Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

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Summary

The runway surface condition at airports is a critical safety concern. The exploratory study described in this paper has examined the influence of wet and contaminated runways on the take-off and landing performance of aircraft.

The operating problems that arise when taking off from or landing on wet or contaminated runways, are explained in detail. Certification of operations on wet and contaminated runways is reviewed. Tests conducted by NLR on water covered runways are briefly described.

In order to quantify the degree to which the runway surface condition is associated with the probability of an accident, both accident and movement data for West-European Airports were collected from the Air Safety databases of NLR. Accident and movement data were evaluated for 136 airports. The accident sample comprised 91 overruns and veer-offs. The study concludes that there is a four-fold increase in the accident risk for aircraft operating on wet and contaminated runways.

Contents

(31 pages in total)

1 Introduction

The runway surface condition at airports is a critical safety concern. The presence of for instance snow or water on the runway can have a significant impact on aircraft take-off and landing performance. The accident involving an Airspeed Ambassador aircraft at Munich in 1958, was probably the first major accident in which runway contamination was listed as the probable cause. Since then research on runway contamination and its impact on aircraft performance has been strongly intensified. Refs 1 and 2 are examples of the first studies on the impact of runway surface conditions on aircraft take-off and landing performance.

Despite the extensive research and numerous publications, accidents in which the runway surface condition (e.g. wet or contaminated) was a contributing factor still frequently occur. Illustrating examples are the accidents with a DC-10 at Boston-Logan Airport (1982), USA, a B-737 at Charlotte Douglas Int. Airport (1987), USA (aircraft overran wet runway and was destroyed), a fatal accident with an A320 which overran the end of the wet runway at Okecie Airport (1993), Poland (aircraft destroyed), with an MD-80 which hydroplaned off the runway at Barajas Airport (1996), Spain (nose undercarriage collapsed) and recently a B727 which veered off the runway during the landing roll on an ice covered runway at Hamilton, Canada (1997).

The objective of this study is to present an overview of the operating problems and certification procedures, and to quantify the degree to which the runway surface condition is associated with the probability of an accident.

2 Runway surface conditions and their impact on aircraft performance and safety

2.1 Description of Runway Surface Conditions

Before describing the impact of the runway surface condition on aircraft performance, the definitions of the runway surface condition itself must be discussed. A combination of precipitation fall rate (e.g. rainfall rate), wind, runway surface texture and design (e.g. grooved) determine the runway surface condition at a particular moment. The following runway surface conditions definitions are normally used (Based on JAR AMJ 25X1591):

- Dry runway.
- Wet runway (the runway is well soaked but without significant areas of standing water).
- Runway contaminated with water, slush[1] or loose snow (more than 25% of runway surface area covered with more than 3 mm of water, slush or loose snow).
- Runway contaminated with compacted snow.
- Runway contaminated with ice.

The last three runway conditions are defined as contaminated runways in general and also in this study. It is, however, not always easy to classify an actual runway surface condition according to the list presented here. For instance the surface condition may vary over the full length of the runway, e.g. a combination of ice and loose snow could exist or an iced-over surface may be sanded. Another problem is that the contaminant depth is usually not constant and varies along the runway.

2.2 Aircraft takeoff and landing performance on wet and contaminated runways

Runways covered with water, slush or loose snow affect both the acceleration and deceleration capabilities of an aircraft. Wet runways and runways covered with compacted snow or ice only reduce the deceleration capability. A more detailed explanation of the impact on deceleration and acceleration will be discussed in the following sections.

2.2.1 Impact on deceleration capabilities

The reduction in deceleration capabilities is caused by the reduced tire-to-ground friction when the runway is wet or contaminated. This friction force is the most important force in stopping the aircraft. Figure 1 shows an example of the braking tire-to-ground friction coefficient[2] of a Boeing 737 as function of ground speed for several runway conditions (data from Ref. 3). The

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[1] Snow that has a water content exceeding its freely drained condition such that it takes on fluid properties.

[2] Defined as the ratio of the friction force and the normal force acting on the tire. Varies between 0 and 1.

impact of runway surface condition on the braking capability of the aircraft is clearly illustrated. The reduced braking results in a longer stopping distance than on a dry runway both during a rejected take-off and during a landing. The braking capability of tires on wet runways can be significantly improved by making lateral grooves in the runway surface or by improving the texture of the runway surface.

2.2.2 Impact on acceleration capabilities

Water, slush and loose snow also affect aircraft acceleration performance due to the generation of additional drag. Both water and slush increase the rolling drag of a tire due to displacement of the water/slush. In addition to the displacement drag there is also impingement drag from the water/slush striking the airframe. The total addition drag caused by the water/slush on the runway, varies linear with water/slush depth and with the square of the ground speed. Loose snow increases the rolling drag of a tire due to displacement and compression of the snow. The impingement drag of loose snow is usually neglected. The drag due to snow compression by the tire varies linear with snow depth and is not a function of ground speed. The drag due to displacement of the snow does not vary linear with snow depth but with the square of the depth. The snow displacement drag of a tire varies (theoretically) with the square of the ground speed. More theoretical details about loose snow drag on a tire can be found in Ref. 4.

