How to assess runway micro texture in overruns on wet runways?

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Summary

Good aircraft tire braking friction on wet runways is of essential importance for safely stopping aircraft. There is a trend of aircraft overrunning wet runways in which the achieved tire braking performance was worse than expected. In a number of cases the overrun could have been avoided if the braking capabilities would have been equal or better to those specified as minimum in the regulations or when the pilots would have been informed that the runway was slippery when wet. It is believed that the cause of the difference in braking performance in most cases was the result of deficiencies in the runway micro texture. Micro texture refers to the fine scale roughness contributed by small individual aggregate particles on pavement surfaces. A smooth micro texture causes low braking friction even when the runway is only damp. Aircraft accident investigators often struggle to assess the contribution of runway micro texture to low braking friction on wet runways. This paper discusses the methods currently used to assess surface micro texture and their limitations. A novel approach to assess the micro texture of a runway using high resolution surface texture laser scanners is also presented. This technique allows a direct and accurate analysis of the micro texture of a runway surface and could be a valuable tool for aircraft accident investigators.

Illustration of the problem

Over the past years, a number of landing runway overrun accidents and incidents occurred on wet runways on both ungrooved and grooved runways. An analysis of the aircraft stopping performance of these events indicated that in a large number of cases the wheel braking friction coefficients achieved during the landing roll were significantly less than assumed in the wet-runway landing distance advisory data provided in the manufacturers' aircraft operating manuals.

The wheel braking friction coefficient that can be used for wet runway calculations during an aborted takeoff is specified by FAR 14 CFR 25.109 and EASA CS 25.109 (see for more details appendix A). Standard curves relating wheel braking friction coefficient with ground speed which are corrected for the anti-skid efficiency are provided in the regulations. The same standard curves have also been proposed and used for computing wet runway landing distances[1]. The wheel braking friction coefficients predicted by the models have been confirmed by flight tests conducted by aircraft manufacturers.

The braking friction levels of FAR 14 CFR 25.109 and EASA CS 25.109 correspond to a Runway Condition Report (RCR) with a runway condition code of 5 in the ICAO Runway Condition Assessment Matrix, assuming an ungrooved or non-porous friction course runway surface[2]. Whenever the runway is more slippery under wet conditions a NOTAM 'Slippery WET' must be issued by the airport. This is an outcome of identifying a substandard portion of a runway. This NOTAM remains in effect as long as this substandard portion is present. 'Slippery WET' and the assigned runway condition code 3 is reported in the RCR whenever the runway is wet and the NOTAM is in effect. Note that for instance EASA regulation permits the ad-hoc reporting of 'Slippery WET' for instance based on reports by pilots. Both FAR 14 CFR 25.109 and EASA CS 25.109 provide credit for grooved runways and runways with a porous friction course[2].

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[1] This will become standard practice for takeoff and landing performance calculations with the introduction of the Runway Condition Assessment Matrix in 2021. In terms of wheel braking friction capabilities there are no large differences between a rejected takeoff or landing under friction limited conditions.

[2] ICAO Doc 10064 specifies the wheel braking coefficients for different runway conditions which are indicated by codes varying from 0 to 6, which is a number describing the runway surface condition to be used in the runway condition report (RCR). A RCR with runway condition code of 5 is used for a wet runway that is not considered to be slippery when wet. The wheel braking coefficient is calculated using the curves specified in specified by FAR 14 CFR 25.109(c) and EASA CS 25.109(c), assuming a smooth runway. FAR 14 CFR 25.109(d) and EASA CS 25.109(d) also specify the wheel braking friction coefficients for a wet grooved or porous friction course runway. After formal approval operators can take credit for the higher braking friction levels achieved on such runways. It requires that the performance data are prepared appropriately by the aircraft manufacturer. Whenever the runway is considered slippery when wet, a runway condition code of 3 should be provided which uses a default effective wheel braking friction coefficient of 0.16 for performance calculations (assuming that a fully modulating anti-skid system is installed).

In a number of landing overruns there were no clear indications that the runway would be slippery when wet. The pilots therefore assumed good braking action when they assessed the landing performance. It is believed that deficiencies in the runway micro texture have resulted in wheel braking friction levels that were below of what was expected from the regulatory models. 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. A sharp micro texture is important in order to achieve high wheel braking friction on wet surfaces as is discussed in more detail in appendix B. The default wheel braking friction coefficients specified in FAR 14 CFR 25.109 and EASA CS 25.109 are based on generalised curves originally developed by Engineering Sciences Data Unit ESDU[3]. These ESDU curves themselves were based on experimental friction data for runways having a sharp micro texture (both ungrooved and grooved runways were considered in the ESDU curves). The standard curves specified by FAR 14 CFR 25.109 and EASA CS 25.109 will therefore overestimate the wet runway braking friction capabilities on runways having a smooth micro texture. These differences will become larger as the micro texture gets smoother.

Examples of overruns on slippery wet runways

An example of the above discussed problem of slippery wet runways is illustrated in Figure 1. This figure shows the wheel braking friction coefficient as computed from the Flight Data Recorder FDR for a B737-700 that overran a wet grooved runway during landing (see appendix C for more details on how to derive wheel braking friction numbers from the FDR). The wheel braking friction coefficients determined using the standard curves of FAR/CS 25.109(d) for a grooved runway, are well above the braking levels that the aircraft was able to achieve[4]. The braking friction levels only match at ground speeds between 110-120 kts. At that time the aircraft passed the intersection of another runway which was much newer. In this example the wheel braking friction that is used for a slippery wet condition in the ICAO Runway Condition Assessment Matrix (RCR with a runway condition code of 3) reflects the actual achieved braking friction levels much better. This would have given a more conservative computed landing distance than when assuming a good braking action (RCR with a runway condition code of 5) which is based on the standard curves of FAR/CS 25.109(d). Note that credit for a grooved runway is taken in this example! This does not mean that the operator involved in the accident also took this credit for computing the landing distances on wet runways.

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[3] Frictional and retarding forces on aircraft tyres. Part II: estimation of braking force, ESDU data Item 71026, 1995 (superseded).

[4] A so-called friction limited condition existed in which the anti-skid system modulates the pressure applied to the aircraft brakes in order to prevent skidding. The standard curves provided in FAR/CS 25.109 corrected for anti-skid efficiency are representative for a friction limited condition.

Another example is shown in Figure 2 for a landing overrun with a EMB145 on a wet ungrooved runway. The wheel braking friction coefficients as determined by the standard curves of FAR/CS 25.109(c) (RCR with a runway condition code of 5) for an ungrooved runway are well above the braking levels that the aircraft (EMB145) achieved. In this example also the standard braking friction value for a RCR with a runway condition code of 3 (slippery wet) is well above the actual achieved braking friction levels.

