Investigating Runway Overruns – a Manufacturer's Perspective

By:

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Introduction

According to IATA Annual Review 2012 (ref. 11), runway excursions continue to be one of the leading causes of accidents worldwide. Although many efforts are being endeavored by the industry to reduce such occurrences, runway overruns remain a major concern. With the Embraer products the picture is the same. Since 2008, 32% of the occurrences involving Embraer jets were runway overruns. Aiming to contribute with the preparation of the next generation of investigators, this paper presents key topics related to runway overruns to take into consideration that were gathered by Embraer from years of assisting investigations of this type throughout the globe. The paper is structured to indicate the key topics related with the main and common contributing factors of a runway overrun. It discusses the physical model that describes an aircraft decelerating on the runway, then the aircraft aspects which involve current design and operational regulations for landing distances, including the requirements for dry, wet and contaminated runways. This topic also addresses wheel braking systems, their operation and expected behavior in terms of anti-skid, auto-brake and touch-down protections. The third relevant topic is the runway itself. Discussion involves runway

aspects that may have impact on the aircraft braking performance. The last topic relates to the aircraft-runway interface, like runway friction and the hydroplaning phenomenon, including some useful investigation techniques. The points illustrated in this paper are supported by investigation data and technical bibliography, with the purpose to increase investigators' awareness during investigation of a runway overrun.

Physical Model

A simple physical model can represent an aircraft rolling on a runway during landing, with all the forces that actuate on an airplane during deceleration on the ground (Figure 1). The understanding of these forces will serve as basis to the investigation aspects discussed in this paper.
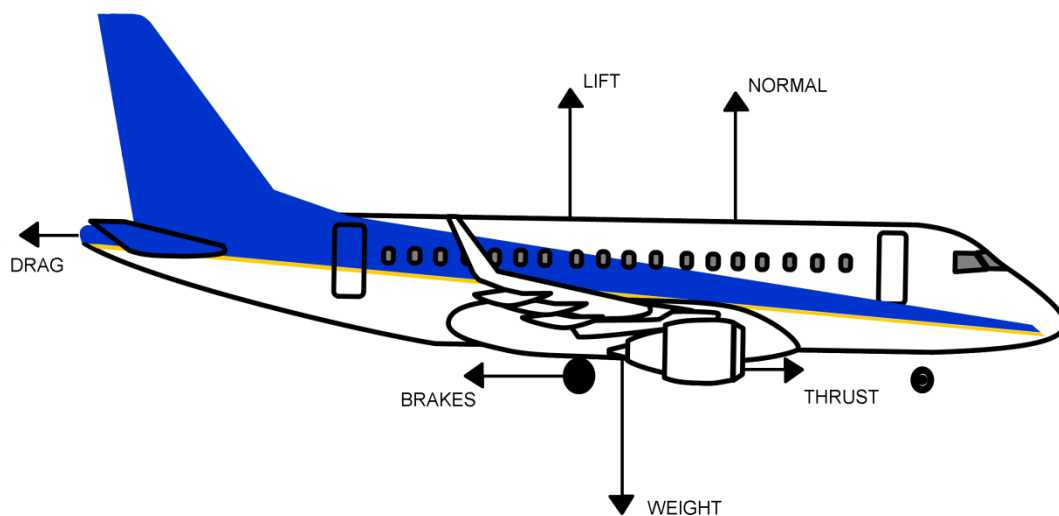

Figure 1 – Physical model of a decelerating aircraft

The model shows six different forces actuating on the aircraft. The <u>weight</u> is the result of gravity on the airplane mass. For the purposes of this paper, the weight is considered to be constant throughout the landing run, in spite of fuel burn. The <u>lift</u> is the net result of aerodynamic forces from the lift-generating surfaces. Since aerodynamic forces depend on dynamic pressure, this force is not constant; its magnitude usually decreases with time as the aircraft decelerates during landing. The <u>normal</u> force is the Earth's reaction to the aircraft weight. The normal load corresponds to the part of the weight that is effectively applied on the ground. Due to the opposing lift, only a fraction of the weight is "felt" by the pavement. This force "perceived" by the pavement determines the normal load, which, as will be discussed, bears an important relationship with the braking force. The model assumes that the aircraft is not accelerating over its vertical axis and therefore, the aforementioned forces balance each other. In other words, the sum of lift and normal load equals the weight.

On the other hand, the acceleration over the horizontal axis is not null. When thrust reversers are not in use, the <u>thrust</u> corresponds to the forward force delivered by the engines. Although landing runs are normally conducted with the engines set to idle, this force is not negligible and has to be considered for landing analyses. The <u>brakes</u> on

the main landing gear cause an important decelerating force. This force is complex to quantify and, as will be discussed ahead, it depends on the runway conditions, braking input by the pilots and the aircraft braking system. The ratio between the braking and the normal forces results in the coefficient of friction, to be discussed later. Finally, there is the aerodynamic drag that is the net result of the resistance to the air flow of the aircraft parts (parasite drag) and the result from the lift (induced drag). If thrust reversers are employed, their contribution may be included in this force.

Like any model that represents reality, it has limitations and its complexity may be adjusted to represent other aspects such as runway slope or presence of contaminants. However, as simple as it is, this model is sufficient to allow for the calculation of the length of the ground run with precision. A good investigation will consider the interplay between these forces and their aspects. Some of these aspects will be discussed.

Aircraft Aspects

Requirements and Regulations

The comprehension of the landing distance figures provided by manufacturers depends on concepts set forth on design and operating requirements. Each country has its own set of aviation regulations. This paper will focus on those from U.S. and European Union. Although recognizing the complexity of the subject, which makes impossible to describe it thoroughly in this paper, the authors aim to show the importance of the knowledge of design and operating rules during the investigation of a runway excursion.

Design requirements are those that prescribe standards for the issue of type certificates as well as changes to those certificates for different categories of airplanes. Examples of such requirements are U.S. 14 CFR parts 23 and 25 and Europe's CS-23 and CS-25. Part 23 prescribes standards for normal, utility, acrobatic and commuter categories, whereas part 25 refers to transport category airplanes. On the other hand, operating requirements prescribe the rules governing the operation of aircraft as well as actions required to support the continued airworthiness of each airplane. On the following pages, whenever there is a requirement section related to the topic in discussion, this section number will be presented in parenthesis.

Design Requirements

Unless otherwise noted, this section will refer to both U.S. and Europe design requirements indistinctly, since their structure is very similar. The most important sections related to landing distances are section 23.75 for part 23 and section 25.125 for part 25. These requirements demand that the manufacturer determines the horizontal distance necessary to land and come to a complete stop from a point 50 feet above the runway threshold at V_{REF}, for standard temperatures at each weight and altitude within the operational limits established for landing. It is important to mention that the main braking devices for determination of landing distances are the wheel brakes. If deceleration means whose operation depends on the engines are used, then landing distance figures for engine inoperative must be determined as well. The

distances obtained by the manufacturer based on these requirements are known as *unfactored landing distances*.

