European Union Aviation Safety Agency

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RWYMT (RUNWAY MICRO TEXTURE) [EASA.2022.C06]

Thresholds for slippery wet runways related to micro texture characteristics obtained from surface scans

D-4.2

An Agency of the European Union

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SUMMARY

Problem area

A slippery wet runway is defined as a wet runway where the surface friction characteristics on a significant portion of the runway have been determined to be degraded. Investigations of various landing runway overruns on wet runway surfaces have concluded that the aircraft wheel braking friction coefficients during the operations were significantly lower than those suggested by methods assumed in airworthiness regulations. Deficiencies in runway micro texture are believed to have contributed to these lower levels of wheel braking friction. However, it has proven difficult for airport operators to identify issues with the micro texture of a runway. The current way to determine whether a runway could be slippery wet has shown some major issues resulting in an overestimation of the braking friction capabilities under wet runway conditions.

Description of work

As part of the EASA Runway Micro Texture research project a method is being developed to identify runway surfaces that could be identified as slippery wet. This method uses high resolution surface scans to analyse the micro texture characteristics of the runway. The current report describes the work done as part of work package 4.2 that aims to develop thresholds for slippery wet runways. The current way of assessing whether a runway is slippery wet is described. The original developments and assumptions that resulted in an ICAO method for runway friction assessments is explained. An approach is described that correlates aircraft stopping performance to the micro texture sharpness of a runway surface. For several commercial transport aircraft stopping distances on wet and dry runways are simulated in order to establish an average relation between the stopping distance ratios (wet to dry) and the micro texture sharpness of a runway considering a range of runway macro texture depths and water depths that are representative for normal operations. Critical values for the micro texture sharpness are proposed that could represent the crossover from a runway with braking action good to medium.

Results and Application

Based on extensive testing and analysis a method is proposed here that can assist airport operators to identify slippery wet runway surfaces. With the help of high-resolution surface laser scanners micro texture of a runway surface can be measured. This can be related to a minimum value needed to obtain sufficient high friction levels under wet conditions. Choices need to be made regarding the actual micro texture parameter to be used. Also the threshold proposed in this study should be evaluated in order to establish a common accepted criterion for slippery wet surface related to micro texture or macro texture (in case the macro texture is very smooth).

CONTENTS

ABBREVIATIONS

ACRONYM	DESCRIPTION
AC	Advisory Circular
CFME	Continuous Friction Measuring Equipment
DBV	Diagonal braking vehicle
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
EASA	European Union Aviation Safety Agency
ESDU	Engineering Sciences Data Unit
FAA	Federal Aviation Administration
FT	Fourier Transform
GRF	Global Reporting Format
ICAO	International Civil Aviation Organization
MFL	Minimum Friction Level
NASA	National Aeronautics and Space Administration
NTSB	NATIONAL TRANSPORTATION SAFETY BOARD
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium (National Aerospace Center)
RWYCC	Runway Condition Code
SDR	Stopping distance ratio
SFT	Surface Friction Tester
USAF	United States Air Force

1. Introduction

1.1 Background

NLR, and its partners DLR and ESDU are conducting a research project for EASA, called the EASA Runway Micro Texture Project, to develop a new method to identify slippery wet runways. This project is funded from the European Union's Horizon Europe research and innovation programme. As part of the EASA Runway Micro Texture Project several tests have been conducted. These tests encompassed braked tests with different aircraft on wetted runway sections and surface pavement measurements using different devices that characterise the friction characteristics of the runway. Braking friction data derived from the flight tests and results from British Pendulum tests have been converted into a micro texture sharpness parameter. Results obtained with high resolution surface lasers scanners have been used to derive several micro texture parameters that have been correlated with the micro texture sharpness parameter [Van Es, (2024)]. These results can be used to develop a methodology to identify slippery wet runways. Aircraft wheel braking performance on such runways can be much lower than assumed.

The present report is deliverable D-4.2 of work package 4. In this report the results presented in deliverable D-4.1 of the EASA Runway Micro Texture Project [Van Es, (2024)] are used to develop a threshold for identifying a slippery wet runway.

1.2 Objectives

This report is deliverable D-4.2 of the EASA Runway Micro Texture Project (EASA.2022.C06). The work presented here represents the output from work package 4. The objective is to develop a threshold for identifying a slippery wet runway using high resolution surface scans of the runway.

2. Some historical background on slippery wet runways

2.1 Current practice

ICAO Annex 14 provides the following definition of a slippery wet runway: '*A wet runway where the surface friction characteristics of a significant portion of the runway have been determined to be degraded*'. This definition does not provide much information of how to quantify a runway of being slippery wet. ICAO has defined methods that help airports in assessing whether a runway could become slippery under wet conditions. These methods include friction measurements with Continuous Friction Measuring Equipment (CFME), observation by airport maintenance personnel, reports by pilots and analysis of aircraft stopping performance that indicates a substandard surface.

The most common approach is using a CFME which is run over several sections of a runway under simulated wet conditions. Information that a runway or portion thereof is slippery wet shall be made available through the issuance of a NOTAM whenever the friction level of the runway or portion thereof is less than a minimum friction level (MFL) as measured by a CFME. Values for the MFL are provided in the ICAO Airport Services Manual, Part 2, (Doc 9137 – fourth edition 2002) for different CFMEs. In fact, a State should define what minimum friction level it considers acceptable before a runway is classified as slippery wet. However, most States simply follow the MFL values provided by ICAO (see Table 2-1). In this table, ICAO has given the criteria used by some States for specifying the friction characteristics of new or resurfaced runway surfaces, for establishing maintenance planning levels and for setting minimum friction levels.

Table 2-1: Runway surface condition levels as provided in the ICAO Airport Services Manual, part 2 (fourth edition 2002)

Test equipment	Test tire		Test speed (km/h)	Test water depth (mm)	Design objective for new surface	Maintenance planning level	Minimum friction level
	Type	Pressure (kPa)					
(1)	(2)		(3)	(4)	(5)	(6)	(7)
Mu-meter Trailer	A	70	65	1.0	0.72	0.52	0.42
	A	70	95	1.0	0.66	0.38	0.26
Skiddometer Trailer	B	210	65	1.0	0.82	0.60	0.50
	B	210	95	1.0	0.74	0.47	0.34
Surface Friction Tester Vehicle	B	210	65	1.0	0.82	0.60	0.50
	B	210	95	1.0	0.74	0.47	0.34
Runway Friction Tester Vehicle	B	210	65	1.0	0.82	0.60	0.50
	B	210	95	1.0	0.74	0.54	0.41
TATRA Friction Tester Vehicle	B	210	65	1.0	0.76	0.57	0.48
	B	210	95	1.0	0.67	0.52	0.42
RUNAR Trailer	B	210	65	1.0	0.69	0.52	0.45
	B	210	95	1.0	0.63	0.42	0.32
GRIPTESTER Trailer	C	140	65	1.0	0.74	0.53	0.43
	C	140	95	1.0	0.64	0.36	0.24

2.2 Development of runway friction standards

The maintenance planning levels and minimum friction levels given in Table 2-1 found their origin in the testing done in the United States as part of a joint FAA/NASA/USAF Runway Research program which started in 1969. Wet runway surface tests were conducted using a Mu-meter and a NASA diagonal-braked vehicle (DBV)[1], which were combined with braking tests using a B727 and a DC-9 aircraft. An important summary of this research is presented by Ballentine of the Air Force Weapons Laboratory [Ballentine, (1975)] which can be seen as the starting point in the development of slippery wet runways criteria [Norheim, (2016)]. Figure 2-1 and Figure 2-2 are plots of actual data gathered during the joint tests conducted by FAA, USAF and NASA. The plots show the measured friction using the Mu-meter and the measured SDR by the DBV as function of the brake on speed of the aircraft being tested on the same wet runway[2]. The solid dots in these plots represent those data points where wheel lock-up occurred of the aircraft main gear tyres, which would indicate a high probability for hydroplaning according to Ballentine (and thus slippery conditions on a wet runway). The research at the Weapons Laboratory identified breakpoints in the values of Mu and SDR which define potential hydroplaning problems [Ballentine, (1975)]. Horizontal lines are drawn on Figure 2-1 at the points where the coefficient of friction equals 0.25, 0.42, and 0.50. Likewise, horizontal lines are drawn on Figure 2-2 at the points where the DBV stopping distance ratio equals 2.0, 2.5, and 3.5. These zones correspond to the skid resistance airfield pavement rating chart proposed by Ballentine [Ballentine, (1975)] shown in Figure 2-3. Ballentine states that the rating system devised using the methods described above must be considered somewhat arbitrary. Ballentine also stated that the rating of "good" for a pavement surface with a stopping distance ratio of 2 or less, is somewhat conservative. In a later publication by the USAF [Ballentine, G. and Burk, D. (1977)] the ratings were adjusted to reflect use of 15 inch tyres on the Diagonally Braked Vehicle (e.g. SDR 2.0-2.5 changed into 2.5-3.2). However, this change was not mentioned or used in later studies.

When looking at Figure 2-1 and Figure 2-2 one could draw the conclusion that the variation in friction levels shown by the Mu-meter and the stopping distance ratio by the DBV are the direct result of the variation in surface texture. The macro texture depth of the runways in the joint tests conducted by the FAA, USAF and NASA, was lower than 0.3 mm for most surfaces except for the grooved runways in the tests. There is no record of the state of the micro texture of the test runways[3]. Close examination of the conditions under which the tests were conducted shows that water depth levels varied between the different tests. This can have an influence on the results. Figure 2-4 gives an example for the B727 and Mu-meter that shows the

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[1] The Mu-Meter is a side force measuring trailer and is one of the first devices developed to assess runway friction. The diagonal-braked vehicle (DBV) is a car equipped with a high-performance engine. This vehicle is equipped with a diagonal braking system to maintain vehicle stability and directional control when the diagonal wheels of the car are locked at high speed (60 mph). Full brake tests are conducted on wet and dry runway surfaces. The ratio of the stopping distance for both conditions form a metric for the slipperiness of the runway (stopping distance ratio-SDR). NASA claimed that correlation tests performed with jet transport type aircraft indicate that the DBV SDR reasonably predicts the aircraft SDR up to DBV SDR's of approximately 2.0 for many wet runway surfaces [Horne, (1977)]. However, this was questioned at the time by aircraft manufacturers as tests often showed large differences [Anon., (1971)]. These differences are partly attributed to the influence of water depth on the SDR.

[2] The brake on speed does not correlate in anyway with the measured friction by the Mu meter or the DBV SDR. It was probably considered a convenient way to show the results obtained with the testing devices. In all tests the runway was artificially wetted using water trucks.

[3] Macro texture is the runway roughness formed by the large stones and/or grooves in the surface of the runway. Macro texture has wavelengths from 0.5 mm up to 50 mm. It is specified in terms of an average macro texture depth which ranges from 0.20 to 1.80 mm for runway surfaces. Micro texture is the sandpaper like roughness of a surface formed by the sharpness of the fine grain particles on the individual stone particles of the surface. Micro texture has wavelengths shorter than 0.5 mm. The micro roughness has an amplitude ranging from 0.01 to 0.1 mm.

influence of the water depth on some of the results shown in Figure 2-1 and Figure 2-2[4]. The low friction values measured correspond to tests conducted on a runway with relatively high water depths (the Mu-meter was run over wetted runways; it did not have a self-wetting system installed as for the DBV). The high friction values were measured on a grooved runway that in a matter of seconds after the water tankers that were used to wet the runway passed, had no measurable depth of water on the runway. Thus, only a damp wetness condition was present during the tests with the Mu-meter (and also the DBV) and the test aircraft. This will normally result in high friction forces unless the micro texture is very smooth. Note that the water depth gauge used had a lower limit of 0.25 mm which is reflected by the grouping of the data points at this water depth in Figure 2-4.

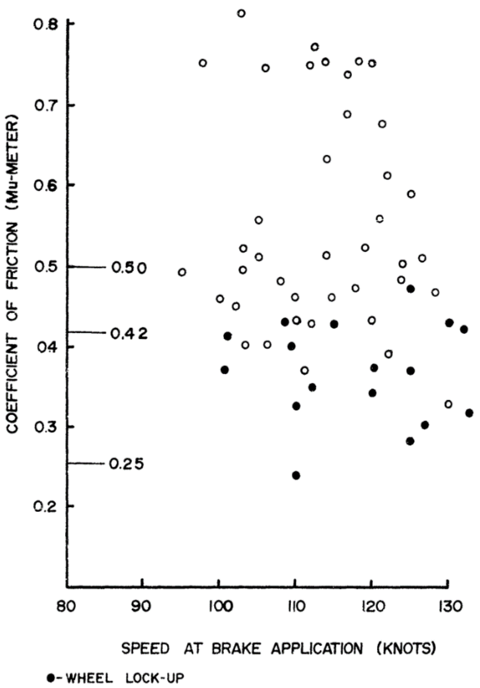

Figure 2-1: relation between coefficient of friction measured by the Mu-meter versus the aircraft speed at brake application [Ballentine, (1975)]

[4] The braking friction coefficient on a wet runway is normally a function of ground speed but it was derived from the test data as an overall average [Blanchard, (1975)].

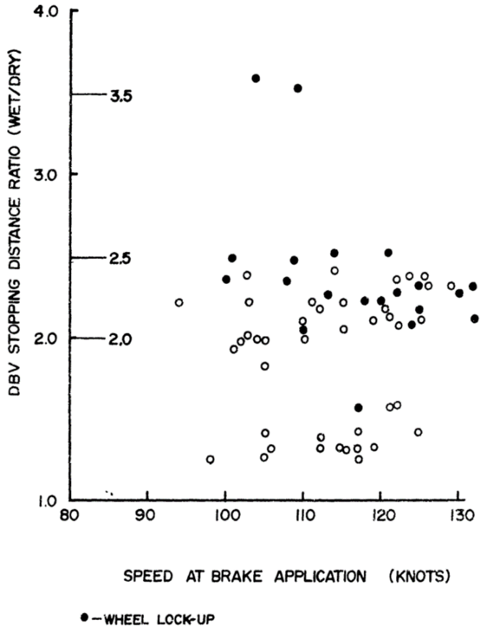

Figure 2-2: relation between DBV SDR versus the aircraft speed at brake application [Ballentine, (1975)]

Table 1. MU-METER AIRFIELD PAVEMENT RATING

Mu	Expected Aircraft Braking Response	Response
Greater than 0.50	Good	No hydroplaning problems are expected.
0.42 - 0.50	Fair	Transitional.
0.25 - 0.41	Marginal	Potential for hydroplaning for some aircraft exists under certain wet conditions.
Less than 0.25	Unacceptable	Very high probability for most aircraft to hydroplane.

Table 2. STOPPING DISTANCE RATIO AIRFIELD PAVEMENT RATING

	Hydroplaning Potential
1.0 - 2.0	No hydroplaning anticipated.
2.0 - 2.5	Potential not well defined.
2.5 - 3.5	Potential for hydroplaning
Greater than 3.5	Very high hydroplaning potential.