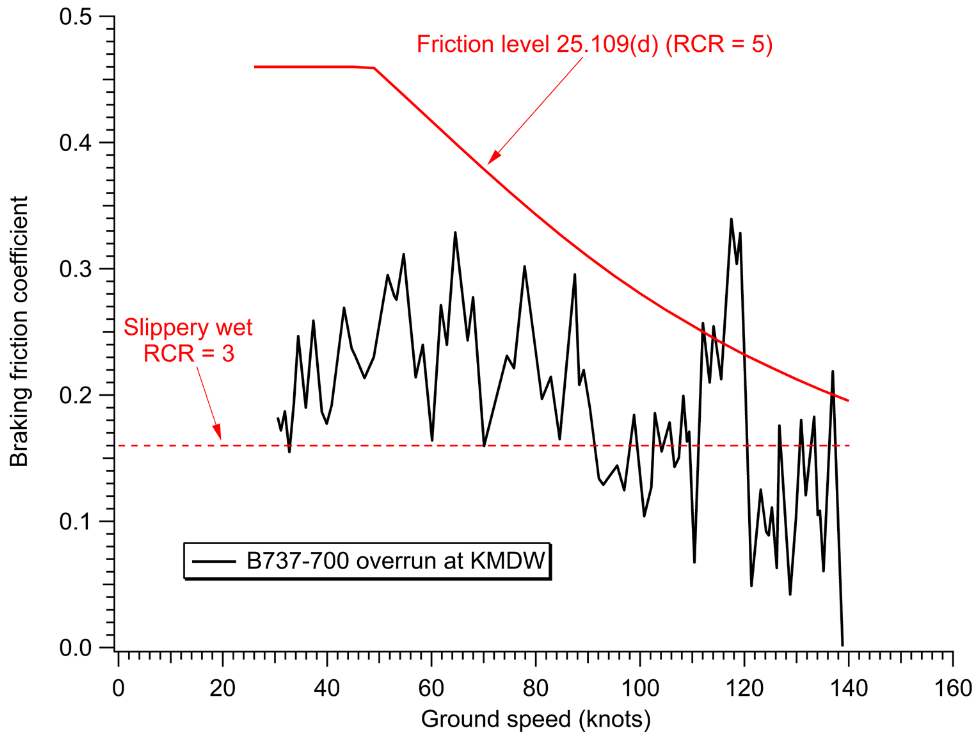

Figure 1: Example of a low wheel braking friction coefficient achieved by a B737-700 on a grooved wet runway (source: NTSB)

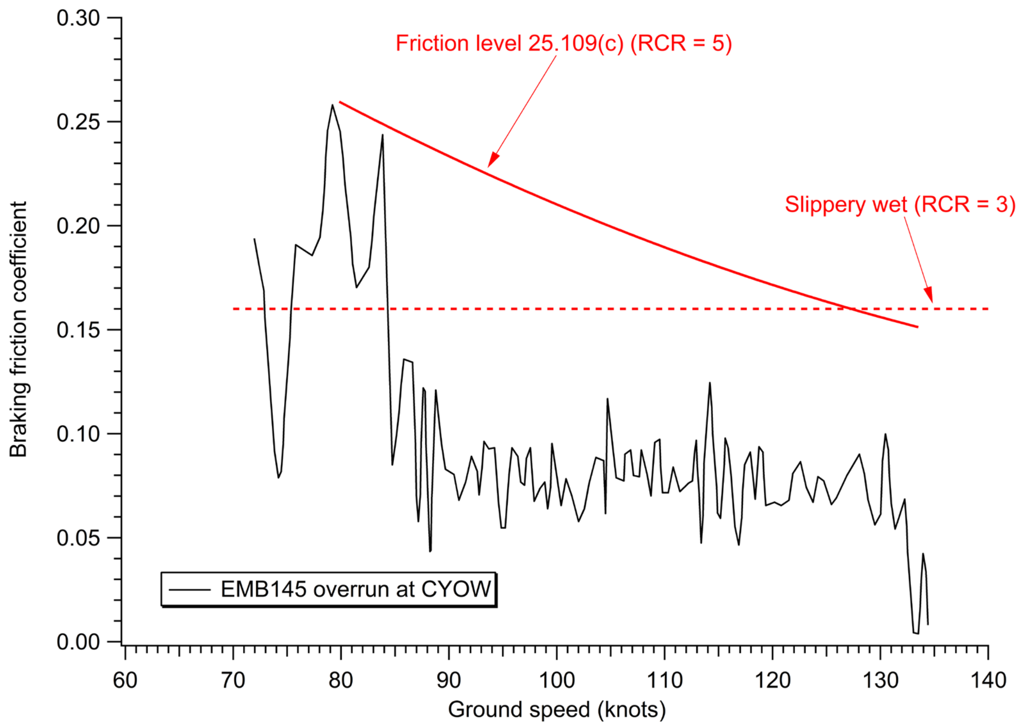

Figure 2: Example of a low wheel braking friction coefficient achieved by a EMB145 on an ungrooved wet runway (source: TSB Canada)

The macro texture depths of the runways in both examples shown in Figure 1 and Figure 2 were not critically low. The overrun involving the B737-700 occurred on a grooved runway with an equivalent macro texture depth in the order of 1.1-1.4 mm. The average macro texture depth of the (ungrooved) runway involving the EMB145 was 0.84 mm. The standard curves provided by the regulations are based on runways having an average macro texture depth of 0.25 mm for smooth[5] runways and 1.01 mm for grooved/porous friction course runways[6]. These macro texture depths in combination with the low water film depths (estimated between 0.3-1.0 mm) should have resulted in braking friction levels achieved by both aircraft close to or in exceedance of those predicted by the regulatory curves. The water depths on the runway were estimated to be much less than 2-4 mm above which dynamic hydroplaning normally can become very dominant. Large areas with significant rubber deposits were not found on the runway. As brakes and anti-skid systems worked as designed in the two examples, and the tires showed only signs of normal wear[7], a (partly) smooth micro textured runway surface seems a plausible explanation for the low braking friction levels

[5] The expression 'smooth' used in the regulations refers to a runway with a low macro texture depth.
[6] Non-grooved runways can also have macro texture depths of more than 1 mm. However, these runways are consider smooth runways in the regulations. Still these runways are able to achieve friction levels equal or better than grooved/porous friction course runways.
[7] The standard wheel braking friction coefficient curves provided in 25.109 account for normal tire wear.

found in these two landing overruns. This is also confirmed by the fact that low braking friction continued down to low ground speeds which is a typical characteristic of viscous hydroplaning (see appendix B). The two examples presented here, occurred under similar conditions as found in many other aircraft overruns on wet runways which showed worse than expected braking friction levels. Another factor often noticed was that results obtained with runway friction testers did not justify a maintenance action or a 'slippery wet' warning. This problem will be discussed in more detail later in this paper.

As explained in appendix B, the role of runway micro texture is associated with viscous hydroplaning. Unlike dynamic hydroplaning, only a thin water film is needed for viscous hydroplaning to occur. Viscous hydroplaning can already develop at low ground speeds whereas dynamic hydroplaning can become dominant on a very wet surface as ground speed increases. The commonly held view that a sharp micro texture is required for low speed conditions and that a good macro texture may in some sense substitute for micro textural sharpness at high speeds, is not correct. Micro textural sharpness is required for the entire speed range from low to high, while at medium to high speeds a macro texture of high drainage efficiency is additionally required[8]. A sharp micro textured runway surface is essential to avoid or to minimise viscous hydroplaning. Low braking friction levels that continue down to low speeds are a clear indicator of viscous hydroplaning.