Design regulation requires manufacturers to provide landing distance figures for dry runways. Landing distances for wet runways are determined by simply multiplying a factor over the dry landing distance. This multiplication is mandated by the operational requirements. In this subject, an important difference between FAA and EASA requirements for landing distances deserves attention. EASA CS-25 also requires applicants to provide landing distance figures for dry and contaminated scenarios for large turbine powered airplanes (CS 25.1591). This requirement will be discussed later.

The dry unfactored landing distance provided by the manufacturer is determined in two parts. The first part corresponds to the airborne distance, which is the distance between the point in trajectory in which the aircraft is 50 ft above runway surface and the touchdown point. The second part is the ground distance, which is the distance from touchdown to the complete stop. The ground distance may be divided into a transition phase, in which the decelerating devices are beginning to be applied, and a full braking phase, in which the decelerating devices are fully operational. Figure 2 illustrates both parts of the landing distance.
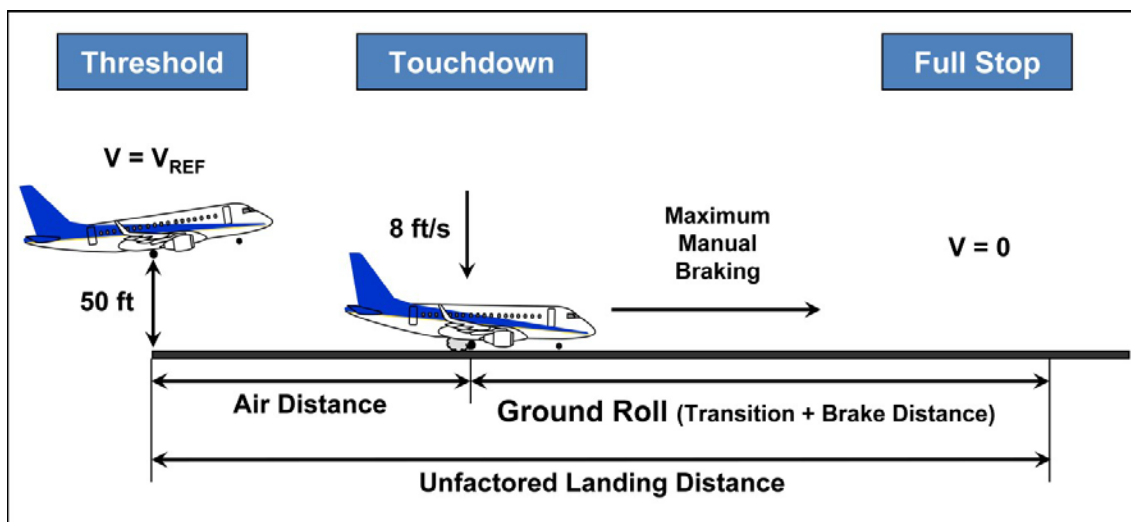

Figure 2 – Unfactored landing distance

FAA Advisory Circular (AC) 25-7C details acceptable means of compliance with landing distance requirements for transport category airplanes (§ 25.125). The airborne distance may be obtained by an upper-bound equation, determined in past certifications, which presents minimum speed loss from 50 ft to touchdown. It is also possible to determine the air distance from flight test data, including a parametric analysis that establishes the relationship between the airborne distance as a function of the rates of descent at 50 ft and touchdown. The parametric analysis allows for the determination of the air distance by assuming a rate of descent of 8 ft per second at touchdown.

On the other side, the ground distance is determined from the deceleration that results from the dry runway braking coefficient as obtained from flight tests. As mentioned previously, for EASA certified aircraft, CS 25.1591 mandates manufacturers to

determine the landing distance for runways contaminated with standing water, slush, snow or ice. As per ICAO Annex 6 (ref. 13), a runway is considered to be contaminated when more than 25% of the runway surface area is covered by:

- Water or slush more than 3 mm (0.125 in) deep;

- Loose snow more than 20 mm (0.75 in) deep; or

- Compacted snow or ice, including wet ice.

If the performance information for runways covered with these contaminants is not supplied, the AFM must contain a statement prohibiting operations on the surfaces for which this information is not supplied. EASA Acceptable Means of Compliance (AMC) 25.1591 provide a methodology for determination of performance data for runways covered with the aforementioned contaminants. AMC 25.1591 also proposes that the airborne distance is determined by assuming that 7 seconds elapse between passing through 50 ft and touching down. The touchdown speed is considered to be 93% of the threshold speed. For the determination of the ground distance, AMC 25.1591 provides default values of coefficients of friction for each of the required contaminants. The effect of the drag due to fluid contaminant also must be considered for the determination of the ground distance. Figure 3 illustrates the determination of the unfactored landing distance as per AMC 25.1591.
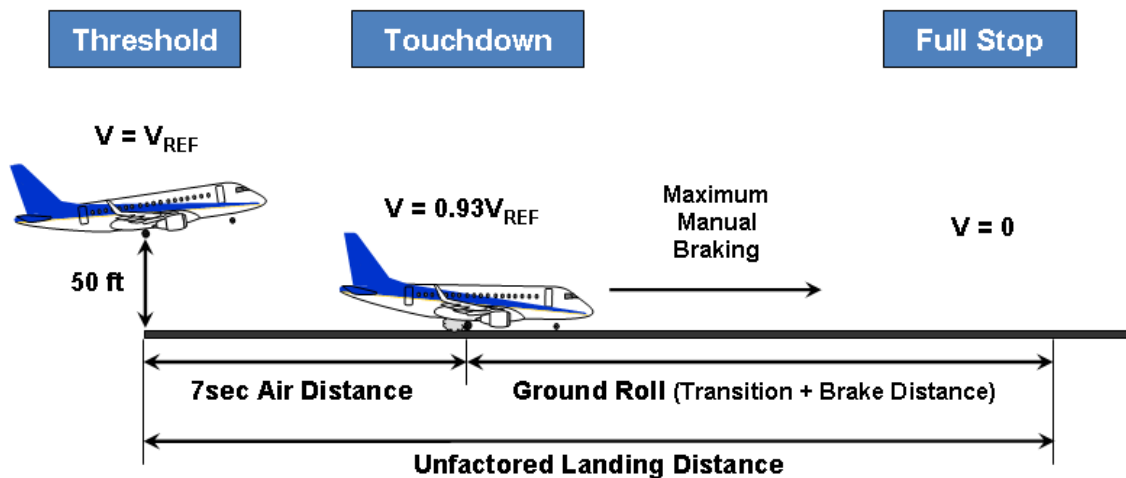

Figure 3 – Unfactored landing distance for a contaminated runway (EASA)

Operating Requirements

This section will discuss about operating requirements that affect landing distance, in particular on the concept of *factored landing distances*. Factored distances are determined from the unfactored landing distances, discussed on the previous section. The unfactored distance is the basis for the determination of landing distances in the majority of operational scenarios, such as wet runways and systems malfunctions. Depending on the kind of operation, regulations also require the multiplication of a factor over the unfactored distance in order to increase the safety margins during landing. These specific requirements are the focus of this section. In particular, requirements related with flight dispatch, i.e., requirements that forbid take-off if specific conditions anticipated during landing at the destination or alternate airport are not met.

Unlike design requirements, operating requirements may vary considerably in terms of structure when comparing regulations of different countries. Because of that, American and European operating requirements are going to be presented separately.