Figure 2-3: skid resistance airfield pavement rating chart proposed by Ballentine [Ballentine, (1975)]

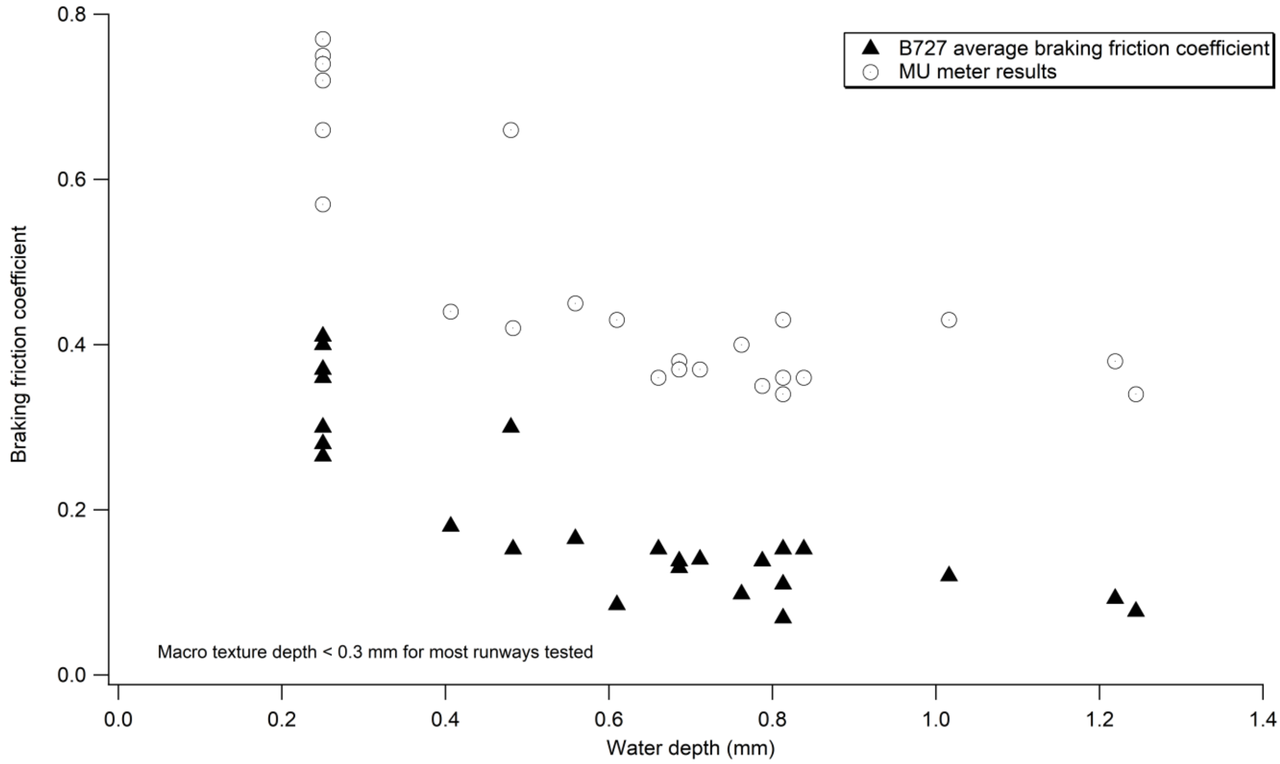

Figure 2-4: measured braking friction coefficient versus water depth for a B727 and Mu-meter gathered during joint tests conducted by the Federal Aviation Administration (FAA), the United States Air Force (USAF) and the National Aeronautics and Space Administration (NASA) [Horne et. al, (1977), Blanchard, (1975)]

In [Norheim, (2016)] a historical account is given on some of the developments related to runway friction assessment. It is shown in this account that the USAF proposed values of 0.50[5] and 0.42 for the Mu-meter were kept in developing guidance material for runway friction assessments. Initially only corrective maintenance action was recommended by the FAA for runways with friction values less than the recommended value of 0.50 as obtained with the Mu-meter at 40 mph. For long the Mu-meter was the only commercially available CFME. However, in the mid 1980's, other friction measuring devices became available such as the BV-11 Skiddometer, the Saab Friction Tester and the K. J. Law Engineers Runway Friction Tester. In 1982-1985, the FAA conducted a series of tests to evaluate the correlation of the Mu-meter with the Saab Friction Tester, Skiddometer, and the Runway Friction Tester under self-wetting conditions [Morrow, (1992)]. These correlations were used to establish maintenance friction levels for these new devices using the Mu-meter as reference (see FAA AC 15015320-12A). It was claimed that excellent correlation was established between the four devices operating at 40 mph [Morrow, (1992)]. Although the correlations often showed high correlation coefficients, the data scatter was sometimes very large. No check was done on the statistical significance of the correlations. In 1991, the FAA also published minimum friction levels for the four CFMEs below which the runway would be declared slippery wet (FAA AC 15015320-12B). The minimum friction level for the Mu-meter was set to 0.42 corresponding to that proposed in 1975. For the other CFMEs listed by the FAA, minimum friction levels were again determined from correlation tests with the Mu-meter conducted at NASA Wallops Flight Facility in 1989 [Morrow, (1990)]. The friction values for the four different CFMEs presented in FAA AC 15015320-12B were adopted by ICAO in 1995[6].

[5] This value was raised at some point to 0.52 from 0.50.

[6] Since 1984, the FAA had also been working with members of an ICAO Study Group on Runway Surface Conditions in establishing standards concerning use of friction measuring devices at airports.

2.3 Work by the ICAO Runway Surface Condition Study Group

In 1991 an ICAO Runway Surface Condition Study Group was working on a more detailed definition of a slippery wet runway [Santamaria, (1991)]. The study group noted that ICAO requires States to specify minimum friction levels and to take specific actions in terms of notification to aircraft operators or corrective measures whenever the measured friction value was below the specified minimum. Below these values the runway could become slippery when wet. The study group agreed that a rationale should be developed so as to provide guidance material to States on the determination of the MFL. It was also agreed that the minimum friction level (MFL) should reflect the actual braking performance of an aircraft. The MFLs published at that time by FAA were based on the value for the Mu-meter of 0.42 and it was determined for other CFMEs using a correlation between these devices and the Mu-meter based on tests as discussed in the previous section. The ICAO study group proposed that a MFL of a wet runway would be that at which an aircraft in the normal landing configuration using maximum wheel braking *only* would need *twice* the dry braked stopping distance (SDR = 2.0). This is somewhat lower than a SDR of 2.5 that corresponds to a Mu-meter value of 0.42 as presented in the Air Force Weapons Laboratory study [Ballentine, (1975)]. The ICAO study group believed that the NASA combined viscous/dynamic hydroplaning theory [Horne, (1976)] could be appropriate to translate the aircraft tyre friction requirements, derived from the operating criteria, into MFL's for the different CFMEs. Two aircraft were considered to verify this rationale: the B737 and DC10. In Appendix 1 of the ICAO Airport Services Manual, Part 2, (Doc 9137 Fourth Edition 2002), the proposed method for determining the minimum friction level is provided based on the approach described above. It also shows the results for the B737 and DC10 in terms of SDR versus a mean wheel braking friction coefficient. It is believed however that this approach was never well understood by airport operators. No evidence could be found that States actually have used this method to establish MFLs for CFMEs.

The NASA combined viscous/dynamic hydroplaning theory is used sometimes by the NTSB in accident investigations to convert CFME measurements into aircraft wheel braking friction coefficients [O'Callaghan, (2016)]. Figure 2-5 shows a comparison of predicted aircraft wheel braking friction coefficients using the NASA combined viscous/dynamic hydroplaning theory and CFME results with full scale aircraft braking wheel friction coefficients at different ground speeds. As shown, the NASA combined viscous/dynamic hydroplaning theory combined with CFME results tends to overpredict the aircraft wheel braking friction. Differences of more than 200% are found with an average error of some 56%[7].

[7] Based on analysis by NLR using available data [O'Callaghan, (2016)] and unpublished results from NLR and NASA.

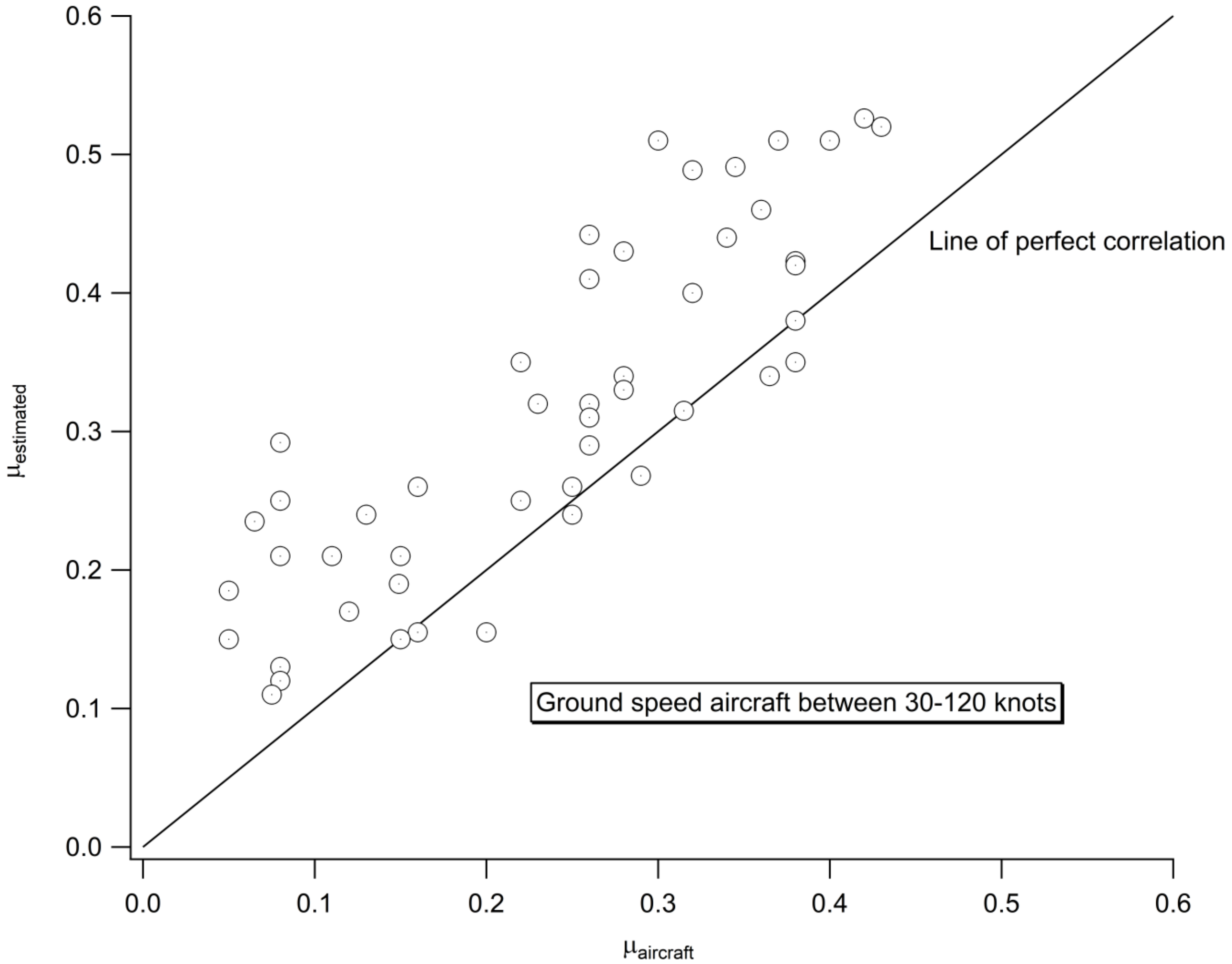

Figure 2-5: comparison of estimated and measured aircraft wheel braking friction coefficient using the NASA combined viscous/dynamic hydroplaning theory and CFME results

3. Current practice for accounting for wet runways on takeoff and landing performance

3.1 Runway Condition Assessment Matrix

In 2005, the FAA chartered an Aviation Rulemaking Committee (ARC) to address Takeoff and Landing Performance Assessment (TALPA) requirements and guidance following the overrun of a Boeing 737 at Midway. Following this event, the FAA found a number of deficiencies in the regulations and guidance affecting certification and operation of aircraft and airports for aircraft takeoff and landing operations on non-dry runways. The rule making committee proposed the use of a Paved Runway Condition Assessment Table for performing runway condition assessments by airport operators and for assessing takeoff and landing performance in a standard way. Based on the work done by the FAA Takeoff and Landing Performance Assessment Aviation Rulemaking Committee, ICAO has published a Runway Condition Assessment Matrix (RCAM) [ICAO, (2020)]. This allows the assessment of the Runway Condition Code from a set of observed runway surface condition(s) and pilot reports of braking action. The Runway Condition Code describes the effect of the runway surface condition on aircraft braking performance. The new methodology for assessing and reporting runway surface conditions applies as of August 12, 2021 in the European Union[8].

The Runway Condition Assessment Matrix is given in Table 3-1 and taken from ICAO Doc 10064 - Aeroplane Performance Manual. Some standard values are used for the braking friction coefficient for the different runway surface conditions to be used for performance calculations. For wet runways two levels of braking action are considered. For a wet runway with *good* braking action the wheel braking friction coefficient is calculated per method defined in EASA CS25.109. The specifications provide standard curves of maximum friction coefficient versus ground speed for wet smooth and grooved/porous friction course runways. These curves are provided in section 25.109(c) and (d) of the EASA aircraft certification specifications of large aircraft. Although these curves are specified for the computation of accelerate-stop distances, they are also used by aircraft manufacturers to compute landing stopping distances on wet runways as defined in the RCAM. The equations given in CS25.109 describe the maximum friction coefficient versus ground speed. These equations are based on curves of maximum braking friction coefficient versus ground speed for unyawed tyres, for five categories of hard runway surfaces in wet conditions developed by ESDU [Anon., (1995)]. Each of these five surfaces typifies a class of runways having surface macro-texture depths lying within different ranges but all with essentially sharp micro texture. The braking friction coefficient curves given in [Anon., (1995)] are presented at four values of tyre inflation pressure namely 50, 100, 200 and 300 psi. From these curves the Aerospace Industries Association of America developed standard equations for a 'smooth' runway and later for a grooved/porous friction course type of runway [Anon., (1995a)] that are now provided in CS25.109. A 'smooth' runway as mentioned in the specifications has an *average* macro texture depth of 0.25 mm (0.01 inch) and a grooved/porous friction course runway has an *average* macro texture depth of 1.02 mm (0.04 inch). The standard curves for maximum braking friction coefficient provided in CS 25.105 account for tyre wear (tread worn to 2 mm). The maximum braking friction coefficient needs to be corrected for the effect of the antiskid system. Specifications in CS25.109 give an efficiency factor which can be used to account for effect of the antiskid. Fully modulating systems have been tuned to efficiencies greater than 80% and up to a maximum of approximately 92%, which are considered to be the minimum and maximum antiskid efficiencies by the specifications that can be used. Lower values can be used if a less efficient antiskid system is used.