It is often believed that a grooved runway can help to prevent viscous hydroplaning. During the early development of grooved runways such claims were made without any hard evidence. Sometimes accident investigators have stated in their findings and recommendations that the runway should have been grooved in order to obtain better friction capabilities whereas the low friction was caused by a smooth micro textured runway surface. Similar to the circumferential grooves on the tires themselves, the edges of the grooves in a runway are not effective in providing peak pressures that can break down the thin water film. A grooved runway will help to alleviate dynamic hydroplaning and will also help to drain the runway much quicker. However, the grooves themselves will not prevent viscous hydroplaning. The surface in-between the grooves therefore needs to have a sharp micro texture. This surface can become damp at low rainfall intensities. Damp surfaces are sufficient to cause viscous hydroplaning whenever the micro texture is smooth. There are numerous examples of overruns on wet grooved runways in which much lower braking friction

[8] Lees, G. et. al. The design and performance of high friction dense asphalts, Transportation Research Record No. 624, Skidding Accidents--which contains ancillary papers to the proceedings of a conference conducted by the Transportation Research Board, May 2-6, 1977.

levels were found than predicted by the regulatory models which clearly demonstrates that a grooved runway does not prevent viscous hydroplaning.

Assessment of runway micro texture – current practice

ICAO assumes that micro texture is a built-in quality of the runway pavement surface. This also applies to the surface between the grooves on a grooved runway. Polishing of the runway surface will normally occur making the micro texture smoother over time[9]. Also the build-up of rubber deposits can reduce the micro texture. It is important that airports can monitor this degradation of the micro texture. At this moment there are no acceptable methods for assessing the runway micro texture. Indirect measurements or human observations are used instead. A number of the most common methods applied are discussed next.

The most simple method is by visual inspecting or touching the surface. A visual inspection does not always provide a good indication that the runway surface has a smooth micro texture. Although rubber deposits are easily spotted in the touchdown zone, the build-up of rubber also occurs further down the runway which is usually not visible to the naked eye. Simply touching the surface is sometimes suggested to get some idea of the micro texture level. Very smooth micro textured surfaces could be identified in this way. However, it is still very subjective and substandard surfaces cannot be identified this way.

Runway friction testers, also known as Continuous Friction Measuring Equipment (CFME), together with measurements of the runway macro texture, are used to monitor the friction levels of runways. 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. ICAO does not 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. 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. Such detailed inspection specifications for the macro texture depth are not available for the micro texture due to the lack of acceptable measuring methods, thresholds and metrics. Instead there is reliance on runway friction testers to fulfil this task. Results from these devices are compared to pre-defined thresholds for new runway designs, maintenance and slippery when wet warnings. A “slippery wet” may be issued whenever a significant portion of a runway drops below the Minimum Friction Level (MFL) as indicated in Table A-1 of ICAO Annex 14 or as determined by

[9] Resistance to polishing is expressed through the polish stone values (see ASTM D3319, CEN EN 1097-8).

the state. Similar guidelines are provided by e.g. FAA and EASA. This sounds like a perfect approach for assessing the state of the runway in relation to the runway condition assessment matrix (RCR 5 or RCR 3 when the runway is wet). Unfortunately, experience has shown that in a number of landing overruns the runway friction tester showed that the runway was complying with the minimum standards provided in e.g. ICAO Annex 14, whereas the aircraft was actually achieving much lower friction levels than expected by the regulatory models of 25.109. An example is shown in Figure 3. This shows braking friction coefficients as function of the position along the runway. Both the measurements by the runway friction tester (CFME) as well as the friction level achieved by the aircraft are shown. Note that these two sources of friction data should not be compared directly with each other! The friction tester results showed that the runway was well above the maintenance level and far above the level which would require the runway to be classified as slippery when wet in a NOTAM. However, the wheel braking friction coefficients achieved by the aircraft are below those assumed by the regulatory models[10]. This would have justified a runway condition code of 3 assuming a much lower wheel braking friction coefficient for performance calculations.

[10] Note that this overrun is still under investigation at the time of writing this paper. Results have been obtained from NTSB docket DCA19IA036. The operator in this overrun occurrence did not take credit for the grooved runway in their landing performance calculations. They assumed a smooth runway. The standard 25.109(c) friction curve for a smooth runway does compare well with the achieved friction levels (not shown here). However, in this paper the friction curves for a grooved runway are used to reflect the actual construction of the runway surface.

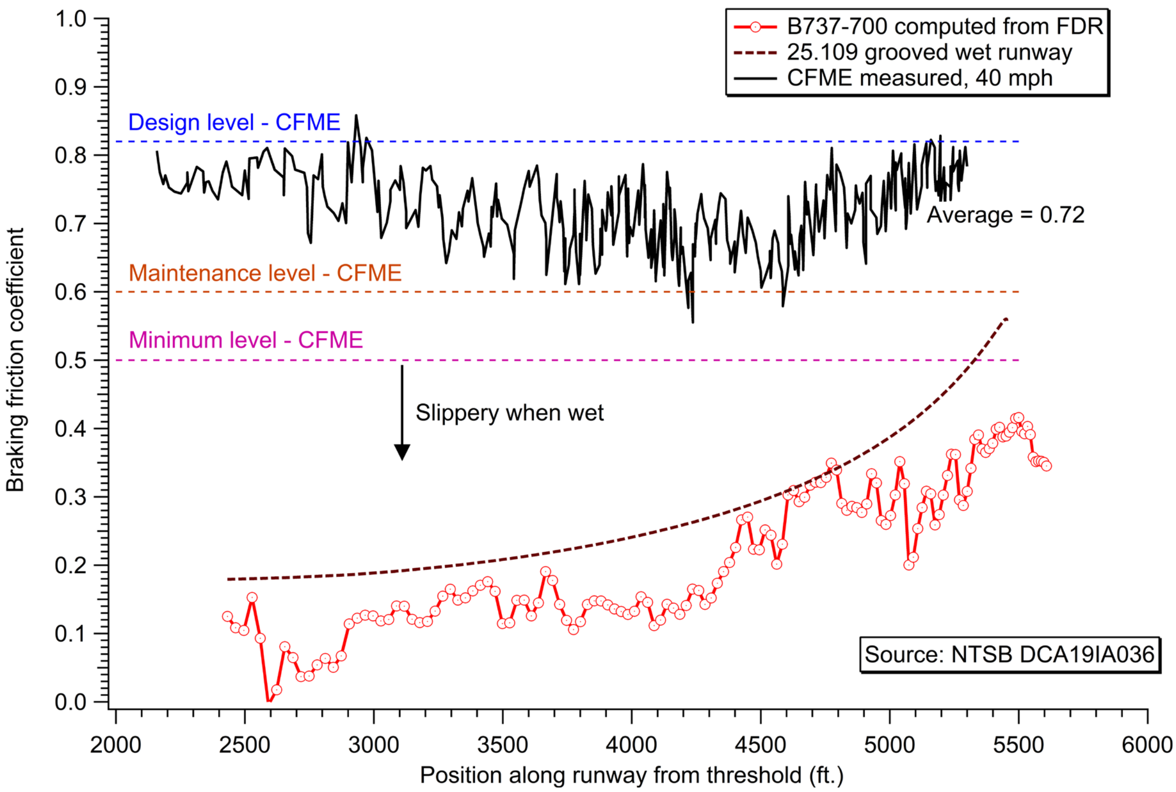

Figure 3: Runway friction as function of position along the runway (source: NTSB)

There are several reasons why runway friction testers sometimes give results which are well above the maintenance and minimum values whereas the aircraft is experiencing a much lower braking friction that would justify a slippery wet warning. There are a few obvious explanations such as no or incorrect calibration of the friction tester device, improper inflation pressure of the test[11] or drive tires, worn test or drive tires, tests conducted far from the actual wheel tracks (were 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 tire. These cause errors or variations in the measured friction values. Also pavement temperatures can cause variation in measured friction coefficients (up to 20-25% between summer and winter season). Some experiments[12] showed differences of more than 30% between the same type of friction tester (poor reproducibility) which could be attributed to one or more of the above mentioned factors. Just a worn test tire or 7% variation in inflation pressure itself can already result in a difference of more than 25-30% compared to results obtained with a new test tire or a tire

[11] Typically this is 20 or 30 psi depending on the device and should stay within ± 0.5-1 psi for correct friction measurements. Some devices use test tires inflated to 10 or 100 psi.