United States

The basic operating regulation in U.S. is 14 CFR part 91 – General Operating and Flight Rules. This regulation establishes requirements for all flights within U.S. territory and encompasses topics such as VFR/IFR flight rules, equipment requirements, maintenance and fractional ownership operations. All citizens who wish to operate their own aircraft will have to comply with the requirements in part 91 (§ 91.1). Additionally, fractional ownership operations demand compliance with subpart K, which brings specific requirements for this type of operation.

Large aircraft are those with a maximum certificated takeoff weight of more than 12,500 pounds (§ 1.1). Except for large airplanes operating under subpart K, there is no requirement for the application of landing distance factors in part 91. Before take-off, as a preflight action (§ 91.103), operators are only required to be aware of the runway lengths at airports of intended use as well as the required landing distances published on the aircraft's approved flight manual, if any. On its turn, subpart K operators of large turbine powered airplanes are required, before takeoff, among other actions, to ensure that the aircraft weight on arrival, allowing for normal consumption of fuel and oil in flight, would allow a full stop landing at the intended destination within 60% of the effective length of the runway (§ 91.1037). In other words, this is equivalent to multiply the unfactored landing distance by a factor of 1.667 (or dividing it by 0.6). As an example, the operation of an Embraer Phenom 100 (which has a MTOW of 10,472 pounds) under part 91 does not require the application of landing distance factor over the unfactored distance.

Requirements for domestic, flag and supplemental operations are prescribed on 14 CFR part 121. Operators of turbine powered airplanes under this part are required, before takeoff, among other actions, to ensure that the aircraft weight on arrival, allowing for normal consumption of fuel and oil in flight, would allow a full stop landing at the intended destination within 60% of the effective length of the runway (§ 121.195). The resulting landing distance based on this requirement is illustrated in Figure 4. This requirement is also applicable for alternate airports (§ 121.197). For turbopropeller powered airplanes that can't comply with this requirement, it is permitted to take off if the airplane can accomplish a full stop landing within 70 percent of the effective length of the runway of an alternate airport.
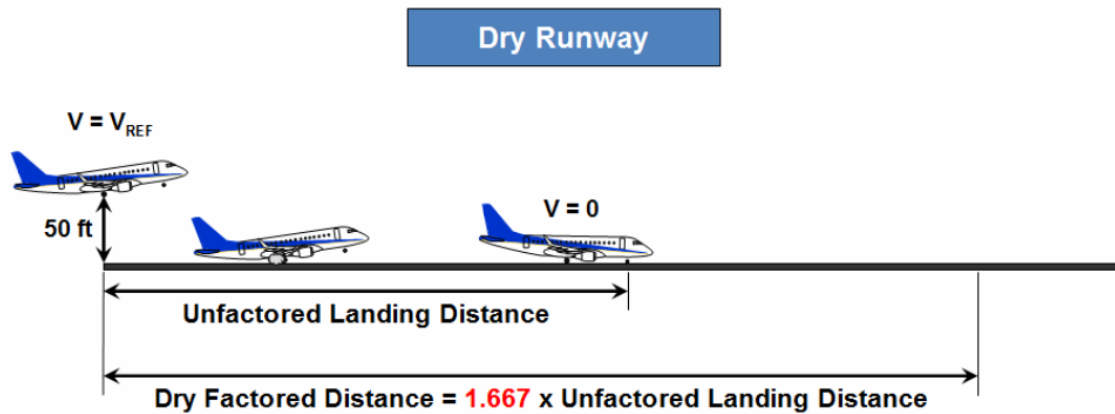
Figure 4 – Factored landing distance (dry runway)

Requirements for commuter and on demand operations are prescribed on 14 CFR part 135. Subpart I presents landing distance limitations at destination and alternate airports for the following categories:

- Large Transport Airplanes / Reciprocating Engines (§ 135.375 and § 135.377)
- Large Transport Airplanes / Turbine Engines (§ 135.385 and § 135.387)
- Large Nontransport Airplanes (§ 135.393 and § 135.395)
- Small Transport Airplanes (§ 135.397)
- Commuter Airplanes (§ 135.398)
- Small Nontransport Airplanes (§ 135.399)

The first three categories from the above list have specific requirements for the application of a factor over the unfactored landing distance. The last three, on their turn, are required to comply with some of the landing distance requirements from the previous categories. For example, commuter category airplanes are required to comply with sections 135.385 and 135.387. Section 135.385 also provides landing distance requirements for eligible on demand operators, which specify that a turbine engine powered large transport airplane may take off if its weight on arrival would allow a full stop landing at the intended destination airport within 80 percent of the effective runway length (§ 135.385(f)).

Regulation also requires operators to apply a factor of 1.15 over the factored landing distance, as applicable for each different kind of operation, if weather reports or forecasts indicate that the runways at the destination or alternate airports may be wet or slippery at the estimated time of arrival (§ 91.1037, § 121.195 and § 135.385). That means an additional safety margin of 15% over the factor described in the previous paragraphs. Figure 5 illustrates the application of this factor over the factored landing distance. Therefore, the resulting wet landing distance is not the product from analytical methodology to calculate the distance based on a theoretical coefficient of friction. Neither is it the result from flight tests on a wet runway. It is simply the result of a multiplication, as mandated by operational requirements. On the other hand, for contaminated runways (presence of standing water, snow, ice, slush or other contaminants), U.S. regulation does not mandate operators to evaluate the required landing distance for such conditions when they are expected to be found at the

destination before take-off. Landing distance figures for contaminated runways are provided in operational manuals as guidance material.
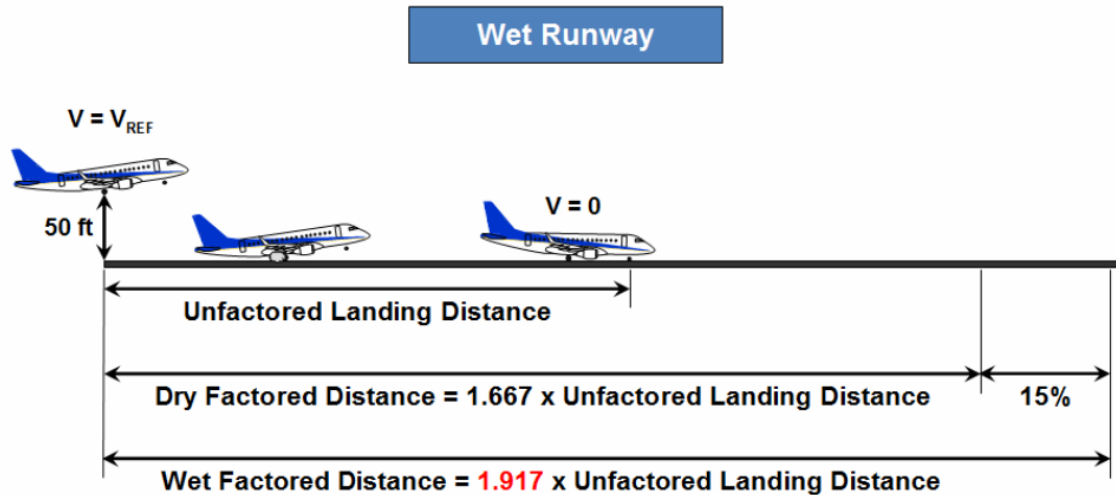

Figure 5 – Factored landing distance (wet runway)

Finally, it is important to point out that the operational requirements discussed here are those related with flight dispatch. If the anticipated conditions are not verified when the aircraft reaches its destination due to contamination or any system malfunction that adversely affects landing performance, the operator does not have to comply with factored landing distance requirements considered for dispatch. Rather, the flight crew is expected to reassess the landing distance for that particular unanticipated situation in order to decide to proceed with landing. However, as of present, there are no operational requirements that mandate pilots to perform this in-flight reassessment of the required landing distance.