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[8] EU has already adopted Regulations (EU) 2019/1387, (EU) 2020/469 and (EU) 2020/2148 which establish the requirements for the implementation of the GRF in EU.

For slippery wet runways a default wheel braking friction coefficient of 0.16 is specified for fully modulating antiskid systems (see Table 3-1)[9]. This value is assumed in depended of ground speed, and is valid for all aircraft tyre types, sizes and tyre inflation pressures. This braking friction coefficient is based on EASA AMC 25.1591 for wet or dry snow which gives a slightly higher braking friction coefficient of 0.17. This value of 0.17 was proposed by a JAA contaminated runway performance working group based on flight test data on snow covered runways as shown in Figure 3-1. The braking friction coefficient used in conjunction to the Runway Condition Assessment Matrix of 0.16 is slightly lower than that of EASA AMC 25.1591 to increase separation between braking actions Medium and Good to medium.

Table 3-1: Runway Condition Assessment Matrix (ICAO Doc 10064 - Aeroplane Performance Manual)

Runway Condition Code	**Runway Surface Condition Description**	**Pilot-Reported Braking Action**	**Wheel Braking Coefficient**
6	□ Dry	—	90% of certified value used to comply with ICAO Annex 8 Part IIB 2.2.7 e)
5	□ Frost □ Wet (includes damp and ⅛″ (3 mm) depth or less or water) ⅛″ (3 mm) depth or less of: □ Slush □ Dry snow □ Wet snow	Good	Per method defined in CS25.109(c).
4	-15 °C and colder outside air temperature: □ Compacted snow	Good to Medium	0.20
3	□ Wet ("Slippery Wet" runway) □ Dry snow or wet snow (any depth) over compacted snow Greater than ⅛″ (3 mm) depth of: □ Dry snow □ Wet snow Warmer than -15 °C outside air temperature: □ Compacted snow	Medium	0.16
2	Greater than ⅛″ (3 mm) depth of: □ Water □ Slush	Medium to Poor	(1) For speeds below 85% of the hydroplaning speed: 50 per cent of the wheel braking coefficient determined for RWYCC=5,but no greater than 0.16; and (2) For speeds at 85% of the hydroplaning speed and above: 0.05.
1	□ Ice	Poor	0.08

[9] For quasi-modulating systems, the braking coefficient is multiplied by 0.625. For on-off systems, the braking coefficient is multiplied by 0.375.

0	- Wet ice - Water on top of compacted snow - Dry snow or wet snow over ice	Nil	Not applicable. (No operations in Nil conditions.)

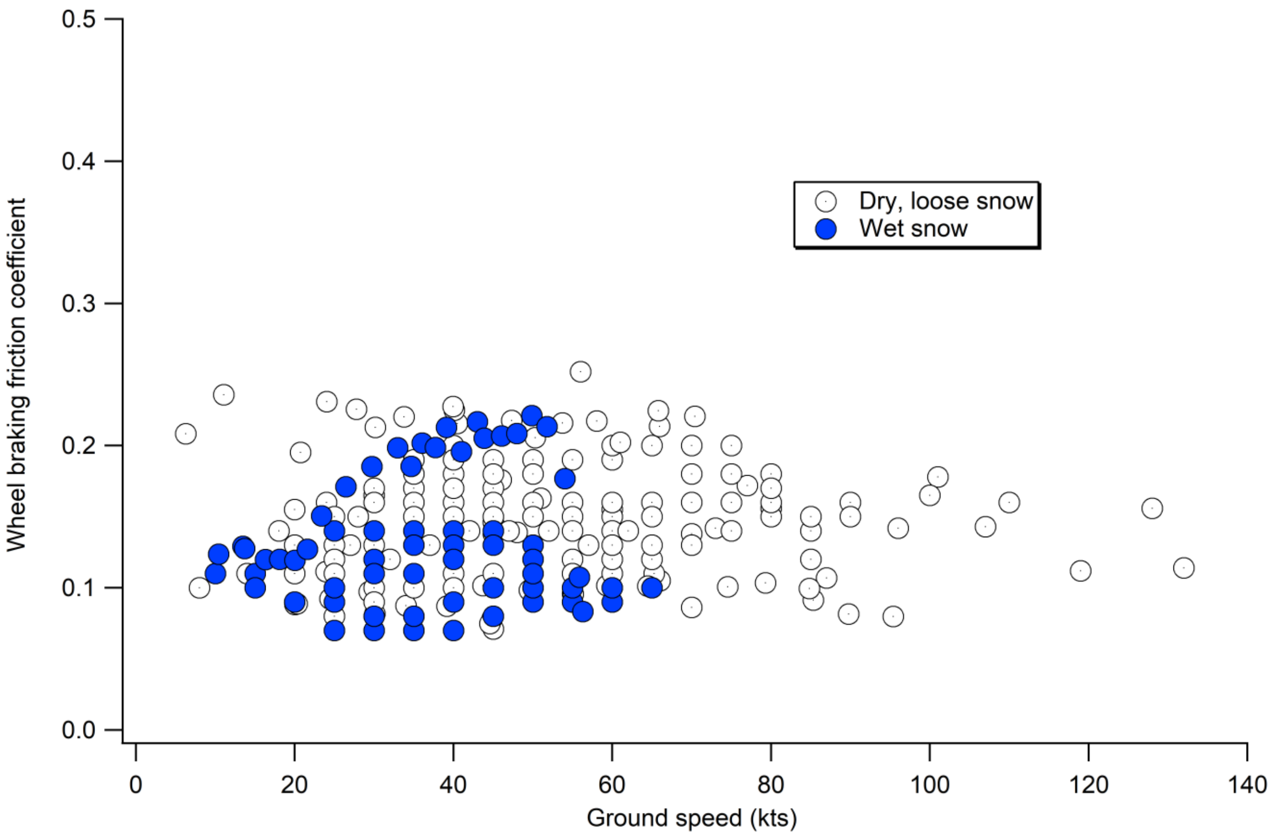

Figure 3-1: Braking friction on dry and wet snow (data used to establish default braking friction coefficient by the JAA contaminated runway performance working group)

3.2 Slippery wet runway braking friction level

The difference in braking performance between a wet and a slippery wet runway is illustrated in Figure 3-2. This figure shows a comparison of the wheel braking friction coefficient as function of ground speed on a wet (braking action good) and slippery wet runway (braking action medium) for a narrow body jet aircraft. The average runway macro texture depth for both cases was very similar. However, the micro texture of both runways was different, one being sharp whereas the other runway had parts with a smooth micro texture. Figure 3-3 and Figure 3-4 give examples of wheel braking friction levels as function ground speed on a variety of wet runways that could be classified as slippery wet as they performed much worse than assumed by the EASA CS25.109 models. The data were gathered from accident investigations and flight tests. Also shown are the wheel braking friction coefficients according to CS25.109 standard curves assuming an antiskid efficiency of 80%[10] for tyre inflation pressures of 100 and 200 psi[11]. The wheel friction coefficient of 0.16 that is used for a slippery wet runway in the RCAM (see Table 3-1) is also shown. Figure 3-3 shows data for ungrooved runways with an average macro texture depth between 0.4-0.8 mm and Figure 3-4 represents grooved runways. Most of the achieved wheel braking friction levels are well below that of assumed by the models in CS25.109 for braking action good (RWYCC of 5). In some cases part of the braking friction level matches with the CS25.109 models. This could be the effect of the variation of the macro and or micro texture along the runway which could be less smooth and or sharper at some positions resulting in higher friction values. Also, variation in the wetness of the surface along the runway could affect the braking friction levels achieved. Accurate information on the wetness of the runways was not available in most of the cases. However, based on the actual rainfall, the average runway macro texture depth and cross slope, water depths were estimated to be less than 2 mm and often below 1 mm. For the results obtained from flight tests, the water depths were normally less than 1 mm. The default wheel braking friction coefficient of 0.16 as assumed in the runway condition assessment matrix seems to represent slippery wet runway braking reasonably well. Differences between actual braking levels achieved by aircraft and this default value are normal, and are caused by the influence of ground speed, variation of macro texture depth, variation of micro texture sharpness and or variation of in water depths. Note that such factors are too difficult to be included into the aircraft takeoff and landing performance assessment as conducted by the pilots. There are also differences that could be caused by the brake system device in particular the antiskid efficiency. This can vary between the different aircraft types. Some of the wheel braking friction coefficients shown in Figure 3-3 and Figure 3-4 are at the level observed for ice covered runways. These low braking friction levels can occur even under damp conditions (water depths of less than 0.25 mm) on runways having a very smooth macro and smooth micro texture as demonstrated by NASA [Horne, (1966)].

[10] For a limited number of aircraft listed in Figure 3-3 and Figure 3-4 the actual antiskid efficiency could be lower or higher.
[11] This reflects the range of tire inflation pressure of the main gear wheels of the aircraft listed in Figure 3-3 and Figure 3-4.

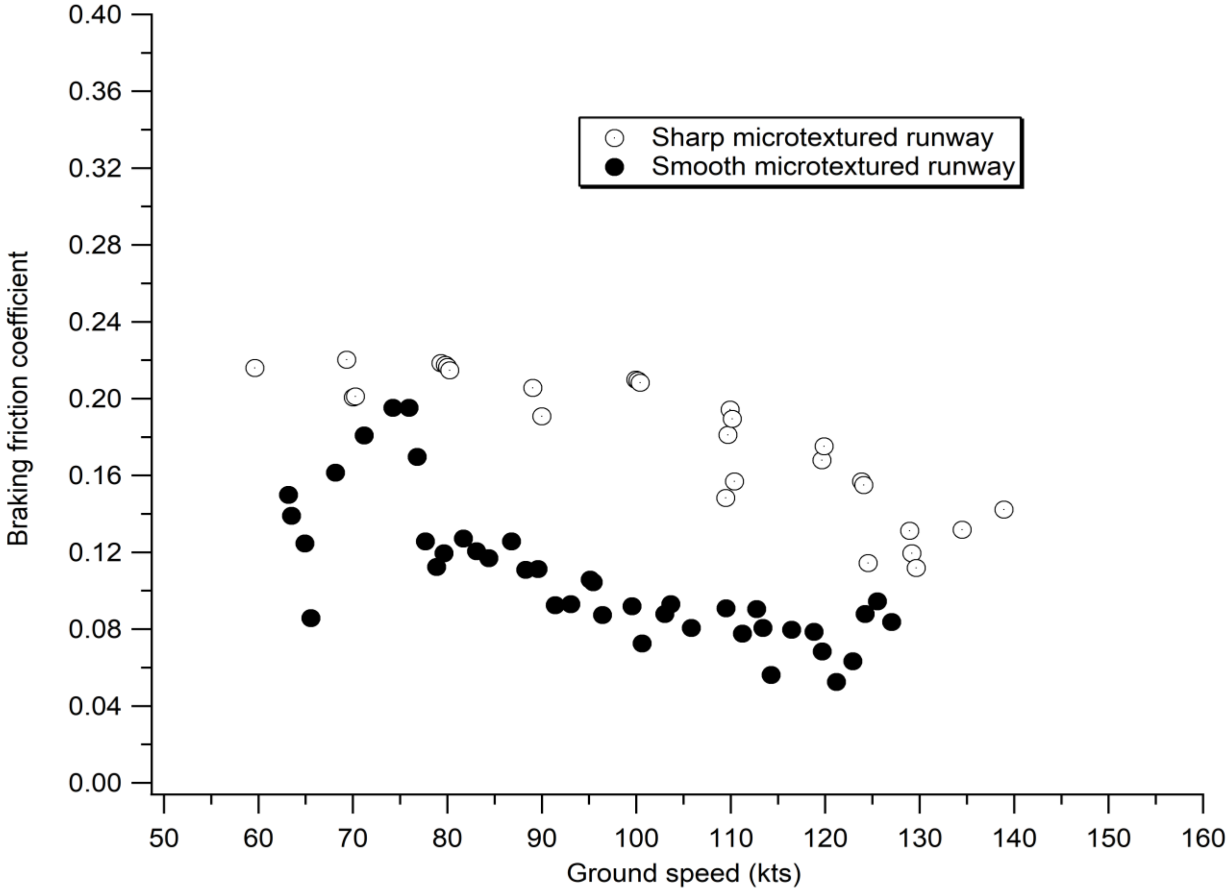

Figure 3-2:comparision of the wheel braking friction as function of ground speed on a wet (braking action good) and slippery wet runway (braking action medium) for a narrow body jet aircraft

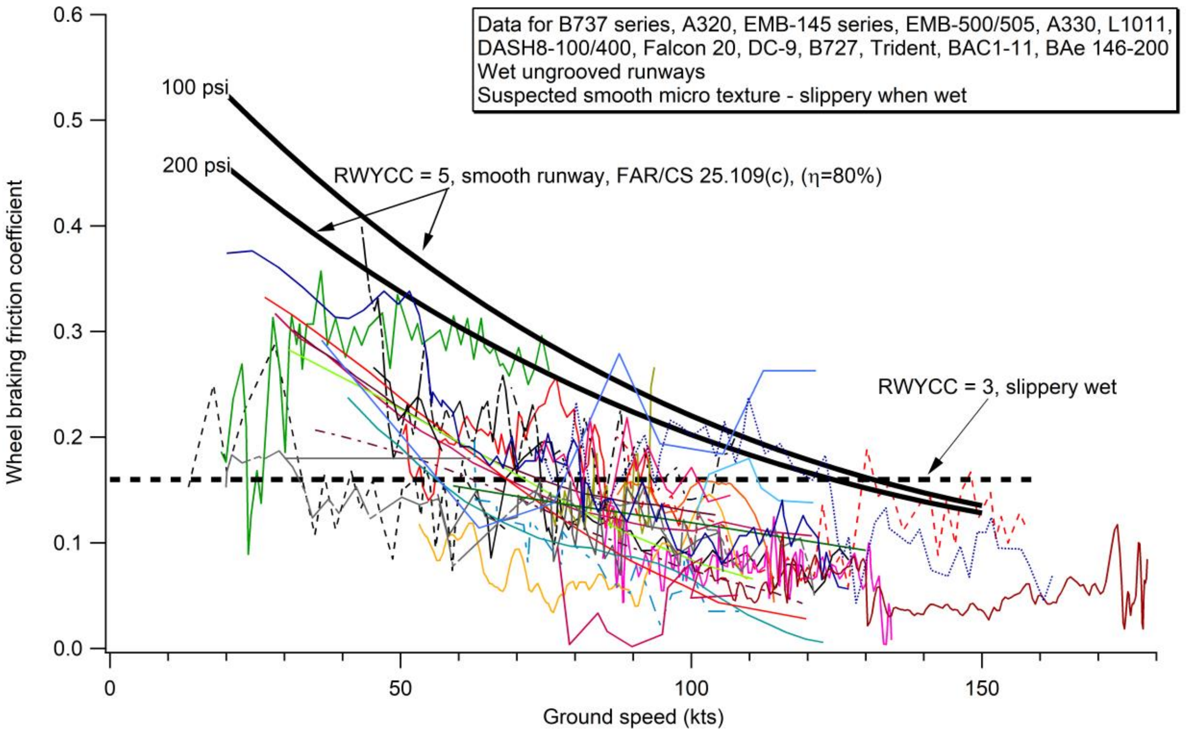

Figure 3-3: comparison of wheel braking friction coefficients versus ground of different aircraft on suspected slippery wet non-grooved runways

