

# **Aircraft tyre hydroplaning and how to analyse it in runway excursion events**

By

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Paper presented at the ISASI 2018 Seminar Dubai, United Arab Emirates.

## **Summary**

Reduced friction between the tyres of an aircraft and the runway is a very common factor in runway excursions. On wet or flooded runways this reduction in friction is related to hydroplaning of the tyres. Determining if (and which type of) hydroplaning occurred during a runway excursion is not straightforward. Investigators often lack proper knowledge about the topic and sometimes use outdated or subjective methods for analysis. This paper discusses how, in an accident investigation, hydroplaning of aircraft tyres can be analysed using the data typically available to an investigator. Examples are discussed that show the different techniques that can be used.

## **Introduction**

The vast majority of takeoffs and landings is conducted on dry runways. Only a small portion is conducted on wet or flooded runways<sup>1</sup>. Statistics show that the likelihood of a runway excursion during takeoff or landing is much higher on wet or flooded runways than on dry runways. Extreme loss of tyre braking can occur during rejected takeoffs and landings of aircraft on wet or flooded runways. As a result the stopping distance increases significantly which could exceed the available runway length. Also loss of control is possible leading to runway veeroffs. The term hydroplaning, or aquaplaning, is used to describe this loss in traction on wet/flooded runways. It is not always easy for accident investigators to determine if and how hydroplaning contributed to an accident. This paper discusses how, in an accident investigation, hydroplaning of aircraft tyres can be analysed using the data typically available to an aircraft accident investigator.

## **Hydroplaning and its impact on braking friction of aircraft tyres**

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 traction 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<sup>2</sup>. 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, the contact surface of the tyre and the ground is divided into three zones. Figure 1 illustrates the three zones under a tyre footprint of a braked or a free rolling tyre moving on a wet or flooded surface. In zone 1 the tyre

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<sup>1</sup> A runway can be considered flooded when more than 25 percent of the runway surface area (within the reported length and the width being used) is covered by water that is more than 3 mm in depth. This is then called a water contaminated runway or flooded runway. For water depths between 0.25 and 3 mm a runway is considered wet.

<sup>2</sup> A very special case of hydroplaning is called reverted rubber hydroplaning. This can occur during heavy braking on wet/flooded runways with a prolonged locked-wheel skid. Reverted rubber hydroplaning occurs less than before the 1980s due to improvements in antiskid systems. Reverted rubber hydroplaning is not further discussed in this paper since it is not truly hydroplaning and its presence during an accident can easily be detected by examining the tyres for certain spots.

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. Each zone in the footprint is discussed in more detail below.

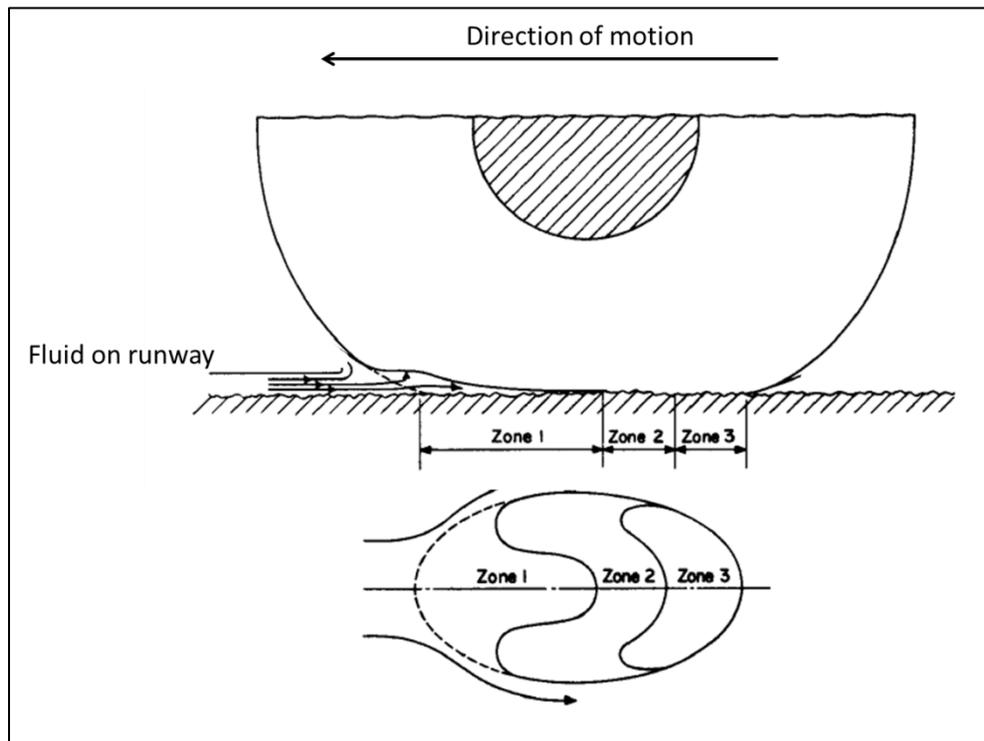


Figure 1: Zones of a tyre footprint when rolling along a wet/flooded surface.

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 hydrodynamic forces developed when a tyre rolls on a water covered surface. This is a direct consequence of the tyre impact with the water which overcomes the fluid inertia. The magnitude of the hydrodynamic force varies with the square of the tyre forward ground speed and with the density of the fluid. The contact pressure developed between tyre tread and pavement establishes the escape velocity of bulk water drainage from beneath the footprint. High inflation pressure tyres can therefore drain surface water more readily from the footprint than low inflation pressure tyres due to the higher water escape velocities. With increasing ground speed zone 1 extends further back into the contact area. At a certain (high) ground speed, zone 1 can extend throughout the contact area. Zone 2 & 3 then no longer exist and the tyre becomes completely detached from the ground. This is called full dynamic hydroplaning. The critical ground speed at which