[12] See e.g. Dardano, J. Analysis of data collected at Australian Friction, 1st Australian Runway and Roads Friction Testing Workshop, 2003.; and Dardano, J. Australia's national friction testing programme, Surface Friction conference, 2005

inflated at the prescribed pressure[13]. A study conducted by Sydney Airport found that many airports were struggling with the poor repeatability[14] of runway friction testers[12]. Variability of some 15% in the results has been recorded[12]. There are also reports that even the manufacturer of the runway friction tester was unable to repeat the accuracy of measurements with the same device[15]. Strict adherence to the maintenance and operational requirements given by the manufacture should help to improve the repeatability and reproducibility. As one manufacturer states “a badly maintained or wrongly calibrated runway friction tester is worse than no friction tester”. However, in practice poor repeatability and poor reproducibility are still experienced.

These above mentioned factors do not always explain some of the high, optimistic friction values measured by runway friction testers. Another explanation comes from the effect of rubber deposits on the surface texture. It is well-known that friction levels will drop as rubber is build-up on the runway. The rubber deposits tend to fill and smooth the pavement macro texture and micro texture which will negatively affect runway friction on wet surfaces[16]. Low friction values are often measured in the touchdown zone by runway friction testers. In this area the highest concentration of rubber deposits on the runway is found affecting both macro and micro texture. In reality more rubber is deposited on the runway surface after the touchdown zone as aircraft tires wear more during the normal braking than during spin-up[17]. However, this rubber is more evenly spread and therefore often not clearly visible on the runway unlike in the touchdown zone. This rubber build-up usually has little influence on the macro texture unlike in the touch-down zone. However, the impact on the micro texture can be significant. Researchers[18] have measured the actual thickness of rubber deposits on a runway and correlated these results with measurements from a SFT runway friction tester. The results are shown in Figure 4 together with the design, maintenance and minimum level

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[13] Gerthoffert, J and Laïmouche, B. Friction Testing: Keeping friction measurements reliable, international airport review, 2013.

[14] The ability of several different devices of type and configuration to report the same friction value for the same surface is called reproducibility. The ability of a friction measurement device to produce the same measured value of the same surface, when measurement runs are repeated under the same conditions, is called the repeatability (see Transportation Development Centre, TP 14064E).

[15] Butterworth S., Runway Friction: The Airport Perspective, Manchester Airport, DGAC Workshop Runway Friction and Aircraft Braking, 2010.

[16] Horne, W. B., Evaluation of High-Pressure Water Blast With Rotating Spary Bar for Removing Paint and Rubber Deposits From Airport Runways, and Review of Runway Slipperiness Problems Created by Rubber, NASA TM-X-72797, National Aeronautics and Space Administration, Hampton, Virginia, 1975.

[17] The rubber deposition on runways is the result of wear of the tire surface. Tire wear depends largely on the amount of work done in skidding and is therefore influenced by the tire slip and friction levels. An aircraft tire spins up after contact with the runway in about 150 milliseconds. The work done in this very brief period is relatively small compared to that in the braked ground roll. Therefore the rubber deposition is small. However, as aircraft all land in the same touchdown area, rubber builds up much quicker than on other areas on the runway as braking of the tires will vary during the ground roll for each aircraft.

[18] Effect of Rubber Deposits on Runway Pavement Friction Characteristics, https://doi.org/10.3141/2068-13.

values specified by ICAO. Up to a rubber deposit thickness of 0.11 mm, the SFT measures friction values well above the ICAO maintenance level. This small amount of rubber is more than sufficient to affect the micro texture (which has amplitudes of typically less than 0.06 mm), making it much smoother. Even as the rubber deposit thickness is increased above 0.11 mm, friction values above the maintenance level were measured by the SFT. The results also show some significant scatter which is explained earlier in this paper. The reduction in friction measured by the SFT seems more to be the result of a decreasing macro texture depth rather than a smoother micro texture. This might explain that in some cases results obtained by runway friction testers do not indicate that the runway could be slippery when wet. Note that the braking friction force between a tire and a rubber contaminated surface in the dry contact zone is somewhat more complex and not always well understood[19]. However, this could lead (in theory) to higher friction values being measured by the runway friction testers.

Finally there could also be a problem with the minimum friction levels provided in ICAO Doc 9137. In ICAO Circular 355, the following statement is given: '*Doc 9137, Part 2, Table 3-1, has not been updated and reflects levels no longer considered unconditionally valid by ICAO ("Design objective for new surface" and "Maintenance planning level"). The minimum friction levels in this table reflect historic levels for the individual friction measuring devices identified and are not adjusted according to more recent comparisons of these devices.*' Basically ICAO states that the minimum friction levels to which the recordings of runway friction testers are compared, are no longer valid for the more recent produced devices of the same manufacturer listed in ICAO Doc 9137, Part 2, Table 3-1. This table was (partly) developed from tests conducted at NASA's Wallops Flight Facility in 1989[20]. Many devices used in these tests are no longer in production and newer versions are available. Tests conducted at the NASA friction workshops[21] showed that newer versions of a device can measure different friction levels than the older models on the same runway surface. Another issues lies within the sometimes poor repeatability of the results obtained with a

[19] Dissimilar materials in the dry that are subjected to contact lead to friction forces due to adhesion and hysteresis. Friction forces between similar materials are subject to a further source of force – known as cohesion.
[20] According to ICAO the minimum friction level MFL of a wet runway would be at which an aircraft using maximum wheel braking only would need twice the dry braked stopping distance during landing. However a State could also define what minimum friction level it considers acceptable before a runway is classified as slippery when wet and should publish this value in the State's AIP.
[21] The first annual NASA workshop was held in 1994 at NASA Wallops Flight Facility. There were six friction devices and six texture techniques on 18 different surfaces tested. At the eleventh annual workshop in 2004 there were 14 friction vehicles, 5 texture and 5 roughness measurement devices evaluating 33 different test surfaces.

friction tester (see e.g. Figure 4). The minimum friction levels provided by ICAO do not account for such issues.