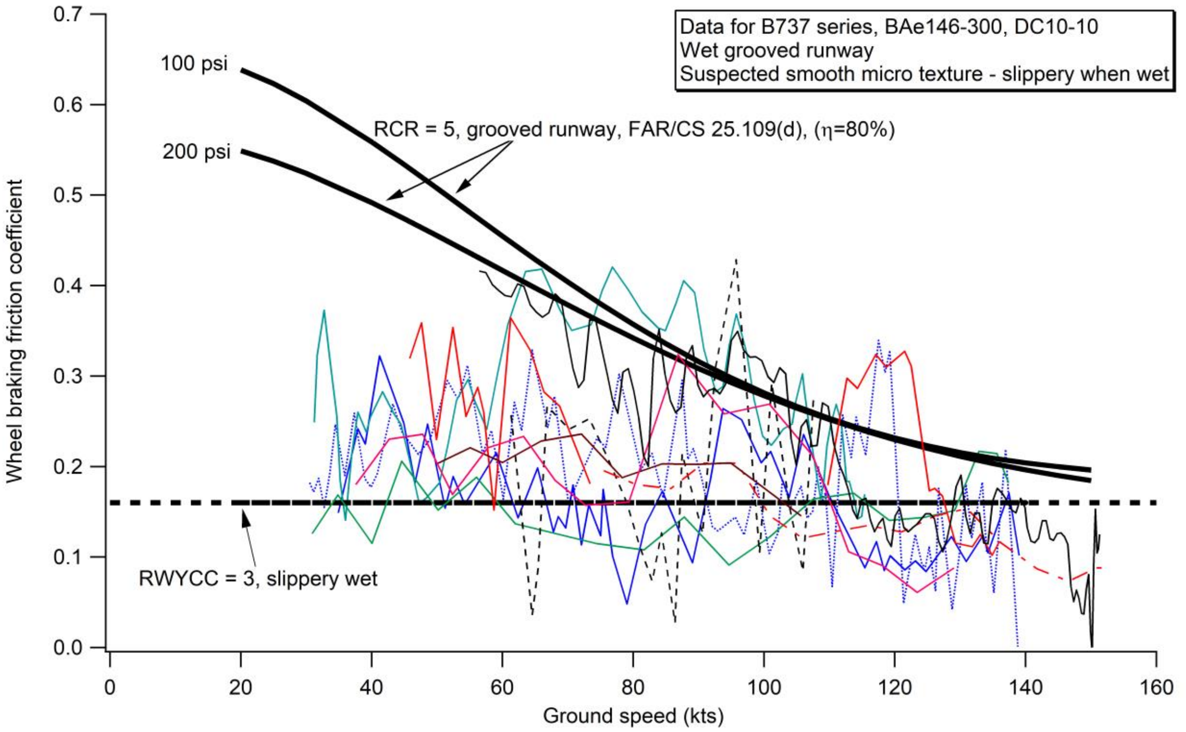

Figure 3-4: comparison of wheel braking friction coefficients versus ground of different aircraft on suspected slippery wet grooved runways

4. Development of a method to identify slippery wet runways

4.1 Introduction

The current way of identifying whether a runway is slippery wet, is based on measurements made using CFMEs which are compared with a MFL set by the State. This approach has been in use for almost forty years. Experience has shown that in a number of landing overruns the runway friction measurements indicated that the runway friction level was above the MFL, whereas the aircraft was actually achieving much lower friction levels than expected by CS25.109 which apply for wet runways with good braking action, see e.g. [O`Callaghan,(2016)]. Figure 4-1 gives an example that illustrates this problem. The results shown in this figure are taken from a NTSB accident investigation involving a B737-800. In Figure 4-1 the coefficient of friction along the grooved runway measured by the CFME and that achieved by the aircraft is shown. The measurements made with the CFME indicated friction levels were higher than the MFL and also the maintenance level defined for the device by the State. The airport was therefore not required to declare the runway slippery wet. However, the aircraft achieved wheel braking friction levels which were below that of the models given in part 25.109(d) of the regulations for a grooved runway.

There are several explanations why friction levels measured with CFMEs do not correspond to the braking action levels experienced by aircraft on wet runways, such as no or incorrect calibration of the CFME, improper inflation pressure of the test or drive tyres, worn test or drive tyres, tests conducted far from the actual wheel tracks (where the runway surface is normally less worn or affected by rubber deposits), worn axle bearings, wrongly aligned water delivery nozzle, and or incorrect amount of water sprayed in front of the test tyre. Also, pavement temperatures can cause some variation in measured friction coefficients by the CFME. Some of the factors individually can cause large errors in the order of 25-30%, as discussed by [Van Es,(2021)]. Such errors would bring the measured average friction by the CFME in the example given in Figure 4-1 at the level of the MFL for this device (0.50). The MFL as used by States introduces another problem. These are often based on the values published by ICAO. First the derivation of these minimum friction levels can be considered somewhat arbitrary. Second some of the CFMEs used in the development of the minimum friction levels are no longer available or the design has changed. The above-mentioned problems with CFMEs have resulted in the exploration of alternative methods for assessing runway friction.

A promising approach is looking at high resolution surface laser scanners to assess runway micro texture. The micro texture is considered an important factor in relation to a slippery wet runway. The EASA runway micro texture project aims at exploring the use of high-resolution surface laser scanners to measure the micro texture of the surface of runways and to determine, based on these scans, whether a runway should be classified as slippery wet. Besides the need for a meaningful micro texture characteristic to be derived from the surface scans, there is also the need to define a threshold related to this characteristic that defines when a runway is slippery wet.

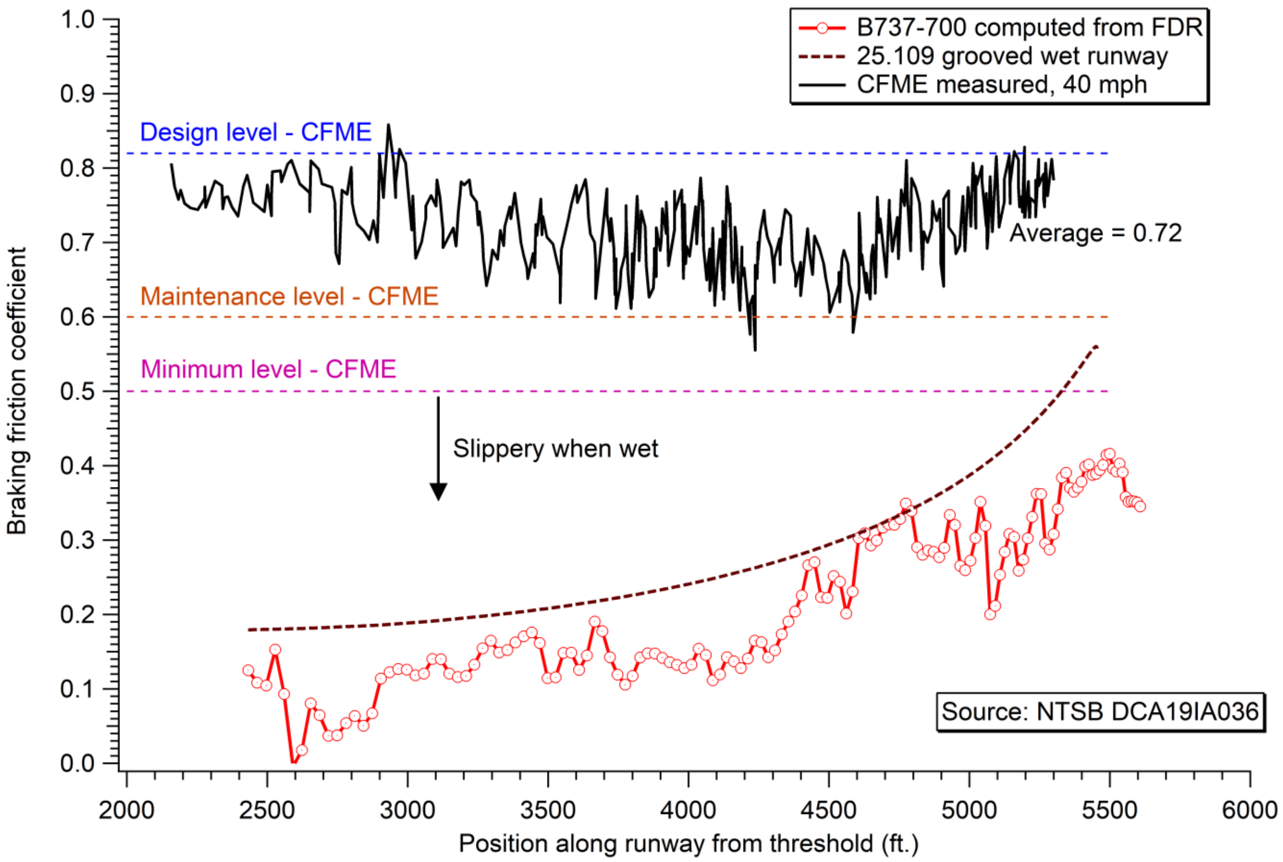

Figure 4-1: Friction along the runway measured by CFME and achieved by a jet aircraft

4.2 Introduction to wet runway tyre braking friction forces

The level of friction between a tyre and a wet surface is primarily related to the ability to remove a water film from the ground contact area. The term hydroplaning, or aquaplaning, is used to describe the process. Hydroplaning is defined as the condition in which the tyre footprint is lifted off the runway surface by the action of the fluid. In such a condition the forces from the fluid pressures balance the vertical loading on the wheel. Since fluids cannot develop shear forces of a magnitude comparable with the forces developed during dry tyre-runway contact, tyre braking friction under this condition drops to values significantly lower than on a dry runway. Water pressures developed on the surface of the tyre footprint and on the ground surface beneath the footprint originate from the effects of either fluid density and/or fluid viscosity, depending on conditions. This has resulted in the classification of hydroplaning into two types, namely dynamic and viscous hydroplaning. Both types of hydroplaning can exist simultaneously and have the same impact on braking friction of the tyre. However, the factors influencing both types are different.

To better understand the influence of both types of hydroplaning conditions on tyre friction, the contact surface of the tyre and the ground is divided into three zones. Figure 4-2 illustrates the three zones under a tyre footprint of a braked tyre moving on a wet surface. This way to describe wet surface braking of a tyre was first proposed by [Gough, (1959)]. In zone 1 the tyre contacts the stationary water film on the runway. The bulk volume of the water is being displaced in this zone. Zone 2 is a transition zone that consists of a thin water film. Finally zone 3 is a dry zone with no water film present between the tyre and the surface.

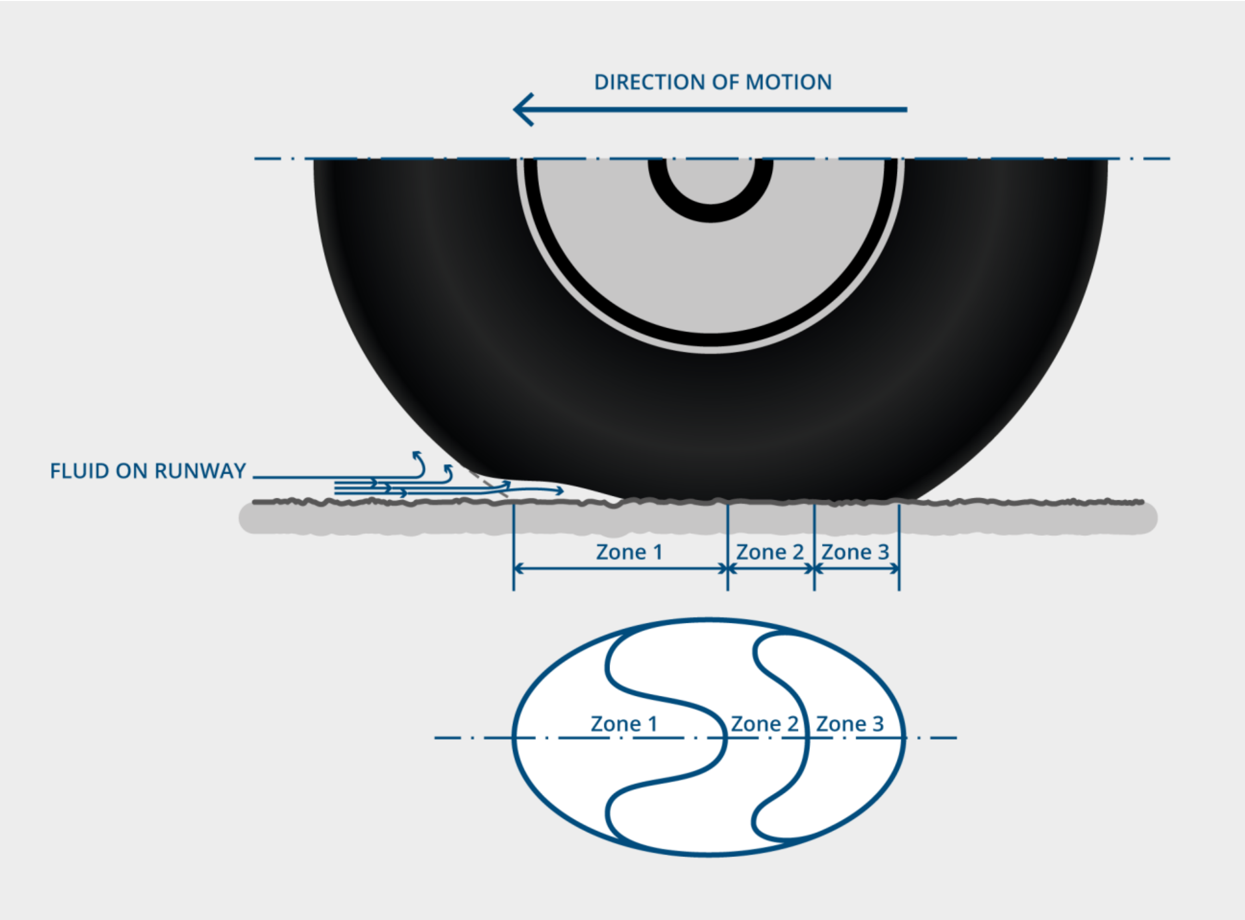

Figure 4-2: Zones of a tyre footprint when rolling along a wet surface

In zone 1 much of the water is ejected as spray and squeezed through the tyre's tread and the runway texture. Hydroplaning in zone 1 is the result of the dynamic hydrodynamic forces developed when a tyre rolls on the water covered surface. This is a direct consequence of the tyre impact with the water which overcomes the fluid inertia. Hydrodynamic theory normally assumes that viscous effects are pre-dominant and the absence of inertia of the fluid. This corresponds to thin lubrication films. As the water film thickness increases inertia effects can no longer be ignored. A wedge region is formed slightly ahead of the leading edge of the tyre footprint and a change in momentum of the water layer creates a hydrodynamic upward force [Moore, (1975)]. The magnitude of the hydrodynamic force and therefore the size of zone 1, varies with the square of the tyre forward speed, the water depth and the density of the fluid [Moore, (1975)]. Dynamic hydroplaning is further influenced by a number of factors like tyre inflation pressure, tyre tread, and runway macro texture. Macro texture is the runway roughness formed by the large stones and/or grooves in the surface of the runway. The macro texture provides escape channels to drain bulk water from zone 1. Zone 2 is a transition region. There is only a thin film of water in this zone and water pressure is maintained by viscous effects. The water film may have a thickness of as little as 0.01 mm [Moore, (1975)]. Viscous hydroplaning typically occurs on wet runways that have a smooth micro texture. Micro texture is the sandpaper like roughness of a surface formed by the sharpness of the fine grain particles on the individual stone particles of the surface. Surface micro texture performs its function by providing a large number of sharp pointed projections that, when contacted by the tyre tread, generate very high local bearing pressures [Moore, (1975)]. These intense pressures break down the thin water film and allow the tyre to regain dry contact with the pavement surface texture. Viscous hydroplaning can already develop at low ground speeds. The pressure build-up in zone 2 is much less dependent on ground speed compared to the pressure build-up in zone 1. Finally zone 3 is a region of dry contact. In this zone the tyre friction forces are generated when the wheel is slipped due to adhesion and hysteresis. The wheel braking friction force on a wet surface is approximately equal to the dry runway friction force multiplied by the ratio of the contact area in zone 3 and the overall tyre-ground contract area (Horne, (1976)]. When a tyre is completely separated by a film of water the braking friction force is very low as fluids cannot develop shear forces of a significant magnitude.