this condition occurs is referred to as the dynamic hydroplaning speed. When the condition of full dynamic hydroplaning is reached, the tyre normally stops rotating (spin-down). Dynamic hydroplaning is influenced by a number of factors like tyre inflation pressure, tyre tread, water depth and runway macrotexture. Macrotexture is the runway roughness formed by the large stones and/or grooves in the surface of the runway (see illustration in Figure 2). The macrotexture provides escape channels to drain bulk water from zone 1. The drainage channels are provided by the tyre tread draping over the asperities of the pavement surface texture leaving valleys between the tyre tread and the low points of the surface texture through which bulk water can drain out from under the tyre footprint. The bulk water drainage through the macrotexture delays the build-up of fluid dynamic pressure to much higher speeds than the speeds found for pavements with no or little macrotexture. The tyre tread grooves in the tyre footprint are vented to atmosphere and provide escape channels for the bulk water trapped in zone 1. The tyre tread grooves act similar to the pavement macrotexture in draining the bulk water. When there is sufficient macrotexture on the surface and/or the tyre has a sufficient number of deep circumferential grooves, full dynamic hydroplaning will normally not occur, unless the water depth is at a level that both tyre grooves and runway macro texture cannot drain the water sufficiently quick enough. Partly dynamic hydroplaning can occur even if there is sufficient macrotexture depth or small amounts of water. However, its influence on traction is then limited. Dynamic hydroplaning is strongly dependent upon the forward speed. The dynamic pressure build-up varies with the square of the speed. At lower speeds the influence of dynamic hydroplaning (hence the size of zone 1) quickly reduces.

**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). Viscous hydroplaning typically occurs on wet/flooded runways that have a smooth microtexture. Microtexture 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 (see illustration in Figure 2). Pavement microtexture performs its function by providing the surface a large number of sharp pointed projections that, when contacted by the tyre tread, generate very high local bearing pressures. This intense pressure quickly breaks down the thin water film and allows the tyre to regain dry contact with the pavement surface texture. Viscous hydroplaning can start at very low ground speeds. Also the water depth needed for viscous hydroplaning is much less than that for dynamic hydroplaning. A thin film of water is sufficient. The pressure build-up in zone 2 is also much less dependent on ground speed compared to the pressure build-up in zone 1. In absence of zone 1 the area of zone 2 remains fairly constant throughout the speed range. This means that its impact on traction is also more or less constant down to low speeds in the order of 20-30 kt. For

runways with a harsh microtexture, viscous hydroplaning is unlikely to occur as the microtexture penetrates and diffuses the thin water film. The area of zone 2 is relatively small or completely absent in this case. On runways with a smooth microtexture viscous hydroplaning can even occur on damp<sup>3</sup> surface conditions. The fluid pressures developed in zone 2 between tyre and ground increases as the fluid viscosity increases. The more viscous the fluid the more difficult it becomes for the tyre to squeeze the fluid from beneath the tyre and the surface. Therefore a high fluid viscosity enhances the possibility of viscous hydroplaning. When full viscous hydroplaning occurs, it is preceded by a wheel spin-down. As indicated a harsh microtexture is required to puncture and drain the viscous water film from the tyre/pavement interfaces that creates viscous water pressures beneath the tyre footprint in zone 2. Some additional thin film water drainage can be provided in zone 2 by the tyre tread design at the contact points between the pavement surface and tread rib. At these points, intense contact pressures are generated which can puncture and displace the water film in the same manner as the pavement surface microtexture. To be effective in draining the thin water film in zone 2, narrow slots or knife cuts in the rib surfaces are needed. Such rib designs are not on commercial aircraft tyres due to tread chunking or tread retention problems. The tyres on commercial jet aircraft always have smooth rib surfaces and the tread patterns solely consist of circumferential grooves. Circumferential grooves have a very small effect on removing the thin water film in zone 2. The effect is limited to the tread groove edges only. The actual depth of the circumferential grooves has no influence on viscous hydroplaning. In the end narrow slots or knife cuts in the rib surfaces are much more effective in draining the thin water film in zone 2 than circumferential grooves alone. In that context it is sometimes suggested that grooved runways can alleviate viscous hydroplaning. However, similar to the circumferential grooves on the tyres themselves, the edges of the grooves in a runway are not effective in providing pressures that can break down the thin water film.

**Zone 3** is a region of dry contact. In this zone the friction forces on the tyre are generated when the wheel is braked or yawed. The braking friction force 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 contact area. Therefore the smaller zone 3 gets, the lower the braking friction forces become. When a tyre is completely separated by a film of water the braking friction coefficient<sup>4</sup> for an aircraft tyre is very low as

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<sup>3</sup> NASA considers a runway to be damp when there is 0 to 0.25 mm of water on the surface. In Europe a runway is considered to be damp when the surface is not dry, but when the moisture on it does not give it a shiny appearance.

<sup>4</sup> Defined as the ratio of the friction force on the tyre and the tyre normal load.

fluids cannot develop shear forces of a significant magnitude. Test data show that the braking friction coefficient on aircraft tyres can be less than 0.10 in this condition.

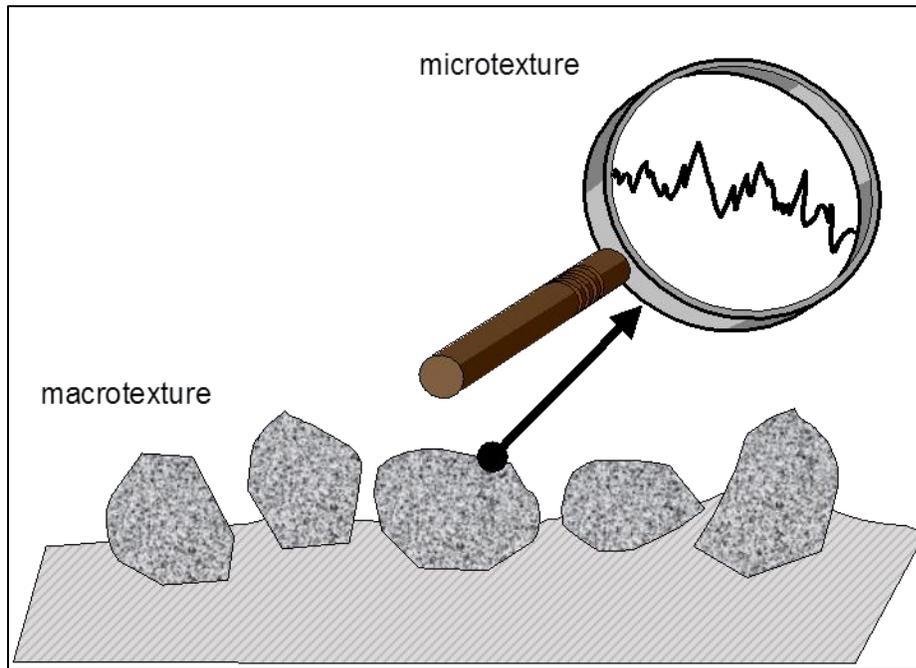


Figure 2: Illustration of macro- and microtexture on a runway surface.