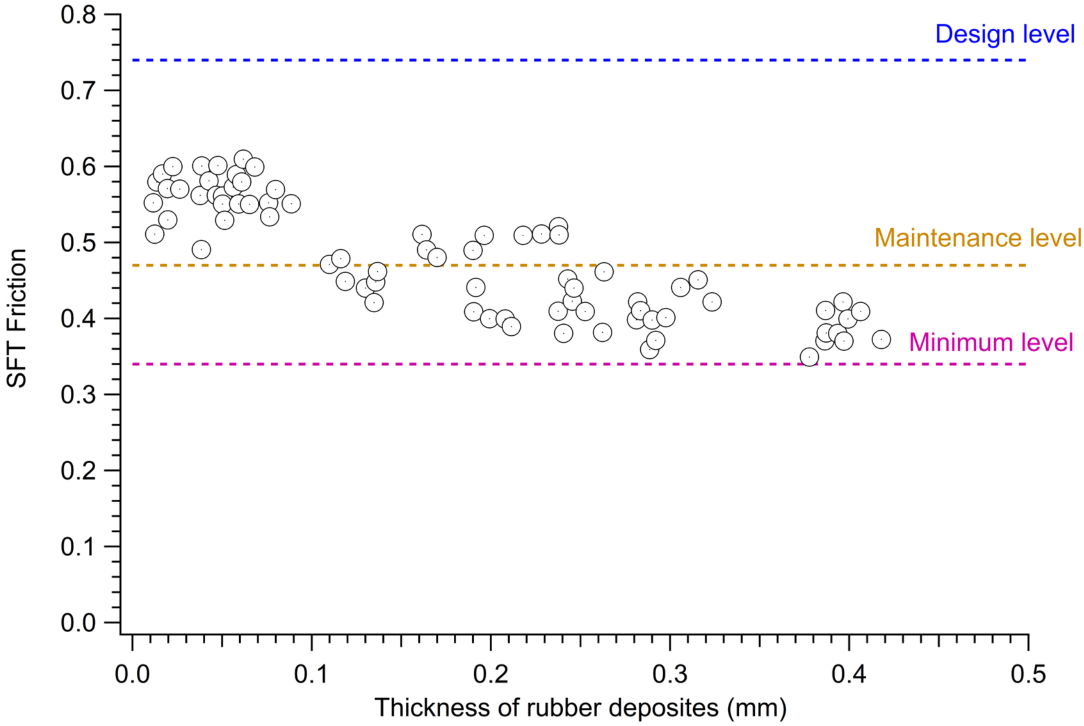

Figure 4: Relation between SFT friction tester results and thickness of rubber deposits on a runway (source: https://doi.org/10.3141/2068-13)

The British Pendulum Tester is a classical device for assessing surface friction. The British Pendulum Tester is a dynamic pendulum impact-type tester used to measure the energy loss when a rubber slider edge is propelled over a small wetted test surface. The measured value is termed the British Pendulum Number (BPN). The greater the friction between the slider and test surface, the more the swing through is retarded, and the larger the BPN. This number is commonly assumed to be representative of the friction component attributed to micro texture as the tests are conducted at relatively low speeds. Several standards are available for using this device. The device is often used in road and indoor floor surface friction assessments. The British Pendulum Tester can only make spot checks. The application of the British Pendulum Tester on runways is limited to mainly research purposes. Interesting is that for instance ICAO does not mention this device for assessing micro texture of runways. The British Pendulum Tester can sometimes give inconsistent results due to the variances in operator technique related to the improper or inconsistent calibration of the device before each test. Also the test conditions (levelness of the test surface, surface wind, wetness of test section etc.) can affect consistency of the results. This is often more of an issue when using the device in the open field than in a laboratory setup. This makes it harder for e.g. airport personnel to use a British Pendulum Tester. Thresholds have been defined for the British Pendulum Number for road surfaces. It is unclear if these minimum values can also be applied to runways. Of all available test devices used in the last 30-40 years, the British Pendulum Tester seems the most suitable to assess the micro texture. However, the use of the device and interpretation of the results can introduce difficulties to airport operators or to aircraft accident investigators.

Assessment of runway micro texture – new methods

Researchers have been trying to develop methods to assess the micro texture characteristics of hard surfaces like public roads for some time. In the 1960s the British Pendulum Tester was developed to assess friction properties of road surfaces. The results are considered to quantify micro texture. As explained earlier in this paper, it is not always easy to obtain consistent results with the British Pendulum Tester. In the 1980s studies were conducted to determine the micro texture characteristics of road surfaces using a microscope-based, automatic image analysis. Different micro texture parameters derived from this image analysis were correlated with measurements obtained with a British Pendulum Tester in a laboratory setup. Favourable correlations were found. However, a microscope-based system is only applicable in a laboratory environment. Other types of image analysis were also explored with limited success.

Texture measurements can be made using line laser scanner devices also known as laser texture scanners. These laser systems have hitherto been applied to the measurement of road and runway macro texture. Due to the resolution of these devices their application was limited to assessing the macro texture only. Compared to the sand or grease patch method that are also used to determine the macro texture depth, laser texture scanners give more consistent results as they are much less depended on operator use. In 1986, the Swedish Road and Traffic Research Institute already explored the feasibility of applying laser techniques to the measurement of road surface micro texture and concluded that the technique was feasible. However, commercial off-the-shelf high resolution surface laser scanners remained scarce and expensive. In recent years more affordable off-the-self high resolution laser texture scanners have come to the market. This has opened the opportunity for many more researchers to further explore the possibilities for assessing the micro texture characteristics of road surfaces. The results of most of these studies are very encouraging. As runways were not analysed in these studies, the Dutch Royal National Aerospace Centre NLR decided to acquire a high resolution laser texture scanner to study its potential for use on runway type of surfaces. This work started in 2018 under support from the Dutch CAA and the European Commission. A high resolution surface laser texture scanner was used on a variety of runway and road surfaces (considered to be representative for runways). The laser scans an area of

108 mm x 72 mm using a pre-set number of scan lines. The surface laser scanner used by NLR has a vertical resolution of 0.003 mm, a maximum length resolution of 0.00635 mm, and a maximum width resolution of 0.0247 mm. Scanning 15 lines takes about 1 minute to complete. Scan results can be downloaded on to a PC for further analysis using the accompanying software provided by the manufacturer. The data can also be exported as text files. As the standard software was not able to produce certain parameters related to the micro texture, special algorithms were developed by NLR to process the raw data file containing X, Y, Z values. These algorithms allowed the separation of the raw data into wavelengths representative for the macro and micro texture. An example of separating the raw laser trace in a micro and macro texture parts, by means of a forward/backward moving average low pass filter, is shown in Figure 5, for a single line scan on a runway surface.