4.3 Measuring texture characteristics

Aircraft tyre-to-ground braking friction on wet runways is dependent on a number of variables. Macro and micro texture of the runway surface play a significant role. It is important that a runway has a high macro texture depth and a sharp micro texture[12] to provide adequate tyre braking friction under wet conditions. Macro texture can be assessed through different measurement techniques. Methods that have been used include the sandpatch and NASA grease test. These are so-called volumetric techniques. The sandpatch method works by putting a known volume of fine sand into the surface texture to form a circular patch in which the voids are filled. From the known volume of sand, the macro texture depth can be calculated. The NASA grease test consists of working a known volume of grease into the surface and measuring the resulting grease-covered area. Dividing the volume of grease used by the area covered provides an average depth of the runway macro texture. A more modern technique for assessing the macro texture of a surface is by using contactless type of devices to scan a part of the surface. Laser profilometers are the most common type used. Direct measurement of the micro texture has been more difficult. Commonly the results obtained by the British Pendulum Tester are often considered as a measure for the micro texture characteristics of the surface. However, the results obtained with a pendulum can be inconsistent with variations in the results caused by the calibration and operational use. With the introduction of portable high resolution laser scanners possibilities have emerged to assess the micro texture of a surface in a more direct way using contactless scanning techniques. Such devices are less affected by calibration errors and operator use. It is the main objective of the EASA project on runway micro texture to explore the possibilities for use on runways in order to determine when a runway is slippery wet.

4.4 Runway characteristics for slippery wet conditions

As discussed earlier it is believed that a smooth micro texture is the main contributor in runway becoming slippery wet. However, a very low macro texture depth of the surface can also result in a slippery wet runway. It can be argued that the macro texture depth should be at least 0.25 mm for runways having a sharp micro texture to correspond to the average macro texture depth for which regulatory tyre friction model given in CS25.109(c) for a smooth runway applies. Note that the term *'smooth'* in CS25.109(c) refers to the macro texture rather than the micro texture. EASA nor ICAO specify minimum macro texture depths for in-use runways. FAA on the other hand recommends that the airport operator should initiate plans to correct the pavement when the average macro texture depth is below 0.76 mm but above 0.40 mm [FAA, (1997)]. When the average texture depth measurement falls below 0.25 mm, the airport operator should correct the pavement texture deficiency within 2 months according to the FAA. This corresponds to the proposed minimum macro texture depth of 0.25 mm[13]. For the case that a runway has a macro texture depth of at least 0.25 mm or more, slippery wet conditions may occur when the micro texture becomes too smooth. It should be noted that other factors also play an important role in the braking friction levels that an aircraft can achieve. In particular the water depth has a significant influence in relation to the available macro texture depth. For most runways under moderate to heavy rain, the water depths near the wheel tracks will not easily exceed 2 mm. Only when the cross slope is relatively low (e.g. non-compliant with standards and regulations) it is expected that it is more likely that higher water depths could occur. During longer times of

[12] Very sharp micro texture is unwanted as this could negatively affect tire wear.
[13] In real practice runway surfaces with such low macro texture depths are rare. Most of runways will have macro texture depths exceeding 0.5 mm. ICAO recommends a minimum macro texture depth of 1.0 mm for new runways. FAA recommends a slightly higher texture depth of 1.14 mm for new runways.

heavy rain or short periods of very heavy rain, water depths could exceed 3 mm resulting in a flooded runway. At such water depths the role of the micro texture in braking friction becomes less significant. Tyre tread depth and macro texture are more dominant in that case. For water depths higher than say 5-6 mm the influence of these factors also becomes much less significant. Tyre inflation pressure is then the dominate factor as this is directly related to dynamic hydroplaning which is much more present at these higher water depths.

4.5 Threshold for slippery wet runways related to micro texture characteristics

As part of the EASA runway micro texture project several tests have been conducted. These include tests with a British Pendulum, flight tests and surface scans using a high-resolution laser scanner. Several micro texture parameters were derived from the surface laser scans using a variety of techniques and approaches including volumetric metrics and spectral analysis. Tests with the British Pendulum Tester and two aircraft were conducted on several wetted surfaces as part of the EASA project. From these tests the micro texture sharpness parameter F_1 , was deduced. This statistic is introduced in Annex A It is assumed that this parameter represents the micro texture characteristics in relation to rubber friction on a wet surface. A correlation was sought between the micro texture sharpness parameter and the micro texture characteristics derived from the laser surfaces scans on the same surface. The results of this analysis are discussed in deliverable D-4.1 [Van Es, (2024)]. The main question now is at what level a runway is considered to be slippery wet. As discussed in section 2 an ICAO study group proposed that a minimum friction level of a wet runway would be that at which an aircraft in the normal landing configuration using maximum wheel braking *only* would need *twice* the dry braked stopping distance (SDR = 2.0). This refers to the distances without the airborne part as this is not related to the state of the runway. This definition can be used as a starting point in defining a threshold for a slippery wet runway using a high-resolution surface scanner to assess the runway. However, it should be noted that a stopping distance ratio of 2.5 corresponds to a Mu-meter value of 0.42 (which is equal to the MFL of this device) as originally proposed in the Air Force Weapons Laboratory study [Ballentine, (1975)]. This is also shown in Figure 2-3. The definition used by the ICAO study group was therefore slightly extended to include this threshold too. A slippery wet runway condition is defined in this study as the condition at which an aircraft in the normal landing configuration using maximum wheel braking only would need 2.0-2.5 times the dry braked stopping distance. This range of stopping distance ratios should be related in some way to the characteristics of the runway surface in term of e.g. micro texture and or macro texture (a very low macro texture can also result in a slippery wet runway).

The proposed approach for defining a micro texture threshold for a slippery wet runway is illustrated in Figure 4-3. To the left of this figure a relation between the stopping distance ratio and the micro texture sharpness parameter F_1 is shown. This is an analytical relation based on the characteristics of the aircraft. To the right the relation between the micro texture sharpness parameter F_1 and a micro texture characteristic as derived from experiments is shown. A stopping distance ratio of 2.0 to 2.5 correspond to a micro texture sharpness parameter that reflects the status of the runway being slippery wet. This micro texture sharpness parameter value is transferred to the correlation that has been established from tests with a micro texture characteristic derived from surface scans. First the relation between the stopping distance ratio and micro texture sharpness parameter F_1 is discussed.

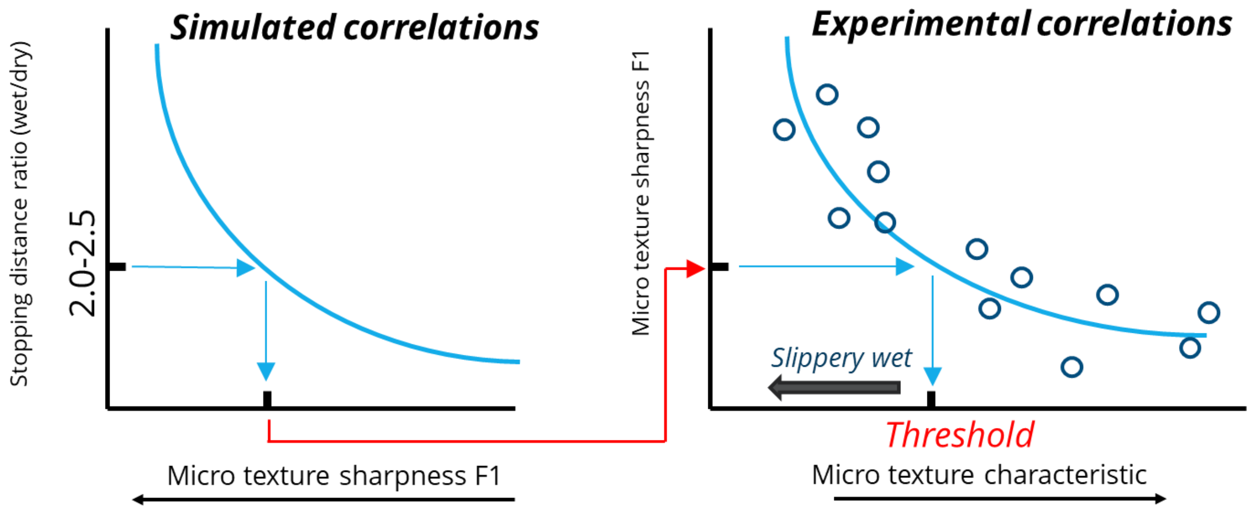

Figure 4-3: process to establish slippery wet runway threshold based on micro texture characteristics

The stopping performance of an aircraft is determined by a number forces. First there is the aerodynamic drag. This force varies with the square of the true airspeed. As the speed drops the aerodynamic drag reduces rapidly. The aerodynamic drag is determined by the overall design of the aircraft (cleanness), the flap setting and the use of ground spoilers. A high flap setting gives higher aerodynamic drag due to an increase of profile and induced drag. Deployment of ground spoilers also increases the drag. Not all aircraft are equipped with ground spoilers. Another stopping force is provided by the tyres. The forces which can act on a tyre on a dry or wet surface are rolling resistance (due to friction in bearings, and tyre hysteresis) and braking friction due to the application of a brake torque which results in frictional forces in the contact area. Both of these forces are influenced by several parameters like tyre inflation pressure, ground speed and normal load on the tyres. On a wet surface the braking friction forces are influenced by the surface macro- and micro texture and the amount of water on top of the surface. The normal load itself is depended on the weight of the aircraft, centre of gravity, aerodynamic lift and the moments arising from engine thrust and aircraft aerodynamics. Finally, the engines can also develop forces in the direction of motion. The definition for a slippery wet runway in relation to SDR assumes that no reverse thrust is being used. The engines are assumed to be operating in ground idle mode.

Considering the above factors that influence the stopping performance of an aircraft, for certain aircraft- wet surface combinations different relations between SDR and F_1 can be expected. A single unique relation that would represent all transport aircraft will simply not exist due to the variations in aerodynamics, engine idle thrust, friction resistance forces and wheel loads. However, a set of combinations of runway wetness conditions, surface macro texture and aircraft could provide an average relation between SDR and F_1 that can be used in defining a threshold. For nine different aircraft ranging from business jet, turbo prop, regional jet, medium and large sized jet aircraft, stopping performance calculations were conducted[14] for both dry and wet runway surfaces. The ESDU tyre braking friction model was used to develop relations between braking friction coefficient and ground speed using the main gear tyre characteristics for each type of aircraft considered on a wet runway [Anon., (2023)]. This was done for different macro texture depths and water depths typically seen on runways (water depths between 0.5-1.5 mm and macro texture depths between 0.5 and 1.5 mm)[15]. Tyre braking friction coefficient versus ground speed relations were established for a range of

[14] Representative data on aerodynamics, engine thrust ect. for these aircraft were available.
[15] It is realised that by definition a wet runway can have water depths up to 3 mm. However, such conditions are extremely rare a requires high rainfall rates. If a runway is experiencing a heavy downpour the runway is more likely to

micro texture sharpness values using the ESDU model. An antiskid efficiency of 85% was assumed for all aircraft considered[16]. The speed at the start of maximum brake application is the same for wet and dry conditions and is based on the reference speed with landing flaps with a 4% reduction[17]. Stopping distance ratios were calculated for each macro texture, water depth, micro texture sharpness combination for typical landing weights for the different aircraft considered. For inflight landing performance on dry runways, 90% of the braking friction coefficient is used by aircraft manufacturers as per Table 3-1. However, for the calculation of the SDR this correction is not made in order to be consistent with the definition used by the ICAO study group.