Europe

As of 2013, each country in the European Union (EU) has its own set of basic operating requirements, as regulated by their respective national aviation authority. However, commercial passenger and cargo transportation operations are regulated in EU countries by EU-OPS, a regulation whose purpose is the harmonization of technical requirements and administrative procedures applicable to commercial transportation by aeroplane (ref. 7). It became effective in 2008 in all EU Member States and also in Iceland, Norway and Switzerland. EU-OPS prescribes requirements applicable to the operation of any civil airplane for the purpose of commercial air transportation by any operator whose principal place of business and, if any, registered office is in a Member State. A new regulation, introduced in 2012, generally known as Implementing Rules – Operations (IR-OPS) is expected to replace EU-OPS in 2014.

Regarding landing performance, there are two relevant sections to be mentioned: OPS 1.515 (Landing Performance – Dry Runways) and OPS 1.520 (Landing Performance – Wet and Contaminated Runways). Section 1.515 states that an operator must ensure that the landing mass of the airplane for the estimated time of landing at the destination or any alternate aerodrome allows a full stop landing from 50 ft above the threshold

within 60% of the landing distance available (turbo-jet powered) or within 70% of the landing distance available (turbo-propeller powered).

On its turn, section 1.520 states that when weather reports or forecasts indicate that the runway of intended landing at the estimated time of arrival may be wet, operators shall ensure that the landing distance available is at least 115% of the required landing distance, as mandated by section 1.515. That represents an additional 1.15 safety factor over the factored landing distance. In addition to that, operators are further required to apply the same 1.15 factor over the required landing distance when runway contamination is anticipated. Since EASA mandates manufacturers to provide contaminated landing distance figures, operators must apply this 1.15 factor over the required landing distance for contaminated runway. Figure 6 illustrates the resulting landing distance for a contaminated runway.
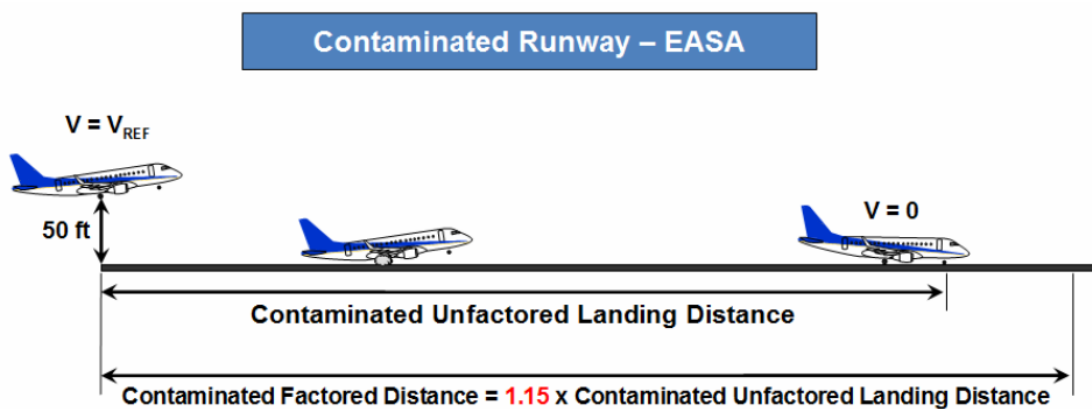

Figure 6 – Contaminated factored landing distance (EASA)

Braking Systems

The braking system plays a critical role in the aircraft deceleration during the landing run on the ground. For this reason, investigators should be familiar with some aspects related to its operation. The basic operation of brakes involves converting the kinetic energy of motion into heat energy through the creation of friction (ref. 22). For larger aircraft, the typical multiple brake disk installation is comprised of stators and rotors in the brake assembly that are pressed against each other during braking. For most aircraft designs, the force which causes the friction between the disks comes from the hydraulic system by means of pistons that receive pressurized fluid from brake control valves. However, brake designs based on electric power are being employed more frequently and investigators should also be familiar with these systems.

While investigating a runway excursion, investigators are advised to check and take pictures of the *wear indicator pins*. These pins are attached to the disk stack. Along the braking cycles, wear occurs on the disks and therefore, they become thinner. As a result, the part of the pin visible outside the brake assembly appears shorter. When the pins are leveled with a reference bracket, the brake assembly should be replaced. Figure 7 illustrate the wear pin on an Embraer 190.
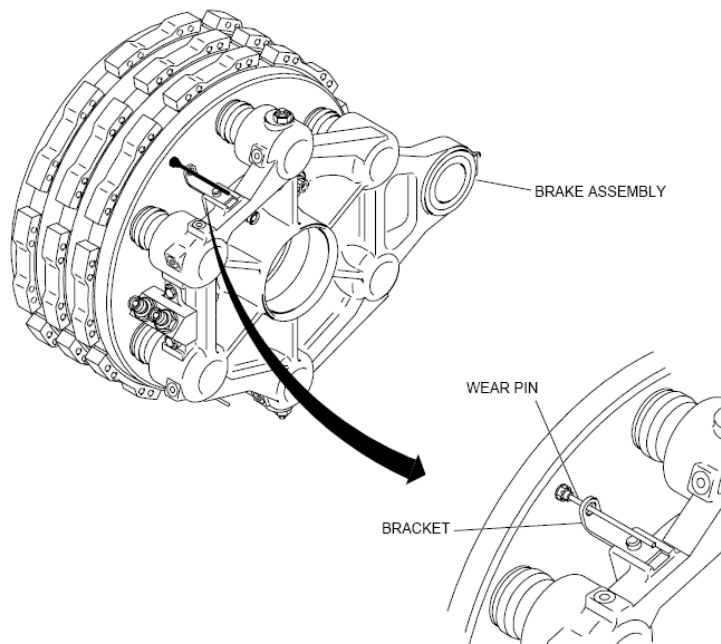
Figure 7 – Brake wear pin (ref. 2)