On a wet/flooded surface the microtexture influences the tyre-runway braking friction starting from relatively low ground speeds up to the point where the runway macrottexture is mainly responsible for reducing friction at high speeds. This combined effect of runway textures is illustrated in Figure 3. The influence of the tyre-ground friction as function of ground speed is illustrated in this figure for different combinations of macro- and microtexture for both dry and wet surfaces. The slope of the friction/speed gradient curve is a function of macrottexture and the magnitude is a function of the microtexture. It is apparent that a pavement surface must possess both high macrottexture and a harsh microtexture to facilitate the relief of water trapped in the tyre/pavement contact zone in order to obtain good aircraft tyre traction during wet/flooded runway operations.

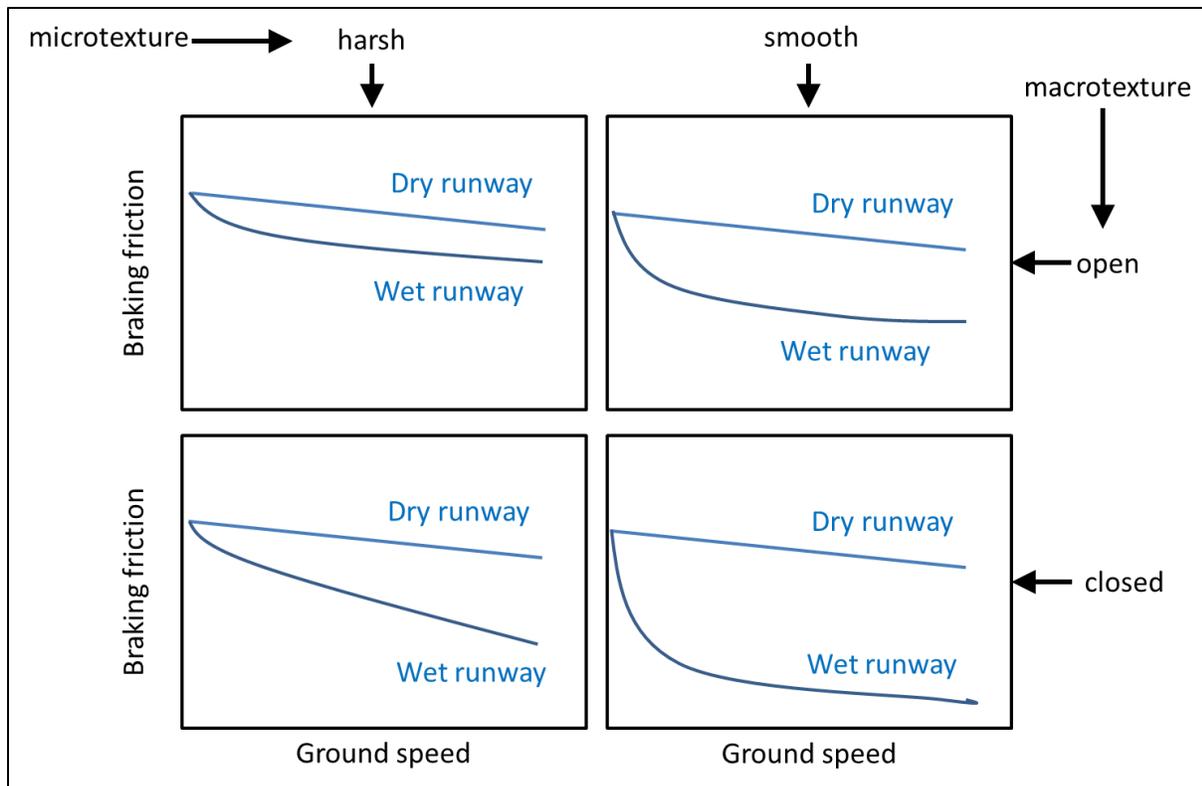


Figure 3: Influence of runway texture on tyre-ground braking friction as function of ground speed.

Although the physics of a braking tyre on a wet surface are similar to those on a flooded surface, the impact on the braking capability is normally much more significant on a flooded surface than on a wet surface because of the larger amount of water underneath the tyre footprint. This effect is most noticeable at high speeds when the dynamic pressure below the tyre surfaces is high and zone 1 becomes large. The size of zone 2 is much less dependent on the water depth and ground speed.

Figure 4 illustrates the braking friction coefficient as function of ground speed of a single tyre on dry, wet, and flooded surfaces. This clearly shows the large impact of a flooded surface on braking capabilities at high speeds.