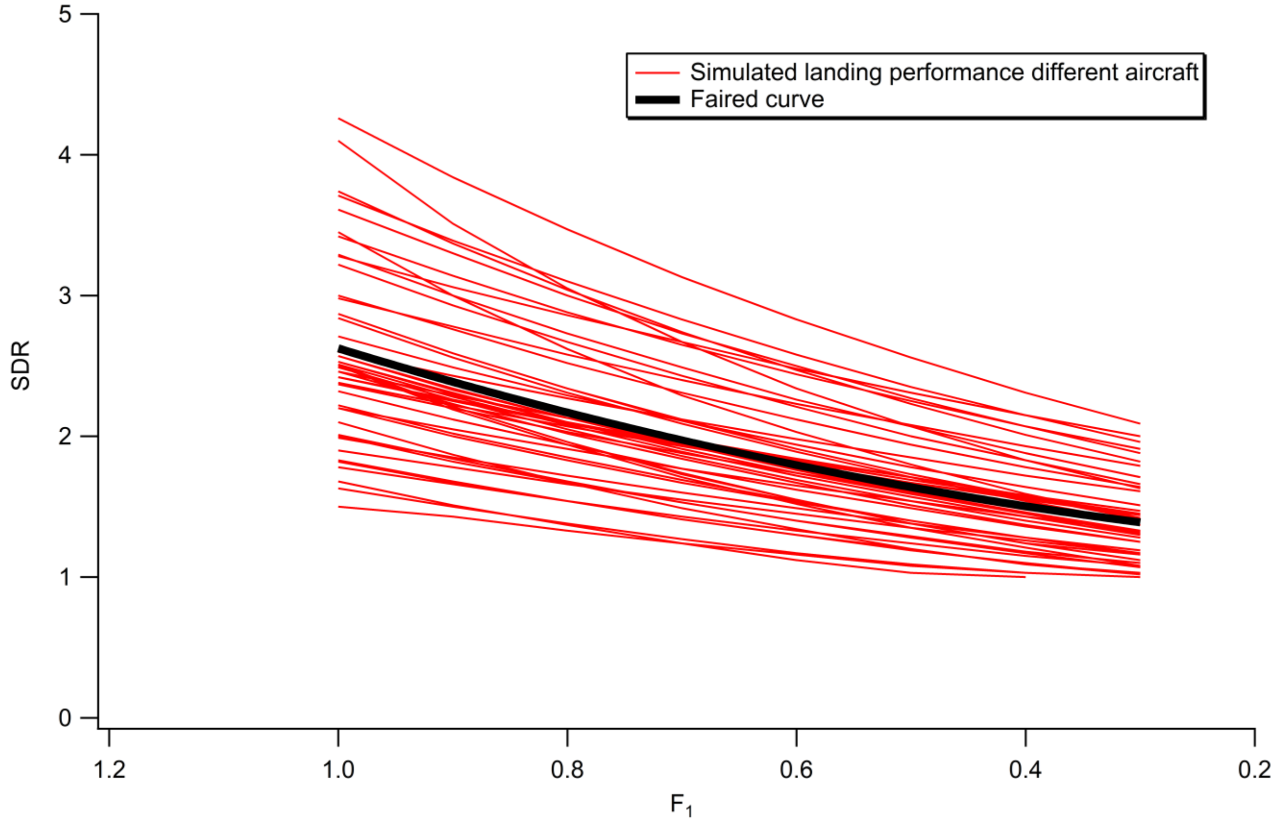

Figure 4-4: relation between stopping distance ratio and micro texture sharpness for different transport aircraft and runway conditions (macro texture and wetness)

Figure 4-4 shows the result of the landing performance calculations. The results are shown in terms of the stopping distance ratio as function of the micro texture sharpness F_1. A *low* micro texture sharpness value corresponds to a runway surface with *sharp* micro texture. Note that the x-axis is drawn in reverse order in Figure 4-4. There is some considerable spread in the results which is not a surprise as already discussed earlier. The combination of a high macro texture (1.5 mm) with a low water depth (0.5 mm) forms the lower band of results whereas a low macro texture (0.5 mm) with a high water depth (1.5 mm) forms the upper band. Some of the aircraft considered in the analysis do not have ground spoilers installed. This means that the contribution of the aerodynamic drag in decelerating these aircraft is less significant than for those

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become flooded (exceeding water depths at around the wheel tracks) exceeding 3 mm. For runways having runway cross slopes according to international standards waters depth less than 1.5 mm are more likely during periods of heavy rain.

[16] This value was assumed to reflect the average of most modern aircraft using fully modulated antiskid systems for both wet and dry runways. However, higher and lower efficiencies are possible resulting in different levels of stopping distance ratios. Aircraft with higher antiskid efficiencies will have lower SDRs.

[17] Commonly used in landing performance calculations.

aircraft that can use this device. Also the aerodynamic lift is not reduced by the lack of these ground spoilers meaning that the normal force on the gear is less resulting in lower frictional forces. This can result in less effective stopping performance on wet surfaces resulting in relatively higher stopping distance ratio's than for aircraft that are equipped with ground spoilers. A thick line also shown in Figure 4-4 which is a curve faired through the different results. This curve could be used as an average relation between the stopping distance ratio and the micro texture sharpness. The micro texture sharpness values corresponding to a SDR of 2.0 and 2.5 are 0.72 and 0.95 respectively based on the faired curve.

In the work done by the ICAO Runway Surface Condition Study Group a similar analysis into stopping distance ratios and braking performance was conducted. However, the ICAO study assumed an average, constant aircraft wheel braking coefficient. Figure 4-5 shows the relation between SDR and a constant wheel braking friction coefficient for the aircraft considered in the ICAO study and of the aircraft considered in the present study. A spread in the relations can be clearly seen. This is attributed to the differences in the aircraft in terms of e.g. aerodynamics and idle thrust. Also indicated in Figure 4-5 is the braking friction coefficient currently assumed in the RCAM for a slippery wet runway. This is related to an SDR between 2.0 and 2.5, the range considered in this study for a slippery wet runway. A thick line is also shown in Figure 4-5 which is a curve faired through the results. On average the results for the different aircraft considered match the condition that $\mu = 0.16$ between SDR =2.0-2.5 reasonably well with the faired curve intersecting the slippery wet RCAM friction value of 0.16 at SDR of approximately 2.25. This would mean that a stopping distance ratio in the order of 2.0-2.5 would be representative to a slippery wet runway braking friction level as currently assumed. It should be noted that Figure 3-3 and Figure 3-4 illustrate that on slippery wet runways the aircraft wheel braking friction levels can vary considerable due to varieties in, for instance water depth, macro/micro texture, antiskid efficiency etc. The default braking friction value of 0.16 used in the RCAM for a slippery wet runway merely represents an average of these variations. In that same respect, the variations in the SDR-F_1 relations in Figure 4-4 should be considered.

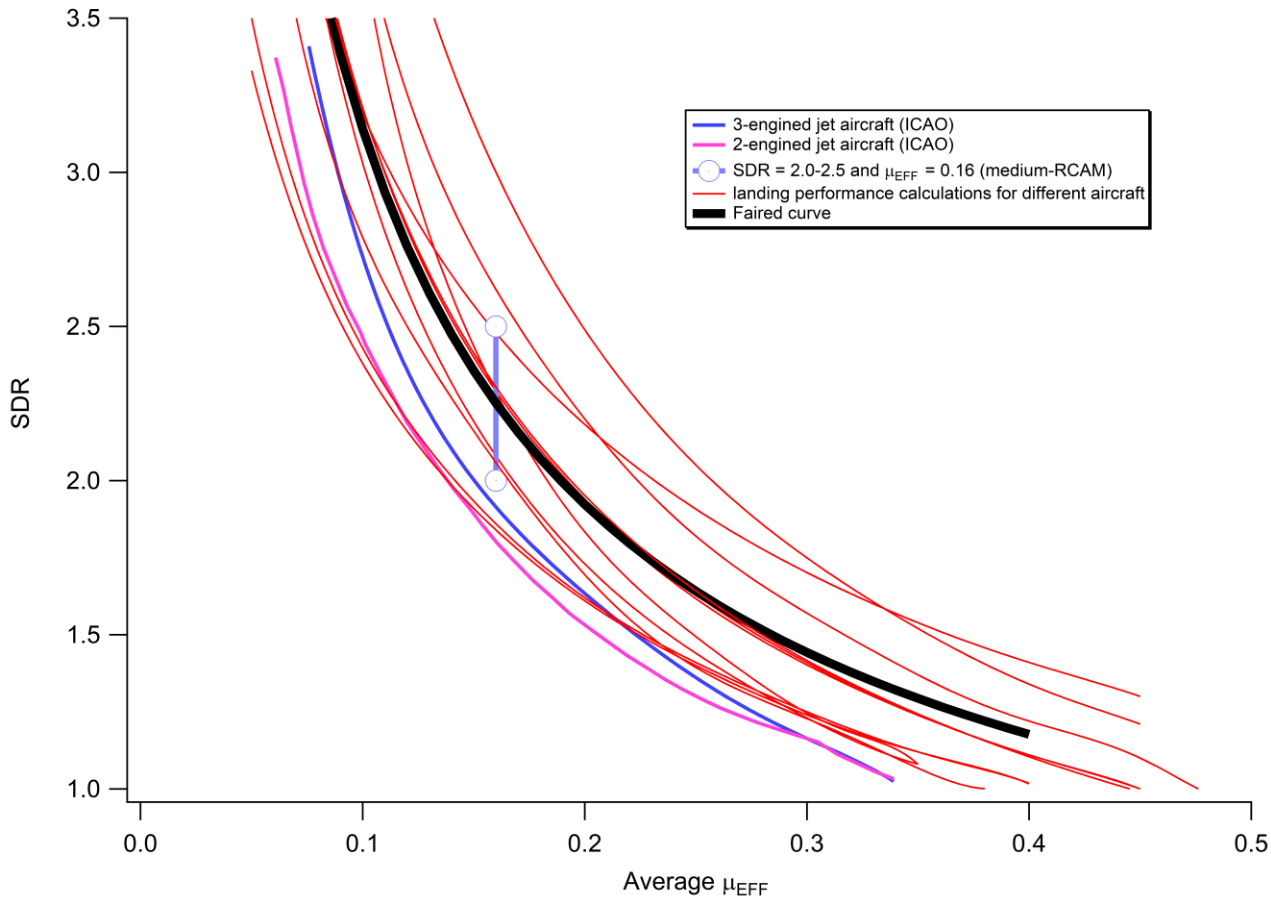

Figure 4-5: relation between SDR and an average braking friction coefficient for several aircraft

The Quick Reference Handbook (QRH) of an aircraft provides landing stopping distances for dry and slippery wet conditions. Aircraft manufacturers have updated the information to be in line with the RCAM and underlying assumptions. The information provided in the QRH can be used to estimate stopping distances for aircraft on slippery wet and dry runway conditions. The landing distances provided in the QRH includes the airborne distance. In order to calculate a SDR, which only considers the ground roll part, the airborne distance was subtracted from the total landing distance (for a given weight and flap setting). Airborne distances were based on either data given in the QRH (fixed distances) or were calculated using the reference speed, assuming a 4% reduction in speed from 50 ft to touchdown and a duration of 7 seconds. It is noted that for a dry runway the QRH assumes 90% of the maximum braking friction as per Table 3-1. This would result in *lower* SDRs due to the longer dry runway stopping distances. Nevertheless, SDRs were calculated for slippery wet runway conditions from available civil transport aircraft QRHs that contained landing performance data in line with the RCAM definitions shown in Table 3-1. The results were compared to the calculations made in the present study as shown in Figure 4-6. QRH data for eleven jet aircraft were available varying from business jet, regional jet and narrow/wide body jet aircraft. An 'average' SDR of all these aircraft is shown together with the highest and lowest value found. This average cannot be considered yet as representative for all commercial transport aircraft. Although a representative set of jet aircraft was used it still could be biased by the aircraft considered. The variation in SDR as estimated from the QRHs comes partly from the influence of the landing weight as illustrated in the example given in Figure 4-7. However, the differences between the individual aircraft could also be caused by differences in aerodynamics and braking performance (e.g. antiskid efficiency). Also aircraft manufacturers could have made some different assumptions or simplifications in their calculations. Note that the faired curve crosses the average SDR derived from the QRHs at the braking friction coefficient used in the RCAM for a slippery wet runway. However, this is just considered mere coincidence rather than anything else.

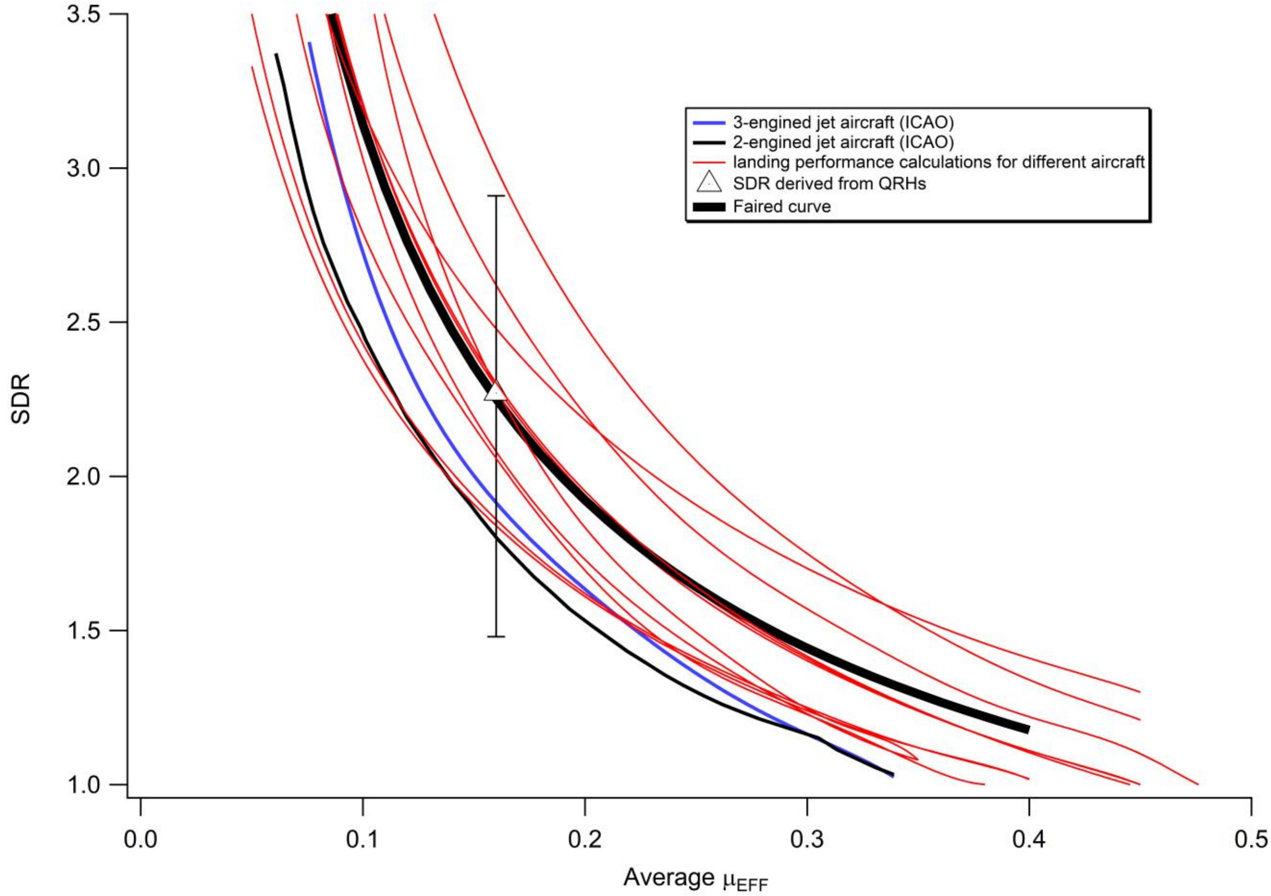

Figure 4-6: relation between SDR and an average braking friction coefficient for several aircraft compared to SDRs derived from QRHs