The braking action inside the brake assembly causes the wheel to reduce its angular speed which on its turn increases the friction force from the runway applied on the tire. This braking force is directed to the opposite direction of the aircraft motion. This force is the braking force presented on the Physical Model section. However, the braking force can't be increased indefinitely. At brake application, the tire begins to slip with respect to the runway surface, i.e., the wheel speed slows down with respect to the airplane's ground speed. As the amount of tire slip increases, the brake force also increases until an optimal slip is reached. If the amount of slip continues to increase past the optimal slip, the tire will begin to skid, and the friction coefficient between tire and pavement will fall down to the dynamic value, which reduces the braking force (ref. 17). Figure 8 presents the typical behavior of the braking force as a function of the slip ratio (ref. 10). It is possible to notice that the maximum braking efficiency is obtained with a slip ratio of approximately 10%. Should the brake pressure in the brake assembly be increased so that the slip ratio goes past the optimal range, the braking force would decrease and consequently, the landing distance would be greater. It is the function of the anti-skid (to be discussed ahead) to ensure that the brake pressure is adjusted so that the slip ratio remains within the optimal range.
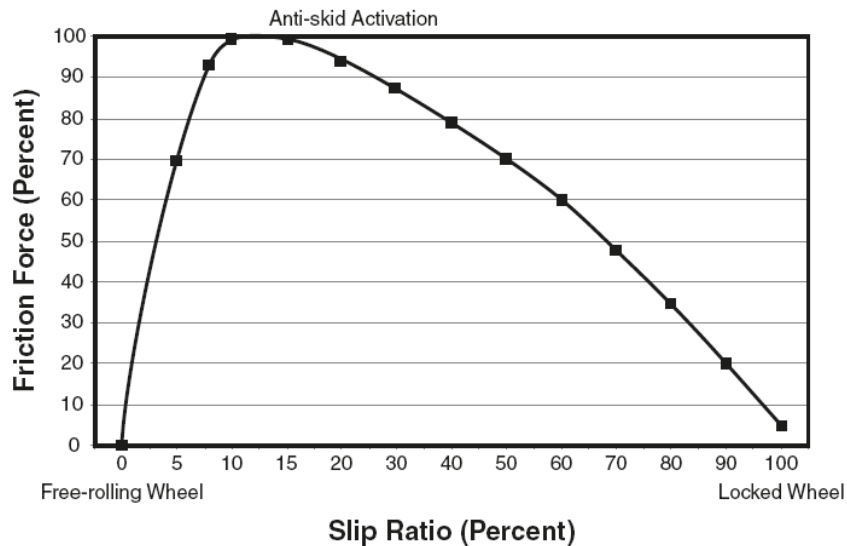
Figure 8 – Friction force as a function of slip ratio (ref. 10)

Aircraft fitted with hydraulic braking systems apply pressurized fluid from the hydraulic systems into the brake assemblies. Hydraulic systems on large aircraft typically range from 3,000 to 5,000 psi. From what has been exposed, it is not possible to apply the maximum braking pressure on the brakes because this would take the slip ratio out of its optimal performance range. Therefore, it is not possible to expect the nominal pressure levels from the hydraulic system inside the brake assembly during normal brake operation. The modulation of fluid pressure inside the brake assembly will be further discussed on the next topic.

Anti-Skid Systems

Maximum braking efficiency exists when the wheels are decelerating at a maximum rate but are not skidding over runway surface. Anti-skid systems have the function to prevent wheels from skidding, attaining the maximum possible braking performance at that particular runway. Each wheel fitted with brakes has its rotation monitored. Whenever the rotation tends to slow down towards wheel skidding, the system alleviates braking action on that particular wheel so that it resumes rotation.

There are several types of architectures of aircraft anti-skid systems. However, there are three components that are usually present on such systems: an electronic control unit, brake control valves and wheel speed transducers. The speed transducers are wheel-mounted sensors that measure the angular speed on each wheel. The brake control valves modulate hydraulic power to the brake assemblies as commanded by the control unit, which implements the operation logic of the system by reading the wheel speed transducers and sending commands to each of the brake control valves. Figure 9 presents the brake system architecture of an Embraer Phenom 300, which is fitted with anti-skid.
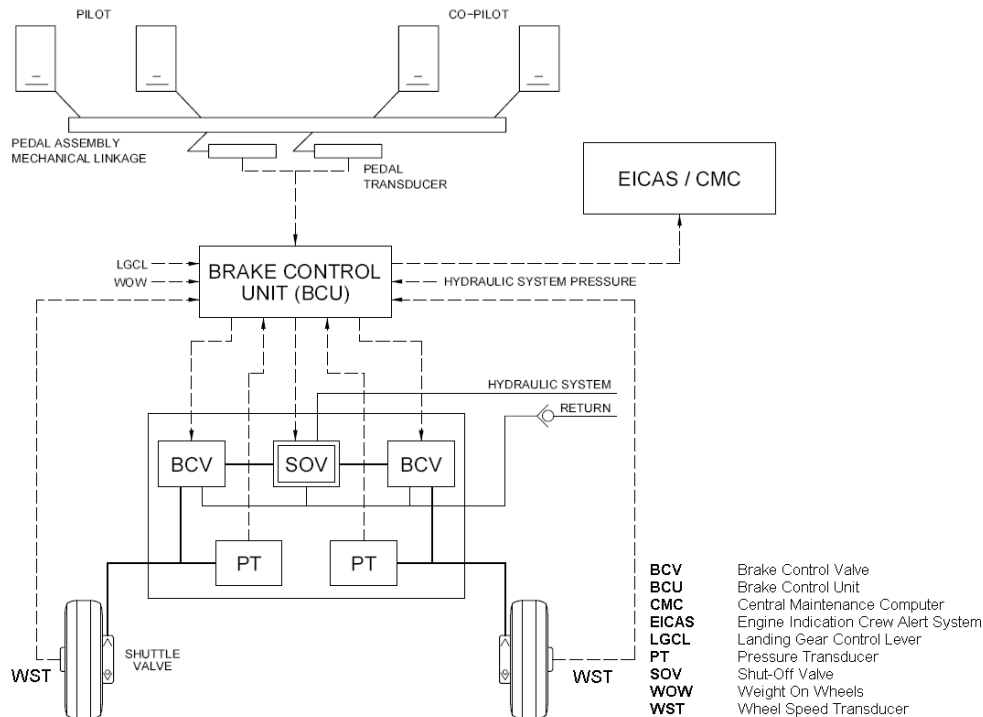
Figure 9 – Brake system architecture (ref. 1)

The logic by which the system controls pressure releases during brakes operation determines the system classification. Design regulations classify anti-skid systems into three types (§ 25.109): on/off systems, quasi-modulating systems and fully-modulating systems. Next, the characteristics of these systems are described.

- On/Off Systems

These systems are the simplest of the three types. Brake pressure is applied as commanded by the pilot until wheel locking is sensed. When that happens, pressure is ceased to be supplied to the assembly until wheel speed resumes normal rotation, when pilot-commanded pressure is re-applied.

- Quasi-modulating Systems

These systems continuously attempt to regulate brake pressure as a function of wheel speed. Brake pressure is released when wheel deceleration rate exceeds a certain value. In general, corrective actions are based on a pre-programmed sequence rather than the wheel speed time history. The wheel speed works as a trigger to activate the pre-programmed response.

- Fully-modulating Systems

These systems are a further refinement over the quasi-modulating systems. During a skid, the corrective actions taken by these systems are based on the sensed wheel speed in a closed control loop for which the reference is pilot braking command.