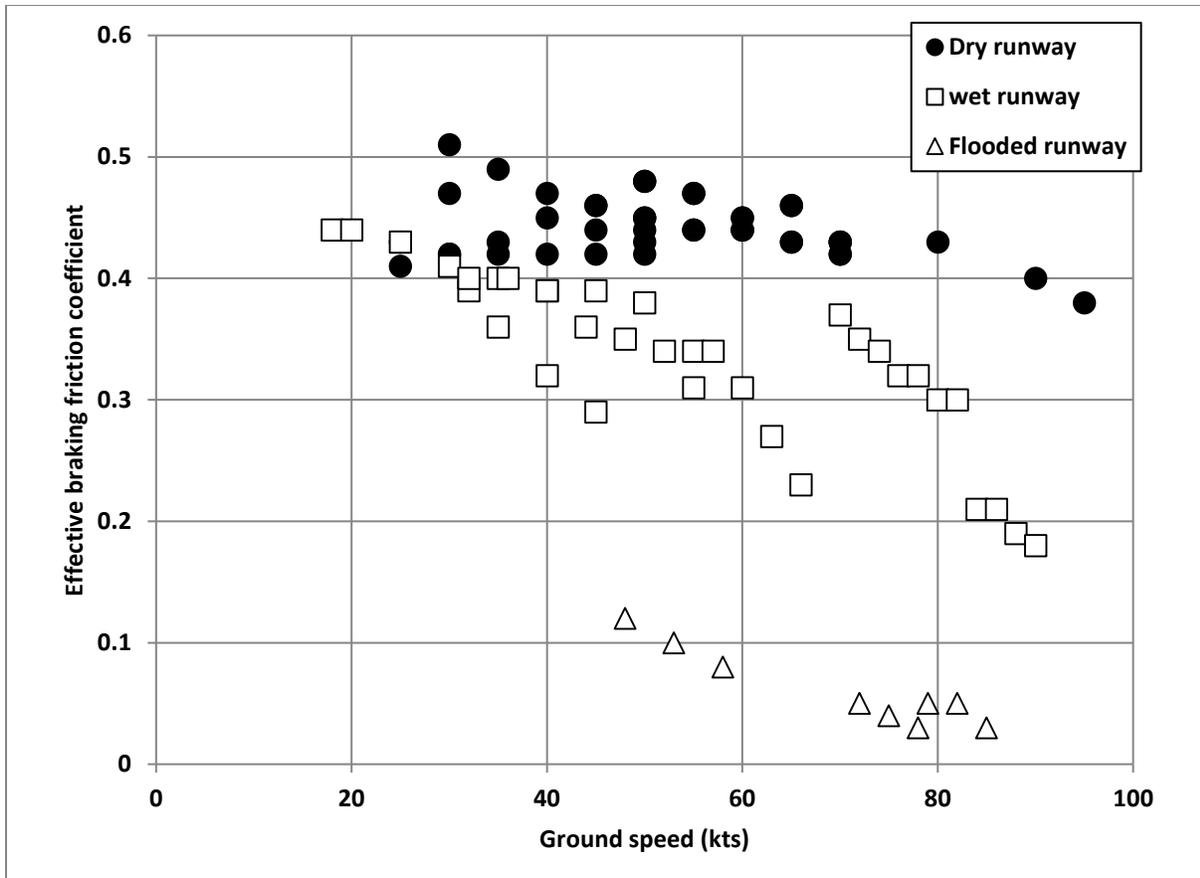


Figure 4: Comparison of the effective braking friction coefficient as function of ground speed on a dry, wet, and flooded runway for a B737-100 (source; NASA flight tests).

### Analysis of tyre hydroplaning in runway excursions

The previous section explained that hydroplaning of tyres comes in two different forms that can co-exist. It is also clear that various factors determine whether hydroplaning will occur and how significant its influence on the braking capabilities of a tyre will be. In this section guidance is provided that can be used to analyse the possible presence and influence of hydroplaning in an aircraft accident.

#### **Runway wetness**

The first thing that can be examined is how wet a runway actually was during the accident. This is not easy to answer since a number of factors play a role. The wetness of a runway is determined by the amount of rain falling, the duration of the rainfall, the macrotexture of the runway, the cross slope of the runway, the longitudinal slope of the runway and the surface wind. All these factors together determine how much water is build-up on top of the asperities of the runway surface. On a well-

constructed runway there is less water build-up near the centreline and more towards the runway edge. In the past simple empirical models have been developed to estimate the wetness of a road surface using many of the mentioned factors as input (except for surface wind). These empirical models are often not very accurate. However, they can be used to get an indication of the actual runway wetness at the time of the accident. Rain fall measurements at and around the time of the accidents should be retrieved from the meteorological office. The runways slopes and macrotexture depth can vary along the runway. This should be considered in the analysis since it could lead to local differences in the water depth (puddles). Security camera footage that has recorded the aircraft moving on the runway (or other video images) can also be used to get an idea of the runway wetness. While rolling on a flooded runway, significant spray will be coming off the nose and main gear tyres which should be visible on the video images. On wet surfaces this spray is much less visible and less intense. This information can be used (together with the estimated water depth) to determine how wet the runway was during the accident. Note that when thrust reversers are used on wing-mounted engines, the video images could be obscured, as the reversers tend to recirculate some of the water spray around the wing. This could provide a false indication of the actual wetness of the runway. During some accident investigations, water was manually put on a part of the runway using e.g. a hose with a controlled amount of water flowing through it to analyse the drainage characteristics. This does not simulate the way water is actual drained by the runway during periods of rainfall. For instance the water droplets falling on to the runway affect the turbulence levels in the water flow on top of the runway surface which influences the actual run-off.

### ***Runway texture***

It is important to have information on the runway surface characteristics when investigating wet/flooded runway related accidents. In particular the runway macro- and microtexture are of interest as both have a significant influence on hydroplaning and therefore on braking performance. An assessment of both surface micro- and macrotexture characteristics is necessary to fully relate tyre friction performance to pavement texture. Macrotexture can be measured using different techniques such as the sand patch method or by using lasers. Lasers have the advantage that large sections of the runway can be measured in a consistent way. The sand patch method is more labour intensive and can give inaccurate results even in the hands of an experienced user. Also amongst experienced users differences can exist in the sand patch results. Macrotexture depths of less than 0.5 mm or less typically make a runway more susceptible to dynamic hydroplaning. However, with sufficient rainfall

runways with a higher macrotexture depth can still experience dynamic hydroplaning. The microtexture is more difficult to determine for a runway surface. There is no direct measure available to define the fine-scale roughness of the individual aggregates in engineering terms (e.g. millimetres of texture depth just like for the macrotexture). Microtexture is hardly detectable to the eye. Instead it is sometimes simply determined from touching the surface. A good pavement microtexture has a sharp, harsh, gritty feel such as obtained when touching fine sandpaper. Unfortunately this is subjective and can only give an indication of the microtexture characteristics. However, experience has shown that runways with a smooth microtexture can be detected in this way. These are the most critical surfaces under wet conditions even when a runway was damp. New methods of analysing microtexture are being investigated e.g. those that make use of laser scanner devices. As these methods progress they could become a valuable tool to aircraft accident investigators. The British Pendulum Tester (BPT) is sometimes considered a method for measuring microtexture. However, the size and shape of the surface macrotexture can affect the BPT results. It should be understood that degradation of microtexture, caused by the effects of traffic, rubber deposits, and weathering, may occur within a comparatively short period when compared with the time required for degradation of surface macrotexture. Even a runway with a good macrotexture or a grooved runway can perform poorly under wet conditions if the microtexture is degraded.