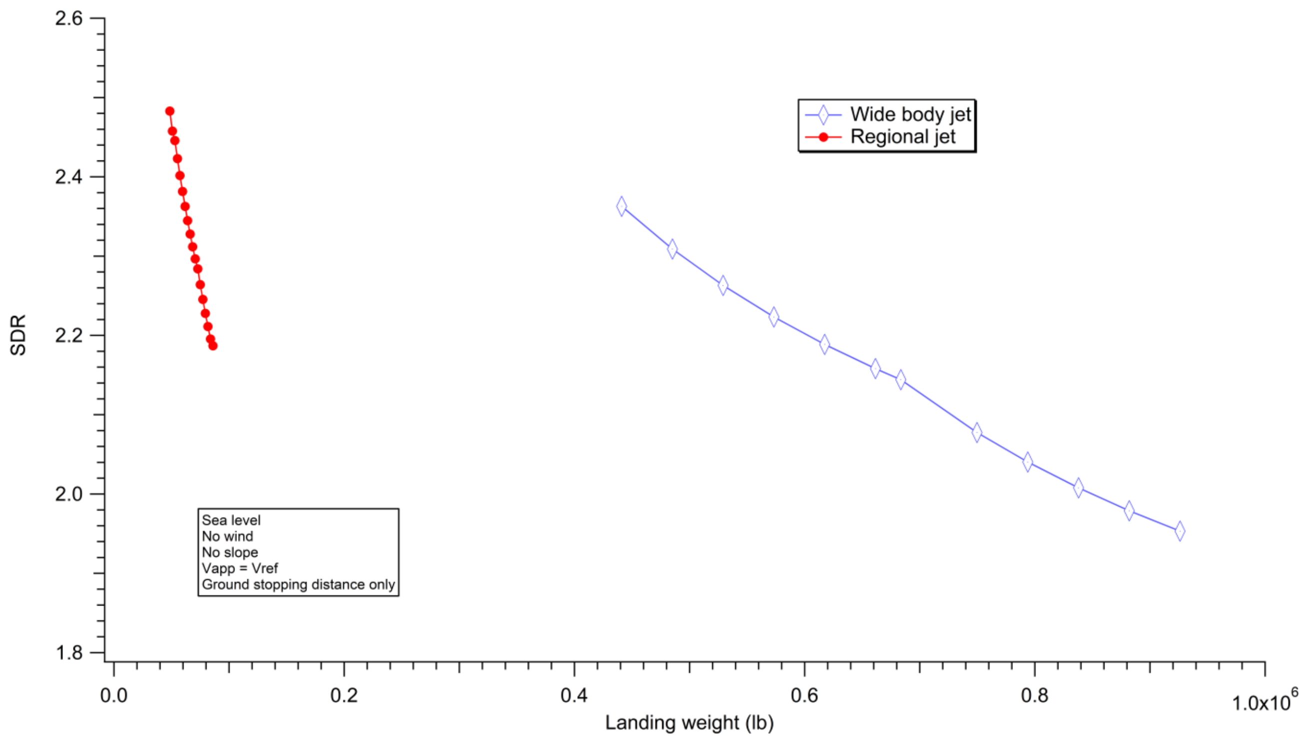

Figure 4-7: stopping distance ratio of a slippery wet runway for two aircraft as derived from the quick reference handbook

From the above made analysis it is proposed that a runway could be considered slippery wet whenever the micro texture sharpness values correspond to a value roughly between 0.72 and 0.95, with an average of 0.84 under the assumption that the runway macro texture is not less than, say, 0.25 mm. As shown in Figure 4-5 this should more or less correspond to the level of stopping performance on a slippery wet runway currently assumed in landing performance assessments based on the RCAM under common operational conditions of runway wetness.

To further validate the threshold some cases in which the runway was determined to have performed well below the expected braking friction levels according to EASA CS 25.109(c),(d), were examined. Results from aircraft accident investigations were the main source of this analysis. Several landing overrun accidents were reviewed in which it was noted that low braking friction levels were achieved under wet runway conditions. Braking friction coefficients as function of ground speed were derived from the analysis of the flight data recorder by the involved accident investigation agency often with assistance from the aircraft manufacturer. The ESDU braking friction model was matched to these results by varying F_1 [Anon, (2023)]. Water depths were estimated using empirical models combined with available information on rainfall at the time of the accident and the characteristics of the runway surface (slope and macro texture). These models are given in e.g. [Gallaway et. al., (1971); Anon., (2019)]. An example of the matching of F_1 with friction-speed data is shown in Figure 4-8. Table 4-1 gives a summary of estimated micro texture sharpness values on slippery wet runways derived from a limited number of landing overrun accidents on wet runways. It should be noted that many more overrun accidents have occurred on slippery wet runways, however, data needed to estimate the micro texture sharpness was not always available (such as macro texture depth). The runway macro texture in all cases listed in Table 4-1 were above 0.40 mm on average, except for the runway of Puerto Williams airport. The runway of Puerto Williams airport had a range of macro texture depths from as low as 0.00 to 0.20 mm next to the runway centreline[18]. The micro texture sharpness values listed in Table 4-1 support the

[18] One month prior the runway had been rejuvenated with a partial slurry seal application with a full fog seal treatment on top as the finishing coat, leaving two strips of bitumen-rich pavement surfaces on either side of the centreline.

critical threshold range between 0.72 and 0.95 with an average of 0.84 for declaring a runway slippery wet as proposed here.

Table 4-1: examples of estimated micro texture sharpness values on slippery wet runways

Year of accident	Location	Aircraft type	Runway type	F_1
2009	Kingston-Norman Manley International Airport (Jamaica)	B737-800	Asphalt	≈0.86
2009	Undisclosed	Jet transport	Asphalt	≈1.36
1992	Aberdeen Airport (UK)	B146-300	Grooved asphalt	≈0.70-0.86
1991	Puerto Williams airport (Chile)	B146-100	Asphalt	≈1.27-1.42
2010	Ottawa/MacDonald-Cartier International Airport (Canada)	EMB-145	Asphalt	≈1.22
2005	Chicago Midway International Airport (USA)	B737-700	Grooved concrete	≈1.10-1.40
2014	Sugar Land Regional Airport (USA)	EMB-500	Concrete	≈1.10-1.20

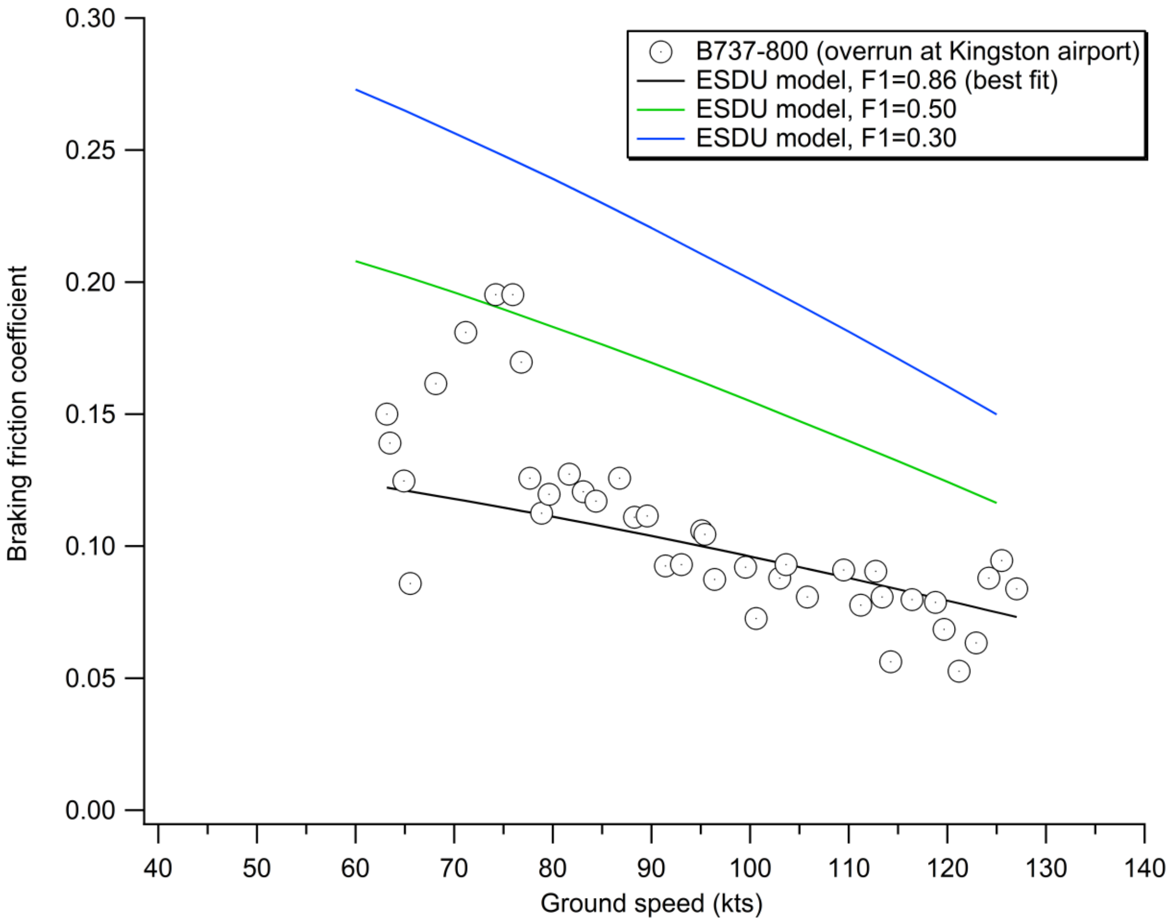

Figure 4-8: example of matching ESDU braking model to braking friction coefficients as function of ground speed

5. Relation of slippery wet runway thresholds to measured micro texture characteristics

In deliverable D.4-1 correlations between different micro texture characteristics derived from high resolution laser surface scans and micro texture sharpness derived from surface friction tests and flight tests are presented. The aim is to define a threshold for the micro texture characteristics as deduced from the high-resolution surface scans that defines the crossover for braking action good to medium (slippery wet) in the RCAM. In deliverable D.4-1 several micro texture characteristics are examined. Here two examples of these parameters are considered in relation to defining a slippery wet runway threshold; the micro texture depth obtained through a Fourier analysis and a spatial micro texture parameter called weighted sharpness. These parameters are correlated with F_1 through a simple equation given by:

$$F_1 = \pi\left(1 - \left(\frac{Microtexture\ parameter}{n}\right)^p\right)$$

This equation is somewhat arbitrary chosen. It aims to describe the relation between sharpness of the asperities with the peak contact pressure (see Annex A). The constants p and n are obtained through a best fit of the data. The equation matches the criterion that that $0 \leq F_1 \leq \pi$. In Figure 5-1 and Figure 5-2 the results of correlation between the micro texture depth obtained through a Fourier analysis and a spatial micro texture parameter called weighted sharpness with the micro texture sharpness parameter F_1 is shown[19]. Also shown is the critical micro texture sharpness of 0.84, matched with the curve fit, together with the lower and upper range (0.72 and 0.95) which indicates the slippery wet runway threshold as discussed in the previous section. In these examples thresholds for the micro texture parameters deduced from the surface scans using a high-resolution laser scanner can be derived. Using the curve fit the critical value for the micro texture depth obtained through a Fourier analysis equals 0.041 mm and the weighted sharpness equals to 0.018 assuming an F_1 of 0.84. These are merely example numbers and the micro texture parameter to be used as obtained through high resolution surface scans is still to be decided. A lower value of F_1 could also be considered to account for some of the variability in the results and measurements. Besides the micro texture characteristics also the macro texture needs to be considered when assessing a runway for slippery wet conditions. As discussed in section 4, a macro texture depth of less than 0.25 mm could be used as a threshold for slippery wet runways regardless of the micro texture.

Although reasonable correlations are found between the micro texture sharpness parameter derived from the British Pendulum tester and flight tests with a number of the micro texture parameters derived from the laser surface scans, there is still scatter noticeable in the examples shown here as well as others as discussed in [Van Es, (2024)]. It is believed that this mainly originates from the characteristics and operation of the British Pendulum tester itself and not from the inaccuracy of the laser scanner. The British Pendulum Tester is subject to a number of errors which are not easy to compensate for. Also some of the micro texture parameters derived from the laser surface scanner do not represent the micro texture characteristic well which can also contribute to a good correlation. Finally, the process of deducing micro texture sharpness parameters from the flight tests is done using a semi-empirical model for tyre braking friction. A number of assumptions are made which could affect the accuracy of the derived sharpness. Taking into account the error range of the results obtained, it is still possible to define a threshold based on the correlation between a

[19] It should be noted that Figure 5-1 also contains some test points taken from another study which used the same laser scanner and data reduction technique to derive the micro texture parameter. These additional test points could not be used for Figure 5-2.

micro texture parameter obtained from the surface laser scanner (or equivalent device) and the deduced micro texture sharpness of the surface.

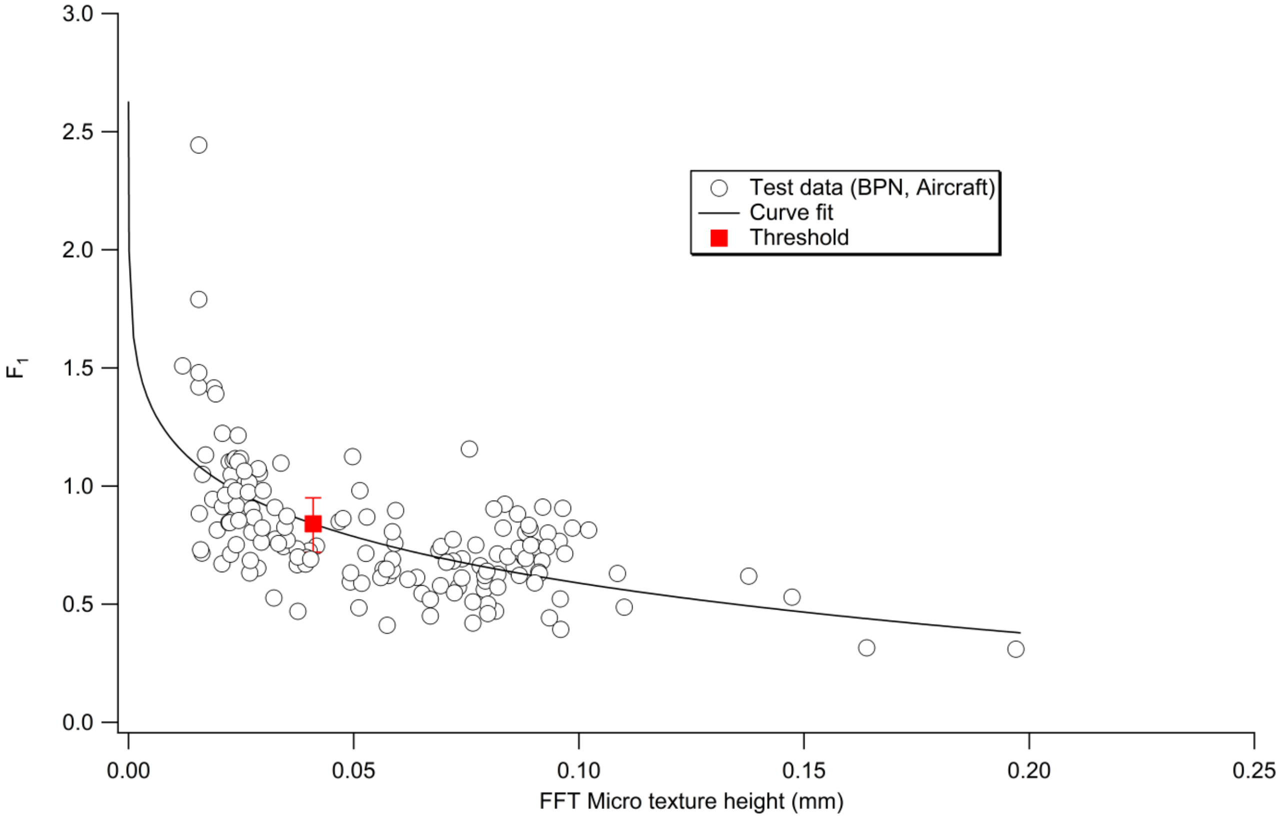

Figure 5-1: correlation between FFT micro texture depth and micro texture sharpness