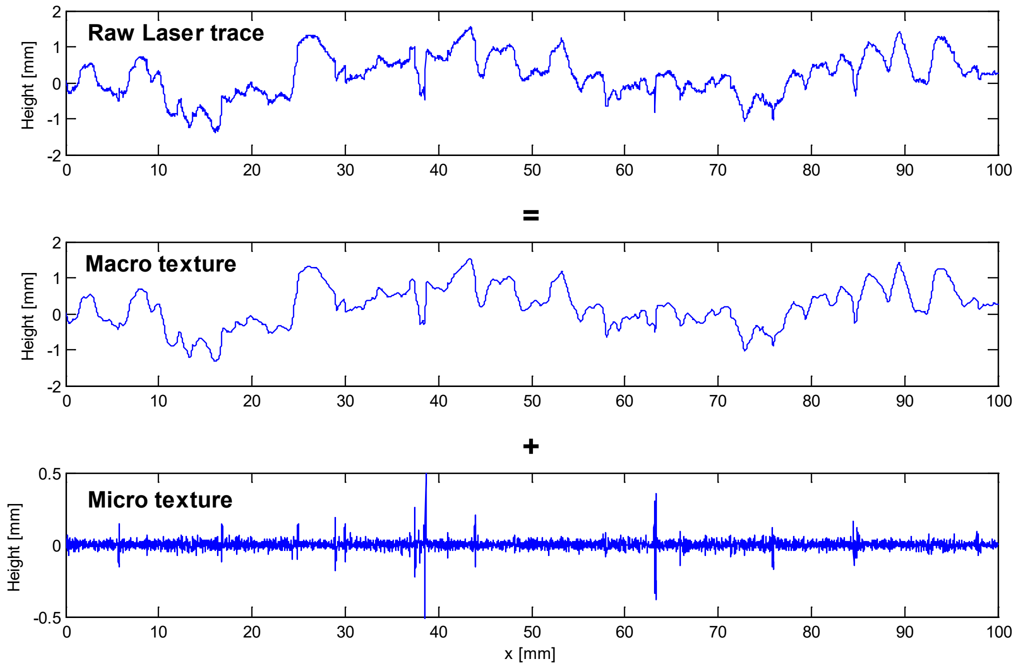

Figure 5: Example of separating the raw laser trace in a micro and macro texture parts (source: NLR)

Comparisons of different micro texture parameters derived from the laser scanner data were made with results obtained from British Pendulum Tester which was used on the same test surface. The measurements taken from the British Pendulum Tester were converted into a micro texture sharpness factor called F1 (developed by ESDU) and correlated with different micro texture parameters derived from the laser surface scans. The physics of the statistic F1 can be explained as follows. Assume that the protrusions in the micro texture be triangular with vertex upward. It may be supposed that a parameter is related in some way to the angle of that vertex. The angle of the vertex is radian when the micro texture is completely smooth. When the micro texture tends towards complete sharpness, then the angle of the vertex also tends to zero. It is therefore asserted that the range of the micro texture sharpness factor F1 is such that $0 \leq F1 \leq \pi$. High peak pressures are needed to overcome the viscous pressures in zone 2 of the contact area and to regain adhesion. As the angle of the protrusions in the micro texture reduces (hence the micro texture becomes sharper) the peak pressure increases. So low F1 values represent a sharp micro texture. As the sharpness reduces F1 increases up to a theoretical maximum of π.

An example of some test results is shown Figure 6. This figure shows the correlation between the micro texture sharpness factor F1 and the micro texture depth as determined from the laser scanner. The micro texture sharpness factors in this figure were derived from measurements taken with the British Pendulum Tester. Also some results obtained from flight tests are shown in the figure which were derived using a different model developed by ESDU. As shown the micro texture sharpness factor correlates reasonably well with micro texture depth. Some of the scatter in the data is caused by the British Pendulum Tester which does not always give consistent results. Other micro texture parameters have been analysed by NLR showing similar correlations with the micro texture sharpness factor.

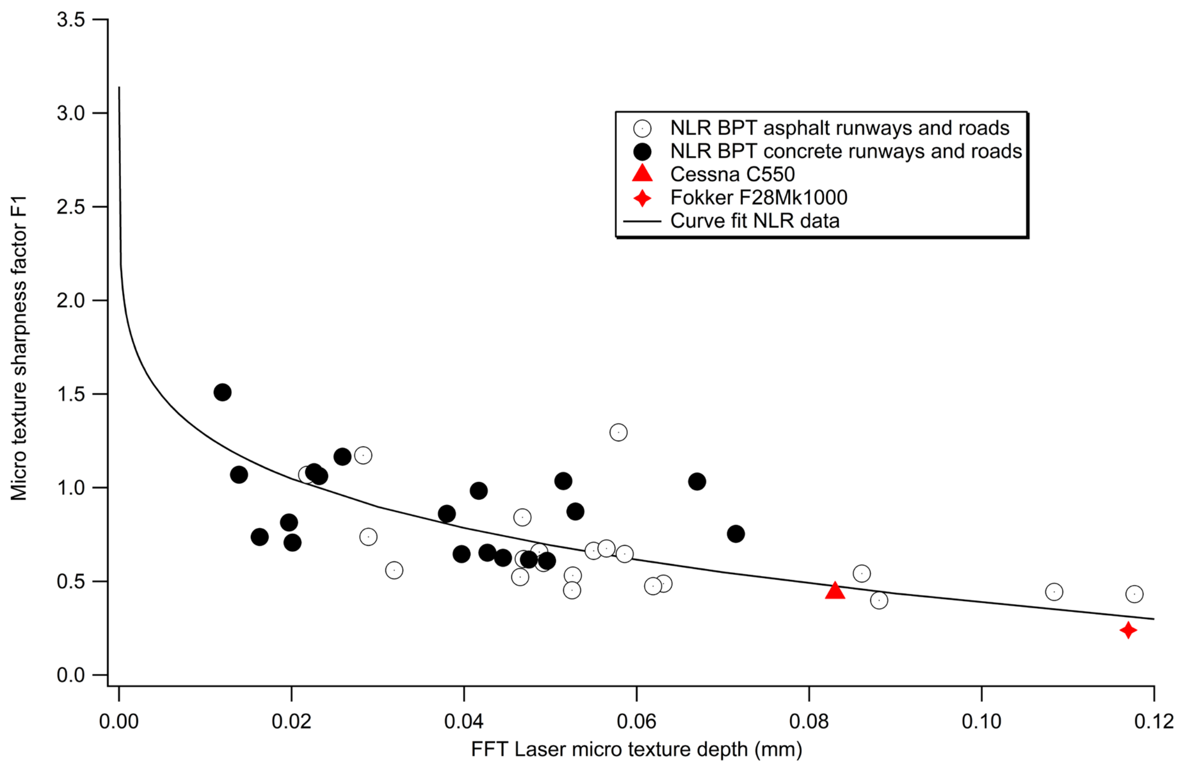

Figure 6: Example of correlation between micro texture sharpness factor and micro texture depth (source: NLR)

The results obtained so far using a high resolution laser scanner to assess micro texture on runways are very promising. More research is needed to gain additional experience. Laser data processing algorithms still need to be further improved and refined. Also the correlation between full-scale aircraft braking friction results on wet runways and laser scanner results should be assessed. Finally thresholds for minimum micro texture characteristics should be developed that can trigger a maintenance action or a slippery wet warning. Such research is planned by both EASA and FAA.

High resolution surface laser scanners are a promising tool that can aid accident investigators with their analysis of overruns on wet runways in identifying the contribution of micro texture (and also macro texture). It can also help airport operators to identify slippery wet runways and start maintenance actions early when needed.

Final remarks

Good aircraft tire braking friction on wet runways is of essential importance for safely stopping aircraft. Low runway braking friction often plays an important role in aircraft overruns on wet runways. Accident investigators are faced with several challenges when analysing such events. For instance the uncertainty regarding the actual wetness of the runway during the overrun is one of the difficulties investigators are confronted with. The role of the runway texture also has its own unique challenges. Investigators often struggle to determine the precise contribution of the runway texture, in particular the micro texture.

In a number of overrun accidents, the wet runway wheel braking friction coefficient as computed from the FDR was well below the levels expected from regulatory models. These accidents occurred on both ungrooved and grooved runways. A smooth micro texture was believed to have caused most of these differences seen. Currently accident investigators do not have the proper tools to assess runway micro texture characteristics which clearly hampers the investigation. British Pendulum Testers could be used to get some indication of the micro texture levels. However, the use of such device by accident investigators or airport operators is currently very limited to none at all. The British Pendulum Tester is also known for its difficult use (e.g. proper calibration) and sometimes gives variable results, making it not the ideal tool.