### ***Runway friction testers***

Runway friction testers are often used to analyse the friction characteristics of a runway under wet conditions. They are often used as part of the runway maintenance program. Great care should be taken when using the results from such devices in an accident investigation. The results from those devices are sometimes inconsistent with what the aircraft had experienced or what would be expected from the surface texture. Friction testers can give incorrect or inconsistent results if they are not well maintained, not calibrated often enough or if tested with a wrong test tyre inflation pressure. Also due to the significant differences in the characteristics between the braking of the friction test tyre and that of full-scale aircraft in terms of, vertical loads, ground speed, tyre inflation pressure and anti-skid, there is no direct correlation between a friction tester and an aircraft braking on a wet or flooded runway. If runway friction testers are used in an investigation, it is important that the measurements are conducted at different speeds. The effect of unsatisfactory macrotexture and/or microtexture may not be found if the tests are made at only one speed. Finally friction testers are only able to measure on wet runways without significant water depths. On flooded runways testers cannot distinguish between the

contamination drag and the braking friction force on the test wheel and will therefore measure higher braking forces.

### ***Estimating full dynamic hydroplaning speed***

Dynamic hydroplaning is strongly influenced by the ground speed. At a certain speed the tyre footprint is completely separated by a film of water. The ground speed for this full dynamic hydroplaning condition (under spin-down conditions, e.g. rolling tyre) is often estimated by accident investigators using the classic NASA formula relating the dynamic hydroplaning speed (in kts.) with the tyre inflation pressure ( $p$  in psi) as  $9\sqrt{p}$ . Unfortunately this equation over-predicts the hydroplaning speed for modern aircraft tyres. This was already anticipated by some aircraft manufacturers which used a modified version of the classic dynamic hydroplaning equation for performance calculations during the late 70s. Following the analogy of the simple NASA equation, available full-scale experimental data suggest that a modern bias ply aircraft tyre would hydroplane (dynamically) on a well flooded runway at around  $8.5\sqrt{p}$ , a H-type aircraft tyre at around  $7.5\sqrt{p}$  and a radial aircraft tyre at around  $6.9\sqrt{p}$ , with the speed in knots and  $p$  in psi. These relations, in absence of other data, can be used for a first estimation of the spin-down, dynamic hydroplaning speed in absence of other data. For landing (tyre spin-up) no test data for modern aircraft tyres are available on the dynamic hydroplaning speeds. A reduction of the spin-down dynamic hydroplaning speed of 15% can be used as a first estimate based on NASA tests conducted in the 70s. Dynamic hydroplaning is generally associated with water depths greater than 0.1 inch (which is normally rounded up to 3 mm). However the critical depth depends on the characteristics of the tyre-pavement surface. Smooth tread tyres operating on smooth pavements surfaces require the smallest fluid depth for dynamic hydroplaning, whereas rib treads tyres operating on an open textured or grooved-pavement surface require the largest fluid depths. The equations given here can be used in an accident investigation to estimate the full dynamic hydroplaning speed for those cases in which the water depth exceeded the sum of the tyre groove depth and the macrotexture depth (rule-of-thumb). For smaller water depths full dynamic hydroplaning is unlikely to occur. Partial dynamic hydroplaning could be still possible.

### ***Wheel speed***

When a tyre is completely separated from the runway surface by a film of water it is possible that the unbraked wheels slow down or stop rotating completely. This can also happen during the braked condition as the anti-skid system will sense the tyre going into skid much quicker. Hydroplaning

protection systems could release the full brake pressure on a wheel that enters a full hydroplaning condition. The fluid lift force under the tyre causes the centre of pressure of the vertical ground reaction to move ahead of the wheel axle with increasing ground speed. This causes a spin-down moment. When near full hydroplaning this spin-down moment will exceed the total spin-up moment caused by all tyre drag forces and the tyre will start to spin-down and can come to a complete stop. Wheel speeds are rarely recorded on flight data recorders or quick access recorders. In the event that such data are available in an investigation they could give information if a full hydroplaning condition existed. If such data are not available indications of a low wheel speed can be derived from other sources that are linked to the wheel speed like the ground spoilers. The ground spoilers will normally only deploy if the wheel speed exceeds a certain threshold value. If the wheels are not rotating, the ground spoilers might not deploy or might even retract after being deployed initially. This situation can be identified using the flight data recorder.

### ***Estimating the braking friction coefficient***

If certain data from a flight data recorder are available, it is possible to determine the wheel braking friction coefficient that existed during the ground roll. Information on the wheel braking friction coefficient can help to determine if hydroplaning has occurred. As a minimum the engine speed (e.g. fan speed N1), thrust reverse selection (if installed), longitudinal acceleration, aircraft weight, aircraft configuration (flaps, ground spoilers, etc.) and (air and ground) speed are needed to estimate the wheel aircraft braking coefficient. Also needed are the engine thrust data and aerodynamic characteristics of the aircraft which can be obtained from the aircraft manufacturer. The longitudinal acceleration data from the flight data recorder need to be corrected for any biases and signalling noise (by filtering), and converted into the proper axis (e.g. from body to runway axis).