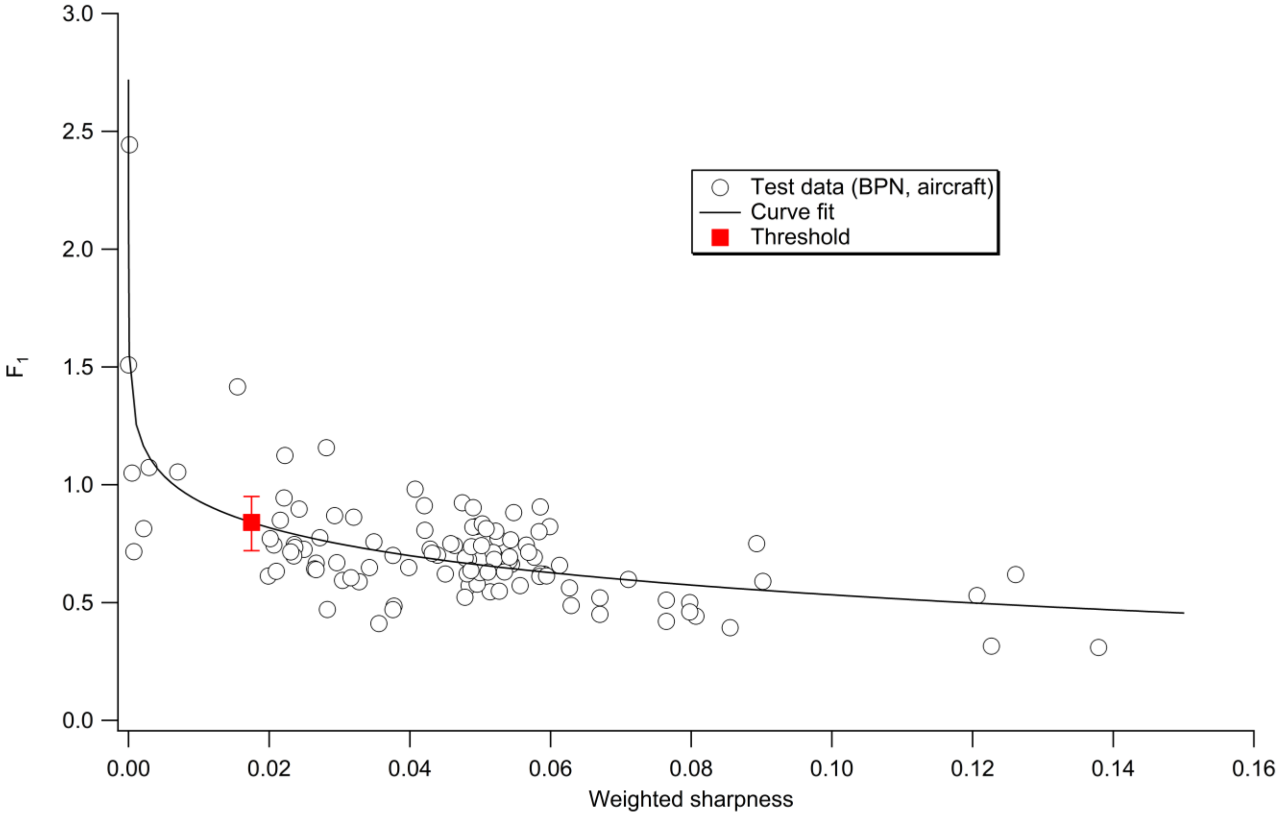

Figure 5-2: correlation between weighted sharpness and micro texture sharpness

6. Final remarks

A slippery wet runway condition is defined in this study as the condition at which an aircraft in the normal landing configuration using maximum wheel braking only, would need 2.0-2.5 times the dry braked stopping distance. This range of stopping distance ratios can be related to the characteristics of the runway surface in terms of e.g. micro texture or macro texture (a runway surface having a smooth micro texture or a very low macro texture can result in a slippery wet runway). In this report an approach is described that correlates aircraft stopping performance to the micro texture sharpness of a runway surface. For several commercial transport aircraft stopping distances on wet and dry runways were simulated in order to establish an average relation between the stopping distance ratios (wet to dry) and the micro texture sharpness of a runway considering a range of runway macro texture depths and water depths that are representative for normal operations. Critical values for the micro texture sharpness were established that could represent the crossover from a runway with braking action good to medium. It is realised that the change from the braking friction levels assumed in CS 25.109 (braking action good) and that associated with braking action medium cannot be clearly defined with just a micro texture sharpness parameter. Water depth and antiskid efficiency are other factors that influence the braking friction force that an aircraft tyre can achieve under maximum friction limited braking conditions on a wet runway. Nevertheless, pilots do need guidance when assessing the takeoff and landing performance on wet runways whereas airport operators need a practical objective method to identify substandard runway surfaces that might lead to lower braking friction under wet conditions. Based on extensive testing and analysis a method is proposed here that can assist airport operators in helping to identify slippery wet runway surfaces. With the help of surface scanners such as high-resolution laser scanners the micro texture of a runway surface can be assessed. This can be related to a minimum value needed to obtain sufficiently high friction levels. Choices need to be made regarding the actual micro texture parameter to be used. Also the threshold proposed in this study should be evaluated in order to establish a commonly accepted criterion for slippery wet surface related to micro texture or macro texture (in case the macro texture is very smooth).

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Annex A Micro texture sharpness parameter

ESDU has developed an empirically based statistic called the micro texture sharpness parameter F_1 [Balkwill, K. (2015)]. It is assumed that the protrusions in the micro texture are triangular with the vertex upward. It may be assumed that a parameter is related in some way to the angle of that vertex. When the micro texture is completely smooth the angle of the vertex is π radians. When the micro texture tends towards complete sharpness, the angle of the vertex tends to zero. It is therefore asserted that the range of the parameter F_1 is such that $0 \leq F_1 \leq \pi$ [Balkwill, K. (2015)]. This is in line with the analysis done by [Sabey, (1958) and Moore, D.F., (1969)] in which it was assumed that the micro texture asperity can be represented by a rigid cone. If the rigid cone is pressed into an elastic plane (like a rubber tyre) the peak contact pressure will be a function of the semi-angle of the cone. This is illustrated in Figure 7-1 which is based on [Sabey, (1958)]. As the semi-angle of the cone reduces (hence the micro asperity becomes sharper) the peak contact pressure increases. This relation is analogous to the micro texture sharpness parameter F_1. High peak pressures are needed to overcome the viscous pressures of the tyre contact area and to regain adhesion under wet surface conditions. Low values of the parameter F_1 represent surfaces with a *sharp* micro texture (hence high contact pressures), high values of the parameter F_1 represent surfaces with a *smoother* micro texture.

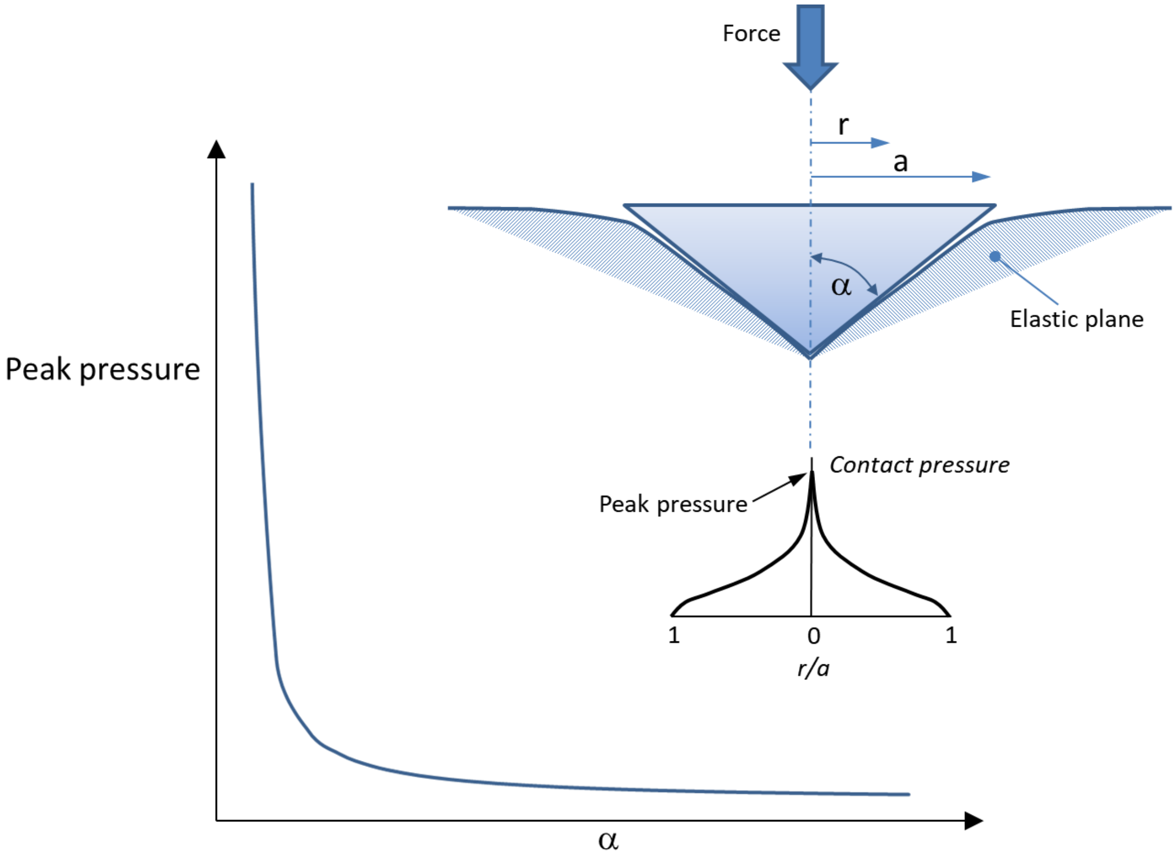

Figure 7-1: Peak pressure in area of contact of a rigid cone pressed into an elastic plane as function of cone semi-angle

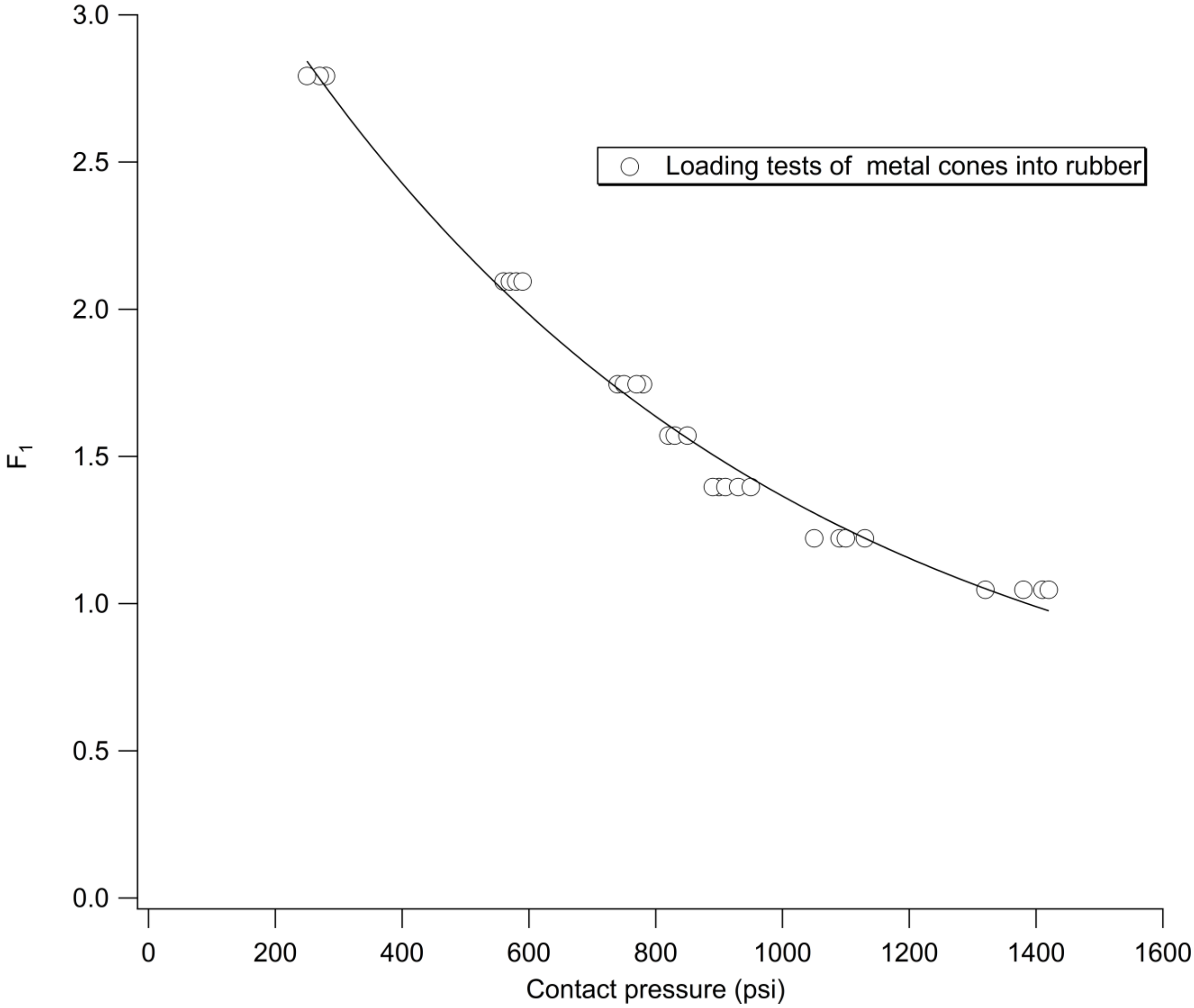

Figure 7-2: measured contact pressures of a metal cone into rubber as function F_1

Simple loading tests were made on tyre-tread rubber by Sabey using steel cones with semi-angles ranging from 30° to 80° [Sabey, (1958)]. These semi-angles can be converted into F_1 assuming that the protrusions in the micro texture are triangular with the vertex upward. Measured contact pressures are plotted against F_1 in Figure 7-2. The results confirm that as F_1 increases the contact pressures reduces rapidly.

EASA

European Union Aviation Safety Agency

European Union Aviation Safety Agency

Konrad-Adenauer-Ufer 3
50668 Cologne
Germany

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Mail EASA.research@easa.europa.eu
Web www.easa.europa.eu

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