New certification designs tend to opt for fully-modulating systems, which provide the best braking performance. Investigators should verify what system type was installed in the aircraft under investigation. Also, it is important to verify if the observed system performance is coherent with that system type. One possible way to look into that is the observation of the brake pressure, wheel speed and brake pedal parameters from the Flight Data Recorder (FDR). AC 25-7C brings typical plots for brake pressure and wheel speed for each of the types of anti-skid. As an example, plots of fully-modulating systems on a dry runway are reproduced below. The high-frequency component on the brake pressure is the result of the anti-skid releasing pressure to control the wheel decelerating rate.
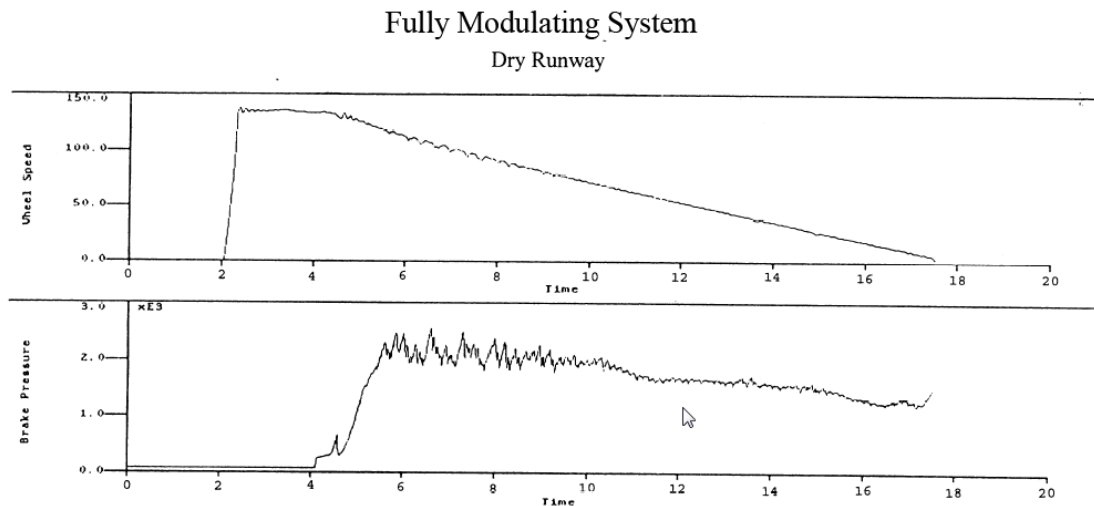

Figure 10 – Fully modulating anti-skid system on a dry runway (ref. 21)

Precaution should be taken when comparing plots such as the one in Figure 10 with FDR data. The reason for that is that FDR sample rates for these parameters are usually less than those used for certification test purposes. Therefore, the high-frequency oscillation might not be noticeable on the FDR plots.

The brake pedals position parameters show the pilot commands to the braking system when the auto-brake is not operating. If the pilots are not requesting maximum braking action on the pedals, the anti-skid system might not operate at all because the braking action is not reaching the skid threshold of that particular condition.

Another useful FDR parameter for investigation of these systems is the electrical command from the brake control unit to the brake valves. It might reveal if the logic of operation of the control unit is coherent. Comparison of this parameter with the corresponding brake pressure might also reveal if the brake control valve operation went as expected.

Electronic Brake Control units from several suppliers also record a fault log for shop maintenance purposes. This fault log might reveal important aspects of the system operation. Download of such non-volatile memories (NVM) should always be considered when investigating runway excursions. On top of that, since anti-skid systems are not developed by the aircraft manufacturer, on most cases, the airframer will not have access to the details of the algorithm of the anti-skid system. Therefore, it might be important to involve the braking system supplier in the investigation as well.

Generally all anti-skid systems for modern jet aircraft incorporate a locked-wheel protection feature. The wheel speed signals on two or more wheels are used to produce an "airplane moving" reference. In the event one of the wheels should lock up, a comparison of that wheel speed with the reference signal provides a basis for the release of the brake pressure of the slow wheel. A reference memory may be provided in the condition of two or more grouped wheels locking up at the same time. Investigators are advised to check if the involved aircraft has this feature implemented on its anti-skid control law.

Modern aircraft braking systems also feature a touchdown protection. Its purpose is to make sure that braked wheels are free to rotate at touchdown even though the pilot has inadvertently applied brakes. The protection is normally implemented using the wheel speed signal and a signal from the airplane's AIR/GROUND logic system. If the AIR/GROUND signal indicates that the airplane is in the air and the wheel speed is lower than a preset level, braking action will be disabled by the control valve. A transition from air to ground indication will enable the braking action, normally after a delay to allow wheel spin-up. Usually, detection of wheel spin-up will also enable the brakes even with an airplane in the air indication.

As mentioned previously, FDR sample rates for brake pressures and wheel speeds are usually lower than what is necessary to evaluate the operation of such anti-skid features. An alternative to that may be found on flight test data, which are performed with instrumented prototypes to produce high sampling rate data for aircraft certification purposes. Usually, manufacturers retain these data for several years, which might then be used to analyze a particular aspect of the braking system operation of that particular type design.

As a final note for anti-skid systems, it is important to mention the fact that even the most advanced systems are not able to fully prevent the hydroplaning phenomenon, to be discussed ahead. In other words, any vehicle supported by tires moving at sufficiently high speed over contaminated surface will hydroplane. The mitigation for this phenomenon resides on removing the conditions for its onset, such as effective drainage systems to prevent contaminant accumulation on the runway surface. Investigators should have this fact in mind during investigations of excursions on flooded runways.

Auto Brake

Auto brake systems provide automatic braking at pre-programmed deceleration rates for landings and rejected takeoffs. The system modulates hydraulic pressure to the brakes in order to provide a constant deceleration rate corresponding to the selected level. If reverse thrust is actuated, the auto brake system will modulate the brake pressure to reach the target deceleration rate. This is an important detail about auto brake systems that investigators should be aware of. Even if the greatest deceleration setting is employed, the resulting braking action might not be the greatest possible for that particular runway. In other words, the auto brake is a control system which tracks a determined deceleration rate, sometimes not being the greatest possible. It is important therefore, to investigate whether or not the auto brake system was engaged during the runway excursion. Modern aircraft with these systems have FDR parameters that register auto brake operation. However, if such parameters are not available,

investigators should resort to other elements of information such as the NVM from the auto brake controller, interviews with the flight crew, etc.

Runway Aspects

As discussed earlier, the landing figures provided by manufacturers depend on concepts set forth on design and operating requirements, which in turn assume that the runway in question complies with design and maintenance requirements. Likewise the aircraft design, airworthiness and operational requirements, each country has its own set of requirements for runways.

The U.S. 14 CFR Part 139 establishes the requirements for airport certifications. The requirement §139.305 introduces the need for maintaining and repairing the paved areas, including the runway. The FAA AC 150/5300-13A, entitled "Airport Design" (ref. 20), and the cascading advisory circulars cited within, include guidance on runway location, orientation, physical characteristics such as length, surface conditions and slope.