Figure 2 gives an example of the additional tire precipitation drag caused by slush on a BAC 1-11. The additional drag increases with the square of the ground speed until a maximum value is reached. At this point the drag decreases with increasing ground speed. The speed at which this occurs is called the hydroplaning or aquaplaning speed.

Figure 3 gives an example of the additional tire precipitation drag caused by loose snow on a Boeing 737 aircraft. The different components of the drag (displacement and compression), are clearly illustrated in this figure.

2.3 Hydroplaning

Figure 2 shows that at a ground speed of approximately 55 m/s (107 kts) the drag starts to decrease with increasing ground speed. At this speed the tires of the BAC 1-11 are completely separated from the ground by a film of fluid which results in a reduction of both displacement and impingement drag. This critical speed is termed the hydroplaning speed. Hydroplaning of aircraft tires has been analysed extensively (see for an overview Ref. 5). In these studies the following simple empirical equation for predicting the hydroplaning speed is frequently mentioned[3]: $v_{HP} = 9\sqrt{p/\sigma}$. The tire pressure p is in psi and the hydroplaning speed is in kts. This

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[3] Known as Horne’s equation after Walter B. Horne, a researcher at NASA who proposed it in 1963.

equation is valid for cross-ply tires moving along a water (specific density $\sigma = 1$) or slush (specific density $0.78 < \sigma < 1$) covered runway, in the spin-down condition (take-off). For a landing aircraft the (spin-up) hydroplaning speed is about 15% lower. Figure 4 shows a comparison of Horne's simple equation with measured hydroplaning speeds of a number of aircraft tires. From this figure it becomes clear that the hydroplaning speed for a radial tire is about 27% lower than for a cross-ply tire of the same pressure. The difference is likely to be caused by the different shape of the tire ground contact area (footprint area) of both tire types (See Ref. 6). Especially the ratio of the tire footprint length and width is important in this respect. Further research is needed to fully understand the reason(s) for the differences in hydroplaning speeds.

At touchdown on flooded and slush-covered runways, wheel spin-up can be delayed due to hydroplaning. This is a very critical situation because the autobrake system, the antiskid system and most automatic spoilers systems need wheel speed to be activated. In case of the automatic spoilers systems this is a safety measure to prevent inadvertent in-flight deployment. The antiskid system initially needs the wheel speed as reference otherwise skidding and locked wheels cannot be detected by the system. Most antiskid systems feature locked-wheel protection upon touchdown, implicating that wheel spin-up must occur before the anti-skid system will allow any brake pressure to be applied at all. The autobrake system, if installed, also activates upon wheel spin-up and provides immediate and symmetrical brake application after touchdown, to a programmable deceleration rate.

An additional effect of delayed spoiler deployment after touchdown is that wing lift is not immediately reduced, causing low normal forces on the landing gear and therefore delaying release of the thrust reverser locks, which are usually actuated by main landing gear strut compression (flight-ground switches). Recognising the importance of the additional stopping power of the thrust reversers (which is not affected by runway surface conditions) some aircraft manufacturers have installed thrust reverse locks that release below 10 feet radio altitude.

Autobrakes, thrust reversers and anti-skid are important means for stopping the aircraft on the runway. Therefore, it is normally advised to pilots to accomplish firm touchdowns when landing on wet and water/slush covered runways. This will improve wheel spin-up.

Table 1 gives an overview of typical main gear tire pressures, rotation speeds, and touchdown speeds for a number of commercial jet and turboprop aircraft. Also included in this table are the calculated hydroplaning speeds for landing and take-off assuming that the main gear is fitted with cross-ply tires. Touchdown and rotation speeds are considered to be the highest ground speeds an aircraft will experience in normal operation. Figure 5 and 6 show that in general, operational ground speeds during both take-off and landing, will be above the theoretical hydroplaning speed. This implies that hydroplaning is likely to occur when operating from flooded and slush covered runways.

In addition to a reduction in displacement and impingement drag, hydroplaning also reduces the tire-to-ground friction and can reduce the directional control authority of an aircraft. This makes the hydroplaning condition a critical safety concern for the aircraft and its passengers.

2.4 Directional control

One of the worst control situations occurs when there is a crosswind in conjunction with a wet or contaminated runway. In this situation the available tire-to-ground side force will be less than on a dry runway which can result in the aircraft weathervaning due to the lateral force on the vertical stabiliser and drifting sideways towards the runway edge. An example of tire side force coefficient as function of yaw angle and surface condition is given in Figure 7. The situation worsens when the wheels are locked. In this case there is no side force on the tires at all. Because of these reasons the maximum allowable crosswind reduces with decreasing runway braking capability. Figure 8 gives an example of maximum crosswind versus braking friction for a Fokker F-28 aircraft. The use of reverse thrust in crosswind conditions on wet and contaminated runways can aggravate directional control problems during rejected take-off and landing. Whenever the aircraft is allowed to weathervane into the wind, the reverse thrust force component perpendicular to the runway centreline adds to the crosswind force component. The reverse thrust will then pull the aircraft to the downwind side of the runway. The tire cornering forces are too low to counteract this drift for the existing runway conditions. The only way for the pilot to overcome this situation is to release the brakes, deselect reverse thrust or even apply some forward thrust and steer the aircraft back onto the runway centreline before reapplying any braking force. Needless to say that this manoeuvre will greatly increase the stopping distance on a contaminated runway.