Although it is the wheel braking friction coefficient that is of main interest, the so-called aircraft braking friction coefficient is sometimes used instead. The aircraft braking friction coefficient  $\mu$  can be estimated using the following equation:

$$\mu = \frac{\text{Thrust (idle or reverser)} - \text{Drag} - \text{Longitudinal acceleration} \times \text{Aircraft mass}}{\text{Aircraft mass} \times g - \text{Lift}}$$

The aircraft braking friction coefficient  $\mu$  is calculated as function of ground speed. It includes the rolling resistance of the nosewheel and possible non-braked main wheels<sup>5</sup>. It is therefore not the true wheel braking friction coefficient. The centre of gravity is needed to derive the wheel braking friction from the flight data. This allows the estimation of the static normal loads on the nose and main gear wheels. In addition corrections to the static wheel normal loads should be made for aerodynamic moment, lift and the pitching moment by the thrust vector and or elevator to obtain the actual normal loads experienced during the ground roll. To differentiate between rolling resistance and wheel braking in the stopping forces on the aircraft, the rolling resistance forces need to be counted against the overall wheel stopping forces derived from the flight data. For the rolling resistance (of e.g. the nosewheel tyre) a value provided by the aircraft manufacturer can be used (typical 0.01-0.02).

Some accident investigators have derived braking friction values themselves with thrust and aerodynamic data obtained from the aircraft manufacturer. This analysis can also be done by the aircraft manufacturer which usually has more experience in doing these kinds of assessments. It is always important to understand whether the aircraft manufacturer provides the aircraft braking or the wheel braking friction coefficient. The aircraft braking coefficient includes the rolling resistance of the nosewheel. For analysis it is more convenient to have just the main gear wheel braking coefficient<sup>6</sup>.

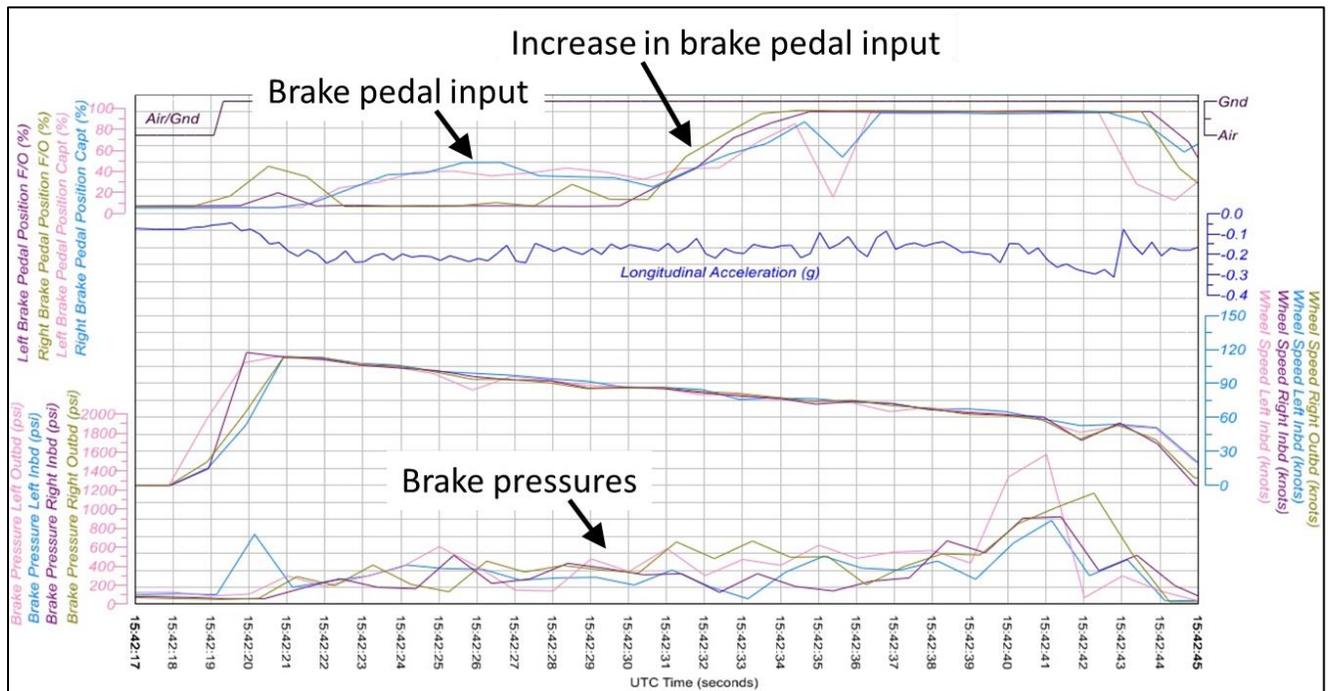
The wheel braking friction coefficient derived from the flight data should be plotted against the (ground) speed for further analysis. For reference it can be helpful to also have the dry runway wheel braking friction coefficients of the aircraft. This should be obtained from the aircraft manufacturer. The way the wheel braking friction coefficients vary with the speed characterise the type of hydroplaning that could have occurred. Wheel braking friction coefficients that are only low at high ground speeds (e.g. less than 0.10-0.15) and that quickly increase in value as ground speed decreases, are consistent with those cases in which dynamic hydroplaning was dominant (see also Figure 3). Wheel braking friction coefficients that remain low as the speed decreases are consistent to cases in which viscous hydroplaning was dominant (see also Figure 3). This last condition is directly related to runway surfaces with a poor microtexture. In the analyses of wheel braking friction it is important to know if there was a friction-limited condition. In

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<sup>5</sup> On some aircraft the rear wheels of the bogie gear have no brakes installed.

<sup>6</sup> For aircraft with multiple-bogie configurations, the rear wheels normally experience a different runway wetness condition than the front main gear wheels. These rear wheels run more on a damp runway surface than on a wet or flooded surface due to the displacement of the water by the front wheels.

such a case the anti-skid system is preventing the tyre to go into a skid by releasing the brake pressure. To know if such a condition existed, the brake pressures applied to the wheels need to be analysed. Flight data recorders do not always record these pressures. If recorded it is often only available at low sample rates (e.g. once per second). However, these brake pressure data can still be used for analysis. Figure 5 shows a typical data trace from a flight data recorder of an aircraft that landed on a flooded runway. Shown are a number of variables as function of time, including pilot brake pedal input and the anti-skid commanded brake pressures. It can be seen that initially one pilot applied about half the maximum pedal input. In a later stage both pilots applied braking and increased the pedal input to its maximum. However, as can be seen from the plots, the anti-skid commanded brake pressures do not increase following this maximum pedal input<sup>7</sup>. The anti-skid is controlling the brake pressures being applied to the brakes of all wheels by reducing the commanded brake pressure to stop the incipient skids from occurring. The low, cycling braking pressures seen in Figure 5 are typical for a tyre braking on a slippery runway in a skid-limited condition. Note that the flight data recorder in this example stored the brakes pressure only once per second. Internally the system works at 200 Hz for this particular aircraft. On slippery runways full brake application by the pilots is not necessary to enter a friction limited condition as illustrated in Figure 5.