EASA aims to have a common aerodrome regulation by the end of 2013. The document "NPA 2011-20 (B.III) – Draft Certification Specification" (ref. 9) reveals that this common requirement will be essentially the ICAO Annex 14 (ref. 12). The chapter 3 of the ICAO Annex 14 contains information on physical characteristics of runways (including shoulders, turn pads, strips), taxiways and surrounding areas. These requirements include, but are not limited to, orientation of the runway, slopes on runway and runway surface.

When analyzing runway overruns, it is of foremost importance to consider the runway aspects which could impact on available friction coefficient between the pavement and the aircraft tires. The effect of surface material on the tire-to-ground coefficient of friction arises mainly from differences in surface texture. There are two components that compose the runway pavement texture:

- Macrotexture: Primarily created by the size of the aggregate used or by treatment of the surface. It is the created texture between individual stones. Can be judged approximately by eye.

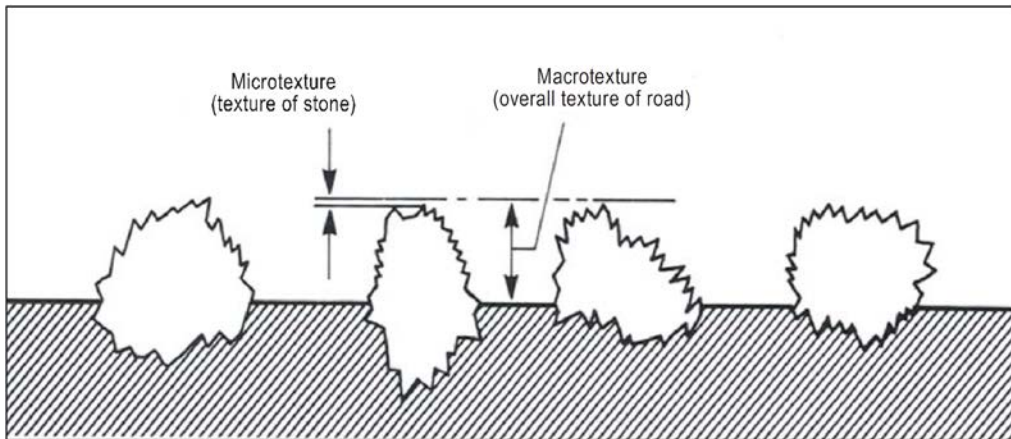- Microtexture: texture of the individual stones. Hardly detected by eye.

Figure 11 – Pavement texture (ref. 14)

The runway texture is also intimately linked to drainage capacity. At aircraft high speeds, the water in the tire/ground interface is highly affected by the pavement macrotexture. Rough surfaces (open macrotexture) provide more drainage capability than smooth ones (closed macrotexture) at high aircraft speeds. As a consequence, poor macrotextures increases the probability of hydroplaning.

Take for example the runway overrun involving an ERJ-135, registered as ZS-SJW, on December 7th, 2009 at George Airport, South Africa. South African Civil Aviation Authority (SACAA) Final Report (ref. 18) demonstrates that the runway surface macrotexture fell below half of the value prescribed by ICAO (ref. 12), paragraph 3.1.25) for a new surface after it had been treated with a bituminous fog-spray, which filled the voids between the pavement aggregates.

Figure 12 – Example of runway before (left) and after (right) surface treatment (ref. 18)

Indeed, the aircraft tires taken after the event show clear signs of hydroplaning, probably induced and/or prolonged by the impaired water drainage capacity on the tire/pavement contact area, as shown on Figure 13. More on hydroplaning evidences will be discussed on the next topic.

Figure 13 – Aircraft tires after the occurrence (ref. 6)

Water drainage may be optimized through the use of slopes (longitudinal or transverse), proper orientation (based on years of wind data to avoid crosswinds that retard water flow), maintenance of proper macro and microtexture or by adding special texture treatments such as transverse grooves (grooving) or porous friction course (PFC).

For a deep and comprehensive description of the runway aspects affecting the braking capability, including measurement methods and reference values, refer to ref. 14. The Transportation Safety Board of Canada (TSB) Final Report on the runway overrun involving an ERJ-145 (ref. 5) contains an analysis of the runway characteristics affecting the aircraft braking capacity.

Interface Aspects

Runway Friction (measurements and limitations)

As discussed on the Physical Model, the friction coefficient is a dimensionless ratio between the friction force between two bodies moving, or tending to move, in relation to another and the normal load pressing these two bodies together. By its own definition, friction involves two bodies and therefore it is not correct to think about it as an inherent characteristic of a body (a runway pavement, for example).

Trying to predict aircraft braking performance on a runway, the aviation industry developed several friction-measuring devices, which act as a "calibrated second body" to measure the friction coefficient developed between the device and the runway surface. Ref. 15, Chapter 5 describes in details the technical specifications of the most used friction-measurement devices.

For the scope of this paper, it is important to highlight that up to this date there is no universally accepted correlation between measured friction coefficient and aircraft braking performance, specially for wet runways, although satisfactory correlation between the friction measuring devices were obtained for dry runways and, to a lesser extent, snow and/or ice covered runways.

With the use of aerodynamic and thrust data for the aircraft, manufacturers are able to estimate the aircraft braking coefficient based on recorded flight data. However, investigators should keep in mind that this is the net result of the interaction between the aircraft tire, pavement, weather (winds, temperature), pilot technique, the design and operation of the aircraft braking system.

Hydroplaning

Hydroplaning is a phenomenon in which a film of standing liquid contaminant on the pavement causes the tire to lose contact, partially or totally, with the surface. When it occurs on the nose wheel tires, it may cause loss of steering capability. On the main wheel tires, it may cause loss of braking. Asymmetrical hydroplaning of the main wheel tires could cause a tendency to deviate from the runway centerline.

Whenever a tire meets a region covered with a film of fluid, the tire exerts a force over it. As predicted by Isaac Newton's third law, the film will react with an equivalent force of the same magnitude with the opposite direction against the tire. This force contributes to reduce the tire footprint (the area of the tire in contact with the surface). As the aircraft groundspeed increases, the hydrodynamic force exerted on the tire increases accordingly and eventually the tire will completely lose contact with the surface, a condition known as total hydroplaning. The speed in which this occurs is known as hydroplaning speed. Figure 14 illustrates conditions of partial (A) and total hydroplaning (B).
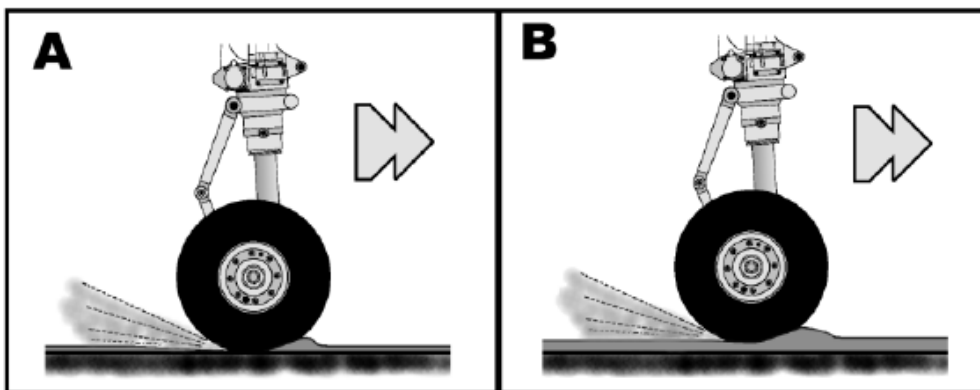

Figure 15 – The hydroplaning phenomenon (ref. 16)

The condition of partial hydroplaning is usually referred to as viscous hydroplaning. It is characterized by reduction of the braking force due to the tire footprint reduction. While in this condition, the tire may tend to skid more easily during braking.