Recent developments in high resolution surface laser scanners have opened the opportunity to new ways for assessing micro texture characteristics of runways. This is beneficial to aircraft accident investigations but also for normal runway maintenance assessments. Further research into the application of high resolution laser surface laser scanners is still needed to gain more experience and develop thresholds. However, at this moment such a device could already be used in investigations to assess the micro texture related to overruns and also veer-offs on wet runways.

Appendix A: Extract from EASA CS25.109

(c) *The wet runway braking coefficient of friction for a smooth wet runway is defined as a curve of friction coefficient versus ground speed and must be computed as follows:*

(1) The maximum tire-to-ground wet runway braking coefficient of friction is defined as (see Figure 1A):

Tyre Pressure (psi)	Maximum Braking Coefficient (tyre-to-ground)
50	$\mu_{t/gMAX} = -0\cdot0350\left(\frac{V}{100}\right)^3 + 0\cdot306\left(\frac{V}{100}\right)^2 - 0\cdot851\left(\frac{V}{100}\right) + 0\cdot883$
100	$\mu_{t/gMAX} = -0\cdot0437\left(\frac{V}{100}\right)^3 + 0\cdot320\left(\frac{V}{100}\right)^2 - 0\cdot805\left(\frac{V}{100}\right) + 0\cdot804$
200	$\mu_{t/gMAX} = -0\cdot0331\left(\frac{V}{100}\right)^3 + 0\cdot252\left(\frac{V}{100}\right)^2 - 0\cdot658\left(\frac{V}{100}\right) + 0\cdot692$
300	$\mu_{t/gMAX} = -0\cdot0401\left(\frac{V}{100}\right)^3 + 0\cdot263\left(\frac{V}{100}\right)^2 - 0\cdot611\left(\frac{V}{100}\right) + 0\cdot614$

Figure 1A: maximum braking friction relations smooth runways

Where:

Tire Pressure = maximum aeroplane operating tire pressure (psi).

$\mu_{t/gMAX}$ *= maximum tire-to-ground braking coefficient*

V = aeroplane true ground speed (knots);

Linear interpolation may be used for tire pressures other than those listed.

(2) (See AMC 25.109(c)(2) The maximum tire-to-ground wet runway braking coefficient of friction must be adjusted to take into account the efficiency of the anti-skid system on a wet runway. Anti-skid system operation must be demonstrated by flight testing on a smooth wet runway and its efficiency must be determined. Unless a specific anti-skid system efficiency is determined from a quantitative analysis of the flight testing on a smooth wet runway, the maximum tire-to-ground wet runway braking coefficient of friction determined in subparagraph (c)(1) of this paragraph must be multiplied by the efficiency value associated with the type of anti-skid system installed on the aeroplane:

Type of anti-skid system	Efficiency value
On-off	0·30
Quasi-modulating	0·50
Fully modulating	0·80

(d) *At the option of the applicant, a higher wet runway braking coefficient of friction may be used for runway surfaces that have been grooved or treated with a porous friction course material. For grooved and porous friction course runways,* *(1) 70% of the dry runway braking coefficient of friction used to determine the dry runway accelerate-stop distance; or*

(2) (See AMC 25.109(d)(2).) The wet runway braking coefficient of friction defined in sub-paragraph (c) of this paragraph, except that a specific anti-skid efficiency, if determined, is appropriate for a grooved or porous friction course wet runway and the maximum tire-to-ground wet runway braking coefficient of friction is defined as (see Figure 2A):

Tyre Pressure(psi)	Maximum Braking Coefficient (tyre-to-ground)
50	$\mu_{t/gMAX} = 0\cdot147\left(\frac{V}{100}\right)^5 - 1\cdot05\left(\frac{V}{100}\right)^4 + 2\cdot673\left(\frac{V}{100}\right)^3 - 2\cdot683\left(\frac{V}{100}\right)^2 + 0\cdot403\left(\frac{V}{100}\right) + 0\cdot859$
100	$\mu_{t/gMAX} = 0\cdot1106\left(\frac{V}{100}\right)^5 - 0\cdot813\left(\frac{V}{100}\right)^4 + 2\cdot13\left(\frac{V}{100}\right)^3 - 2\cdot20\left(\frac{V}{100}\right)^2 + 0\cdot317\left(\frac{V}{100}\right) + 0\cdot807$
200	$\mu_{t/gMAX} = 0\cdot0498\left(\frac{V}{100}\right)^5 - 0\cdot398\left(\frac{V}{100}\right)^4 + 1\cdot14\left(\frac{V}{100}\right)^3 - 1\cdot285\left(\frac{V}{100}\right)^2 + 0\cdot140\left(\frac{V}{100}\right) + 0.701$
300	$\mu_{t/gMAX} = 0\cdot0314\left(\frac{V}{100}\right)^5 - 0\cdot247\left(\frac{V}{100}\right)^4 + 0\cdot703\left(\frac{V}{100}\right)^3 - 0\cdot779\left(\frac{V}{100}\right)^2 - 0\cdot00954\left(\frac{V}{100}\right) + 0\cdot614$

Figure 2A: maximum braking friction relations grooved/PFC runways

Where:

Tire Pressure = maximum aeroplane operating tire pressure (psi).

$\mu_{t/gMAX}$ *= maximum tire-to-ground braking coefficient*

V = aeroplane true ground speed (knots);

Linear interpolation may be used for tire pressures other than those listed.

Appendix B Wet runway braking friction - theory

The level of friction between a tire 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 tire 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 tire-runway contact, tire braking friction under this condition drops to values significantly lower than on a dry runway. Water pressures developed on the surface of the tire 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 tire. However, the factors influencing both types are different.

To better understand the influence of both types of hydroplaning conditions on tire friction, the contact surface of the tire and the ground is divided into three zones. Figure 1B illustrates the three zones under a tire footprint of a braked tire moving on a wet surface. This way to describe wet surface braking of a tire was first proposed by Gough[22]. In zone 1 the tire 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 tire and the surface.

[22] Gough, V. E. "Friction of rubber on lubricated surfaces-contribution to discussion of paper by Tabor, D.," Revue Générale du Caoutchouc, 1959, Vol. 36, No. 10, pp.1409.