<sup>7</sup> The brake pedal input and the commanded braked pressure do not always follow a linear correlation over the entire range of brake pedal deflections.

Figure 5: Example of an anti-skid working on a flooded runway (source: Colombia, Aeronautica Civil, Accident Report, HK 4536, 2010).

In a number of overrun accidents pilots have used the emergency parking brake as a last resource. This system will bypass the anti-skid system and could put maximum braking pressure on the wheels which could then lock. The parking brake selector is normally not recorded on the flight data recorder nor is the parking brake pressure. Also the actual pressure applied to the brakes is normally not available (only the anti-skid commanded brake pressure). Analysis of the cockpit voice recorders could help to determine whether the parking brake was used or not. Use of full parking brake will always result in a locked wheel condition. If this condition exists long enough, clear marks (flat spots) will be visible on the tyre.

#### **Example of a landing overrun accident on a wet runway**

The following example is used as an illustration of an analysis of tyre hydroplaning in an overrun accident. The accident concerns an Embraer EMB-145 that landed on Runway 07 at Ottawa/MacDonald-Cartier International Airport, and overran the wet runway. The nose and cockpit area were damaged when the nose wheel collapsed. There were thirty-three passengers and three crew members aboard. Two of the flight crew and one passenger sustained minor injuries. More details are provided in TSB Report Number A10H0004. This example is of interest since the investigators looked at several aspects that are also discussed in this paper.

Testing after the accident indicated that macrotexture depth on Runway 07/25 varied from 0.42 mm to 1.26 mm, with an average depth of 0.93 mm. The investigators considered the runway topography and the rain fall data at the time of the accident. These data were used together with an empirical water depth equation (the Texas Transportation Institute model of 1971<sup>8</sup>) to estimate the wetness of the runway. The accident investigators determined that the runway was wet (not flooded), with water depths typically between 1-2mm or less depending on the location on the runway. The combination of the tyre groove depth and macrotexture depth for the estimated water depth levels was such that full dynamic hydroplaning could not have occurred. Partial dynamic hydroplaning would only have had a

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<sup>8</sup> Texas Transportation Institute Research Report Number 138-5. Note that the empirical water depth model of 1971 was updated afterwards, showing different correlations than in the original version of the model. TSB and NTSB for instance have been using the original 1971 model.

small influence at high speeds considering the macrotexture depths. Figure 6 shows the aircraft braking coefficient as function of speed (IAS), as derived from the flight data recorder from an EMB-145 by the accident investigators. The aircraft departed the runway at around 70 kts. The data from Figure 6 clearly show that the aircraft braking friction coefficient hardly changes as speed reduces which supports the conclusion that dynamic hydroplaning was not a factor (see also Figure 3). During viscous hydroplaning the wheel braking friction coefficient typically varies between 0.05-0.15. The friction levels were between 0.05 and 0.10 during the landing overrun. Note that the data shown in Figure 6 are not the wheel braking friction coefficients but the aircraft braking coefficients. The wheel braking friction coefficients would be somewhat higher than the aircraft braking friction coefficients (roughly 15-20% higher in this case which would still be in the range of 0.05-0.15). It is interesting to compare Figure 6 with the data shown in Figure 7. In Figure 7 the aircraft braking friction coefficient for another EMB145 is shown as function of ground speed, however, now on a smooth, but flooded runway surface. Clearly dynamic hydroplaning was a factor in this case as there is a significant variation of the friction with the speed visible, unlike what is shown in Figure 6.

