1 \;+\; \beta\dfrac{0.5\rho V^2}{p}} = \frac{1}{1 \;+\; 0.181\times\dfrac{0.5\times1000\times(65/3.6)^2}{140000}} = 0.83$$

From this example it follows that the measured friction coefficient by the *GripTester* of 0.70 at a ground speed of 65 km/h corresponds with a friction coefficient of 0.83 for the *BV-11* on the subject runway at the same ground speed of 65 km/h.

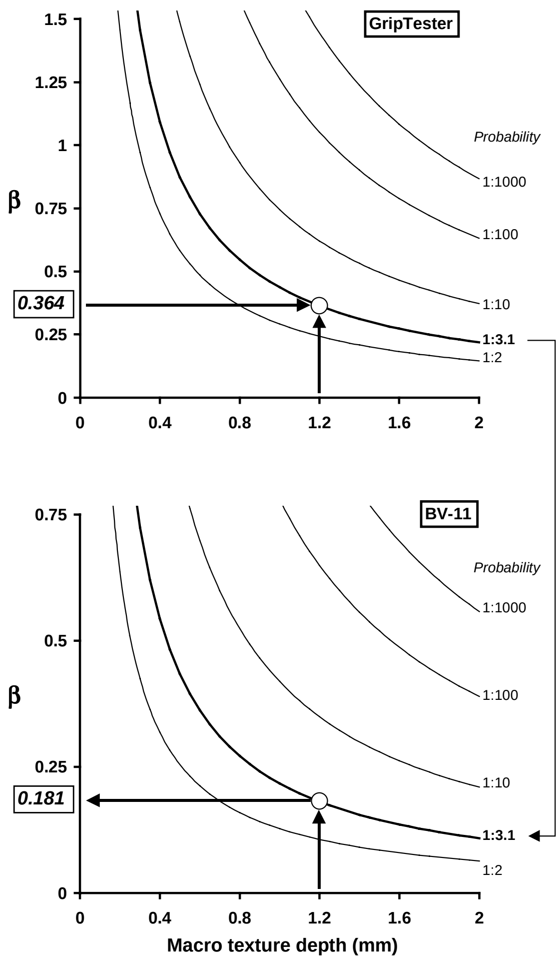

Figure 5. Example of correlating two friction-measuring devices.

SOME WORDS OF CAUTION

The user of the ESDU method should be cautious when comparing the predicted friction values by the method with measured values. As the measured friction values are subjected to random uncertainties differences can be noticed between the predicted and the measured friction values. The ESDU method predicts the friction level for a friction-measuring device based on the uncertainty levels in the measurements made with another device. The friction database used for this, is not more than a *probability model* that describes the behaviour of a friction-measuring device on a wet runway (Balkwill [9]). The correlation exists of a transfer of a *probability of exceedance* which is derived from the test data for one particular friction-measuring device (see e.g. Figure 5). In that perspective the ESDU method is wholly statistical.

APPLICATION OF THE ESDU METHOD TO OTHER DATA

In addition to the PIARC data, some results obtained in the Harmonisation of European Routine and Research Measuring Equipment for Skid Resistance of Roads and Runways (HERMES) project with devices such as the French designed IMAG friction-measuring device, and results obtained from an experimental study in the Netherlands using devices such as the MU-meter MK6, were also analysed using the ESDU method ([10]). All these results showed the suitability of the ESDU method to correlate the output of self-wetting friction-measuring devices.

CONCLUSIONS

- Based on the results presented in this paper it can be concluded that the ESDU method can be used to correlate the output of friction-measuring devices that are operated in a self-wetting mode. The method has the advantage above previous developed methods that it accounts for random uncertainties to which all friction-measuring devices are subjected.
- To establish a friction database for self-wetting friction measuring devices it is important to have a comprehensive data set in which the square root of the macro texture depth is normally distributed or close to a normal distribution.

REFERENCES

1. G.W.H. van Es, and M.K.H. Giesberts, “A Literature Survey on Tire Surface Friction on Wet Pavements: Application of Surface Friction Testers,” CROW, Report 03-06, Ede, The Netherlands, 2003. (Free downloadable from the CROW website: www.crow.nl/mailforms/download/tekst%20rapport%2003-06.pdf)

2. L.R. Merritt, ”Concorde landing requirements evaluation tests,” FAA, FS-160-74-2, 1974.

3. Anon.,“Government/Industry meeting on Runway Traction and proposed change to 14CFR 25-125-Landing,” FAA, AFS-160-75-4, 1975.

4. W.B. Horne, and F. Buhlmann,”A Method for Rating the Skid Resistance and Micro/Macrotexture Characteristics of Wet Pavements”, Frictional Interaction of Tire and Pavement, ASTM STP 793, 1983.

5. J.C. Wambold, et al,”International PIARC experiment to compare and harmonise texture and skid resistance measurements,” PIARC, 1995.

6. K.J. Balkwill and D.J. Mitchell, "Statistical Method for relating Aircraft and Ground-Test Machine Friction Data," In proceedings of the technical advisory group steering committee meeting on aircraft performance on contaminated runways, Transport Canada, TP 13257, 1997.

7. Anon.,”Statistical analysis of wet runway friction for aircraft and ground-test machines,” Engineering Science Data Unit, ESDU Item 99015, 2000.

8. G.H.W. van Es,”Correlation of Self-Wetting Friction-Measuring Devices: Evaluation of the ESDU method,” CROW, Report 03-10, Ede, The Netherlands, 2003. (Free downloadable from the CROW website: http://www.crow.nl/mailforms/download/tekst%20rapport%2003-10.pdf).

9. K.J. Balkwill, “Friction databases: definitions, derivations, and uses,” JAA Contaminated Runway Working Group Meeting, Toulouse, France, 1999.

10. 10. C.A.P.M. van Gurp, G.H.W. van Es, R.H.J. Diele and H. Plakke, “Correlation trial of self-wetting skid resistance measurement devices for Dutch airfield pavements”, CROW, Report 04-.., Ede, The Netherlands, 2004. (Free downloadable from the CROW website: www.crow.nl ‘Producten en diensten’)