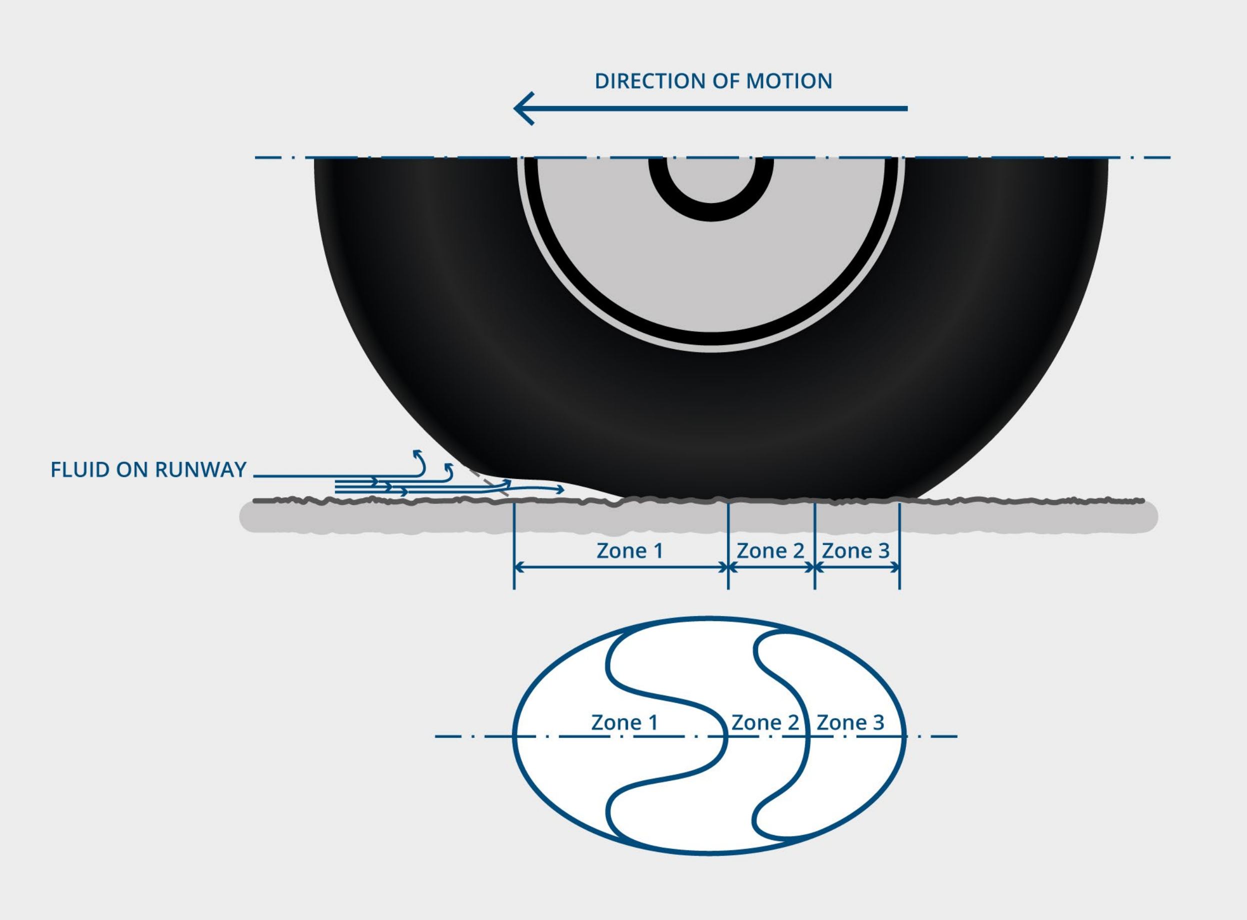

Figure 1B: Zones of a tire footprint when rolling along a wet surface (source: NLR).

In zone 1 much of the water is ejected as spray and squeezed through the tire's tread and the runway texture. Hydroplaning in zone 1 is the result of the dynamic hydrodynamic forces developed when a tire rolls on the water covered surface (hence the name dynamic hydroplaning). This is a direct consequence of the tire 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 tire footprint and a change in momentum of the water layer creates a hydrodynamic upward force. The magnitude of the hydrodynamic force and therefore the size of zone 1, varies with the square of the tire forward speed and with the density of the fluid. Dynamic hydroplaning is also influenced by a number of other factors like tire inflation pressure, tire tread, water depth, and runway macro texture. Macro texture is the runway roughness formed by the large stones and/or grooves in the surface of the runway. It is specified in terms of an average macro texture depth which ranges from 0.20 to 1.80 mm for runway surfaces. 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 (hence the name viscous hydroplaning). The water film may have a thickness of as little as 0.01 mm. Due to the predominance of viscous effects this water film is difficult to dislodge. 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. The micro roughness has an amplitude ranging from 0.01 to 0.1 mm. Surface micro texture performs its function by providing a large number of sharp pointed projections that, when contacted by the tire tread, generate very high local bearing pressures. These intense pressures break down the thin water film and allow the tire to regain dry contact with the pavement surface texture. Unlike dynamic hydroplaning, 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 tire 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 tire-ground contract area. When a tire 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.

Viscous and dynamic hydroplaning may exist simultaneously. At low forward speeds, viscous hydroplaning will be more dominant than dynamic hydroplaning. As the forward speed increases dynamic hydroplaning can become more significant. However, this depends on the water film thickness and macro texture depth. For low water film depths (e.g. less than 1.0 mm) and runway surfaces with a reasonable macro texture depth (e.g. more than 0.8 mm), the influence of dynamic hydroplaning is small. The micro texture is very critical in such conditions and completely determines the level of braking friction that can be achieved. A small amount of rain might already be sufficient in such cases to cause slippery conditions.

Appendix C - Wet runway braking performance analysis - some recommended steps

In order to determine whether the runway was slippery wet in an overrun occurrence, a number of analysis steps should be taken involving the computation and assessment of the wheel braking friction coefficient. These are summarised as follows:

1. Compute the wheel braking friction coefficient using the information from the flight data recorder FDR. The aircraft manufacturer should be asked to do this analysis as they have all the required data and knowledge. However, some accident investigators choose to do this by themselves with help from the aircraft manufacturer (providing engine thrust and aerodynamic data). Note that some aircraft manufacturers compute an aircraft braking friction coefficient. It is recommended to ask for the wheel braking friction coefficient instead which is more useful;
2. Determine which parts of the ground roll involved a friction-limited condition. This can be determined by analysis of the recorded brake pressures. The analysis of the braking friction coefficients should only focus on the friction-limited part;
3. Assess the wetness of the runway[23]. Note that wetness can vary along the runway;
4. Compare the braking friction coefficients computed from the FDR with those predicted by the regulatory model (25.109). For wet smooth runway surfaces use 25.109(c) and for wet grooved or wet porous friction course runways use the standard curves given in 25.109(d). Interpolate the curves for the applicable tire inflation pressure[24]. For fully modulating anti-skid systems multiple the calculated maximum braking friction coefficients with a factor of 0.80 as per regulations. Higher efficiencies have been found during flight testing by aircraft manufacturers. The value of 0.80 could be considered as a lower limit. Whenever large parts of the runway at the location of the wheel tracks are believed to have been flooded (e.g. more than 3 mm of water), use the standard braking friction coefficients for contaminated runways defined in e.g. EASA AMC 25.1591[25].
5. Compare the friction-limited braking friction coefficients computed from the FDR with the friction values according to the regulations. Whenever the FDR computed braking friction coefficients are (well) below the friction coefficients according to regulations, a slippery wet

[23] See e.g. for more details: "Aircraft tire hydroplaning and how to analyse it in runway excursion events", Paper presented at the ISASI 2018 Seminar Dubai, United Arab Emirates.
[24] Great care should be taken when using inflation pressures that were measured after the overrun event. The tire inflation pressures could have been affected by the impact.
[25] Micro texture has little influence on braking friction on flooded runways. The current paper deals with wet runways only which is a runway with any visible dampness or water that is typically 3 mm or less in depth.

runway condition existed. As the conditions along the runway may vary in terms of runway wetness and runway texture, differences between the expected and achieved braking friction could also vary.