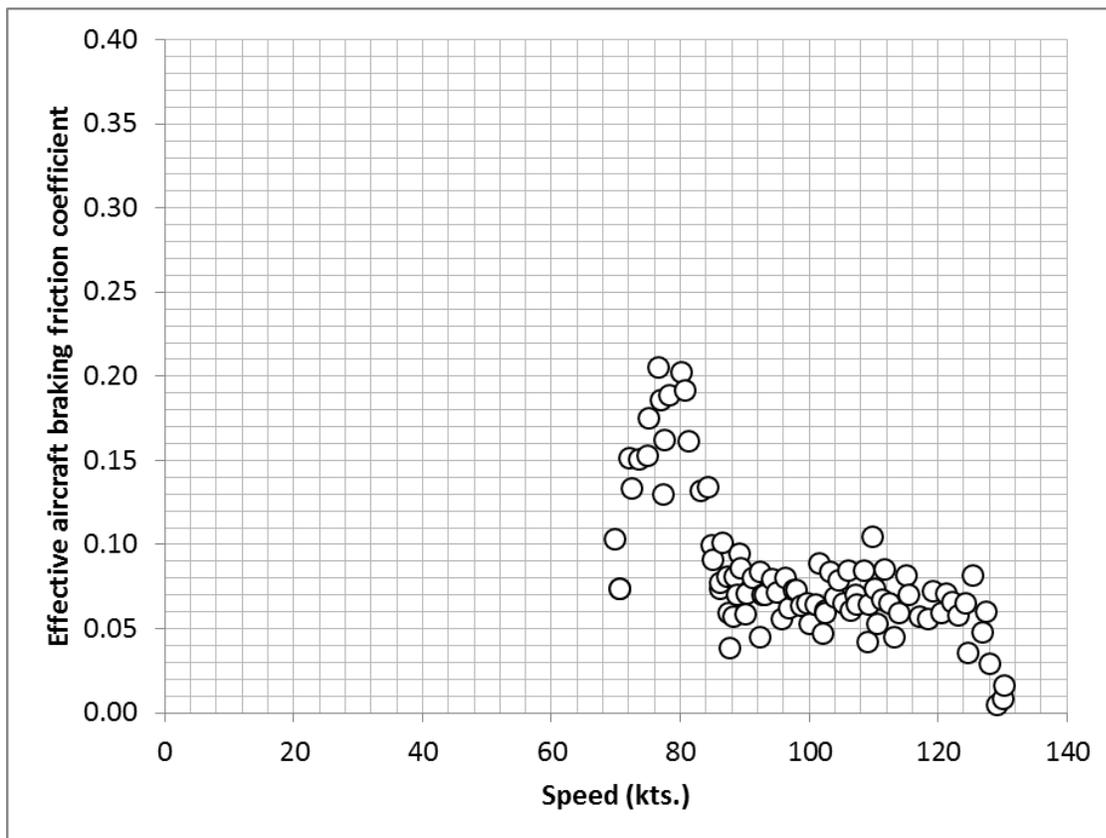


Figure 6: Effective aircraft braking friction coefficient as function of speed on a wet runway (source: Transport Safety Board, Canada, Report A10H0004).

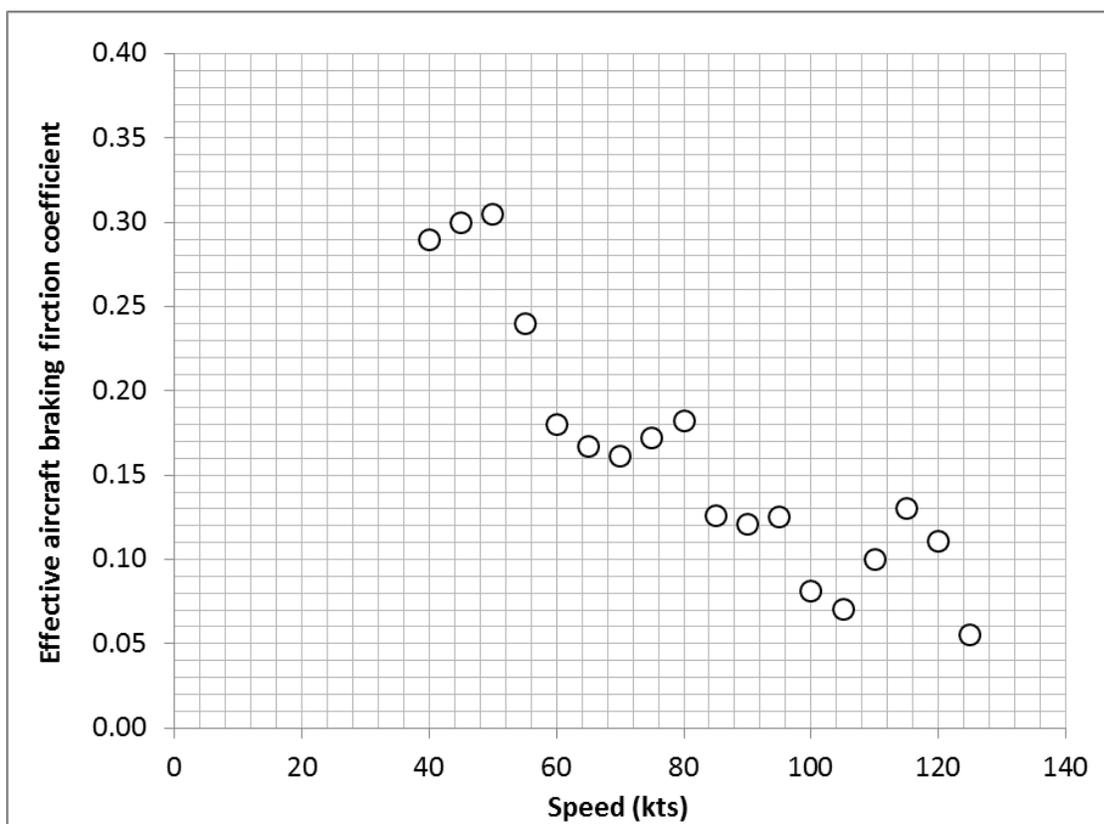


Figure 7: Effective aircraft braking friction coefficient as function of speed on a smooth flooded runway (source: Transport Safety Board, Canada).

The anti-skid controlled wheel brake pressures and the brake pedal positions that were available from the flight data recorder, suggested that a friction limited condition existed throughout the landing roll. Low, cycling braking pressures were seen on the time traces. The flight data recorder data showed that the main landing-gear wheels, although slower than normal to spin up, did continue to turn throughout the landing roll. So no locked wheel condition occurred in the landing roll. During a post-accident examination, no reverted-rubber burns were found on the aircraft's main landing-gear tyres. The investigators did mention that there were steam-cleaned marks at the end of the runway, which according to the investigators would indicate that the temperature had reached a value at which steam is formed. It should be noted that such marks on the runway are not always present during viscous or dynamic hydroplaning. The absence of those or any other marks does not prove that hydroplaning did not occur!

Runway friction tests conducted by the airport authorities using a Saab friction tester before the accident did not indicate that the runway was deficient in its microtexture. The investigators did not examine the runway microtexture itself. In this case it would be of great interest to have an idea of the microtexture characteristics as viscous hydroplaning was identified as the main cause for the low braking friction levels achieved. Just by touching the runway surface could have given some indication on the state of the microtexture.

In this example the accident investigators had access to a wealth of data such as wheel brake pressures, wheel speeds, etc. On some older model aircraft such data are often not available. There is usually sufficient data available to estimate the (wheel) braking friction coefficients. Together with the information of the runway texture, rainfall etc. a good assessment on the presence of hydroplaning is possible.

### **Final remarks**

In theory hydroplaning will always occur when operating on a wet or flooded runway. Depending on different factors like such as runway texture and wetness the influence on braking performance can be small or significant. During an accident investigation that is related to stopping or controlling of aircraft on a wet or flooded runway, it is important to understand if and how hydroplaning might have contributed to the event. The investigators can analyse different data sources to determine the type of hydroplaning that might have occurred. Data from the flight data recorder (and quick access recorder), runway surface texture characteristics, video images, rain fall data etc. are examples of such sources. The present paper provides background information on how investigators could analyse such data to make a proper assessment of the role of hydroplaning in the accident.