The condition of total hydroplaning is also known as dynamic hydroplaning. Its main characteristic is the complete loss of contact between the tire and the pavement, which are separated by a layer of fluid. In this regime, an unbraked wheel may considerably

slow down its angular speed and in more critical cases, even cease to rotate. While in this condition, the breaking force is negligible and the only deceleration force due to the tire comes from the drag resulting from the displacement of fluid.

When a locked wheel slides over a layer of water, a third type of hydroplaning known as reverted rubber (or vapor) hydroplaning occurs. Tire heating in the footprint contact patch causes the film of water to become a cushion of steam. The heat reverts the rubber to its uncured state (thus, reverted rubber).

The Brazilian Aircraft Accident Investigation and Prevention Center (CENIPA) Final Report on the runway overrun involving a Phenom 100 (ref.3) presents an example of reverted rubber hydroplaning, which is easily identifiable by the aspect of the tire tread, presented on Figure 16.

Figure 16 – Reverted rubber evidence on the tire surface (ref. 6)

From what has been exposed, the aspect of tire treads may reveal important circumstances of their interaction with the pavement. Therefore, investigators are advised to take pictures of the entire circumference of the tires. If the tires get covered with mud or other substances due to the excursion, it is advisable to take pictures before and after the tires are washed.

Reverted rubber and, to a lesser extent, dynamic hydroplaning are likely to leave a white mark on the runway due to formation of steam that cleans the surface. Good investigation practice dictates, independently from suspicion of any type of runway contamination, to document tire marks on the runway with a handheld GPS. When doing so, investigators are encouraged to check the relative color of the marks left by the tires. Marks with a clearer shade when compared to the runway could hint the occurrence of dynamic or reverted rubber hydroplaning. Figure 17, also regarding the same occurrence (ref. 3), shows this kind of marks.

Figure 17 – Vapor marks left on the runway by hydroplaning tires (ref. 6)

Embraer experience to this point suggests the reverted rubber condition is more related to wheels locked by the action of the Emergency Parking Brake (EPB) actuation rather than dynamic hydroplaning. The usage of the EPB overrides the main braking system and its anti-skid function, and can cause the wheels to lock if applied above a certain point. When facing this type of evidence on the tires, investigators are encouraged to verify if the EPB was used during the landing run. It is possible to confirm this from FDR or CMC parameters such as EPB discrete, wheel speed or brake pressure parameters. Since the FDR brake pressure parameters are normally obtained from pressure transducers located on the main braking system, which is segregated from the EPB system, the brake pressure parameters actually are an indirect way to confirm that the anti-skid was disabled due to EPB actuation.

There are several factors that influence the occurrence of hydroplaning. Among these, we have: thickness of the water film, airplane groundspeed, tire pressure, tire tread quality, tire footprint, runway friction and runway construction. Together, these factors determine the degree of reduction of the braking force and loss of directional controllability.

During the 60's, the U.S. National Aeronautics and Space Administration performed several studies on the hydroplaning phenomenon and has kept improving its studies since. It has come to the conclusion that a film of water as thin as one tenth of an inch is sufficient to cause dynamic hydroplaning. From these studies, NASA produced equations that determine the critical speeds above which hydroplaning may occur. These equations provide a good reference for the comprehension of the hydroplaning mechanism. For a non-spinning wheel that touches down on a flooded runway, NASA determined the critical speed (V_P) as:

$$V_P = 7.7 \sqrt{P}$$

Where P is the tire pressure in psi. It is important to mention that once a wheel starts to hydroplane, it will not necessarily leave this condition when its speed falls below VP. This effect is known as hydroplaning hysteresis. Aeronautica Civil of Colombia identified evidences of hydroplaning on the runway overrun involving an ERJ-145 (ref.

4). The FDR plot on Figure 18 shows the occurrence aircraft decelerating on the runway prior to the overrun. It is possible to notice a significant increase in the brake pressures when the aircraft departs the hydroplaning condition at approximately 15:42:39 UTC. It is also possible to notice the effect of the anti-skid releases on the wheel speed parameters, in spite of the relatively low sample rate. The plot ends immediately prior to the aircraft departure from the runway surface.
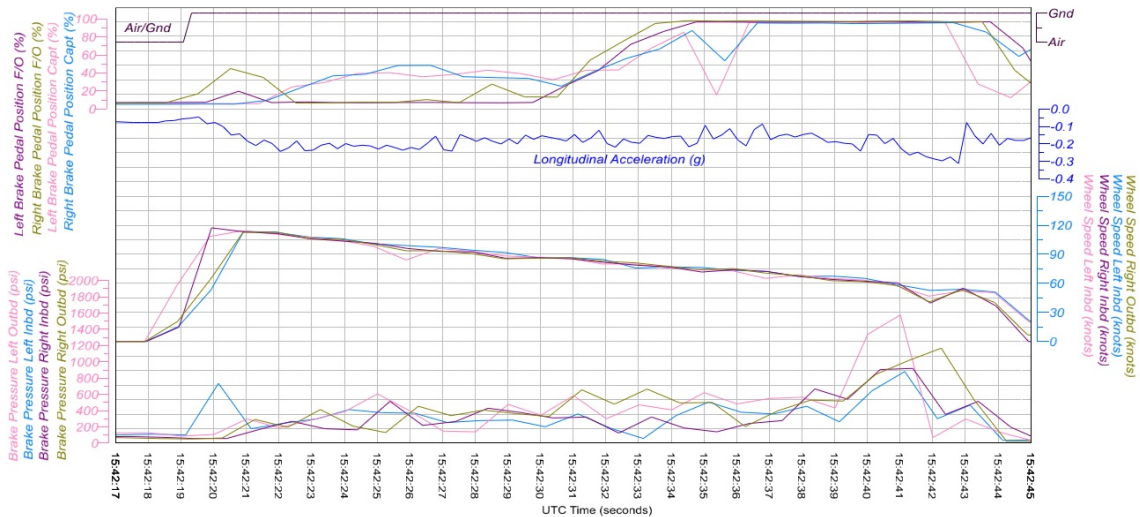

Figure 18 – Aircraft decelerating on a contaminated runway (ref. 4)

Conclusion

This paper went through several subjects with the purpose to provide a manufacturer's perspective learned from runway excursion investigations in which Embraer took part of. The authors recognize that the complexity of these topics makes it impossible to compile all the knowledge that is desirable to be part of the repertory of next generations of investigators in a single paper. However, we hope this paper, which originated from Embraer's commitment to continuously assist investigations involving its products, may serve as a reference and contribute to better investigations, with the purpose of making air transport safer.

Acknowledgement

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