Directional control problems can also arise due to frozen ruts of ice on the runway. These ruts may form furrows that catch the nosewheel and may force the aircraft from the centreline.

2.5 Other safety aspects

Besides affecting acceleration, deceleration and loss of directional control, runway contamination may also cause power loss due to water/slush spray ingestion, jammed landing gear doors and wing flaps and slats due to frozen slush or snow and damaged flaps due to impact of water or slush. Loss of forward visibility may occur during the landing roll-out due to snow blown forward by reverse thrust.

3 Certification Aspects

3.1 Take-off and landing performance on wet and contaminated runways

The world's two major certification branches, FAA and JAA have different rules for accounting for wet and contaminated runway conditions. The JAA has aircraft certification and operational rules accounting for runway surface conditions. FAA employs neither aircraft certification nor operational rules. The JAA has issued Advisory Material Joint AMJ 25X1591, providing information, guidelines, recommendations and acceptable means of compliance concerning take-off and landing on wet and contaminated runways. This AMJ provides acceptable analytical means to comply with JAR 25X1591, however, flight testing can also be used for this. The FAA has published an Advisory Circular AC-91-6A dealing with contaminated runways. In contrast to AMJ 25X1591, this Advisory Circular does not provide mathematical methods for calculating the take-off and landing performance on wet and contaminated runways. In fact it provides only limited information compared to the AMJ 25X1591. In 1986, the FAA proposed an update of it's current Advisory Circular AC-91-6A. This update provides guidelines similar to AMJ 25X1591 but is less detailed. Note that the proposed revision is still not adopted. Figure 2 presents a comparison of experimental slush drag values and calculated slush drag according to AMJ 25X1591 for a BAC 1-11 aircraft. The overall comparison between calculated and measured drag values in this example is good.

The current AMJ 25X1591 still has some shortcomings. For instance, the precipitation drag for small aircraft (e.g. business jets) appears to be underestimated by the method. Therefore, a European Commission sponsored project has been commenced in order to remove this deficiency in the current AMJ 25X1591. Partners in this project are Dassault, Saab and NLR. For this project, NLR has conducted a series of tests on the Cranfield water pond facility with its Citation II jet aircraft. Results of these tests indicate that the precipitation drag of the main gear is highly underestimated by the AMJ 25X1591 method. The difference between calculated and measured precipitation drag of the main gear is about 50% (See Figure 9). More test results are presented in Ref. 7. Another shortcoming of the AMJ is that loose snow drag is calculated using the methods for water and slush, which is incorrect from a physical point of view, since snow is compressible, and water/slush are not. This is also clearly illustrated in Ref. 8 in which a comparison between experimental and calculated precipitation drag of loose snow for a Falcon 20 aircraft, shows large differences. Both Saab and NLR have also conducted tests on snow covered runways. Results of these tests are expected soon.

It is interesting to note that both Boeing and McDonnell Douglas have developed their own methods to calculate aircraft performance on contaminated runways. These methods are mainly based on results from tests conducted with a Convair 880 aircraft (Ref. 9). The results are presented as advisory material in the aircraft operator's manual.

In general, manufacturers like Boeing, McDonnell Douglas and Airbus consider reduced V_1 and reduced screen height (from 35 ft. to 15 ft.) for take-off on wet and contaminated runways.

3.2 JAR-OPS

As from April 1, 1998 the JAR-OPS 1 requirements become effective in the JAA states for large commercial aircraft and on April 1, 1999 for small commercial aircraft. JAR-OPS prescribes requirements applicable to the operation of any civil aircraft for the purpose of commercial air transportation by any operator whose principal place of business is in a JAA Member State. Basic requirements that specifically require to account for wet and contaminated runways are stated in the JAR-OPS. General the JAR-OPS states about operations on wet and contaminated runways that *"an operator shall ensure that, for the wet and contaminated runway case, performance data is determined in accordance with JAR 25X1591 or equivalent acceptable to the Authority is used"*.

3.3 Water/slush ingestion

Another important certification aspect is water/slush ingestion. Both JAA and FAA require that "*The airplane must be designed to prevent water or slush on the runway, taxiway, or other airport operating surfaces from being directed into the engine or auxiliary power unit air inlet ducts in hazardous quantities, and the air inlet ducts must be located or protected so as to minimise the ingestion of foreign matter during takeoff, landing, and taxiing"*. Therefore manufacturers conduct water pond tests to demonstrate compliance with the air induction requirement (see JAR and FAR 25.1091). Normally this requirement sets limits to the maximum allowable water or slush depth[4]. The requirement does not speak of snow ingestion. However, there are cases known in which snow ingestion caused RTO's.

3.4 Crosswind take-offs and landings on wet and contaminated runways

As discussed in section 2.4 a landing on a wet or contaminated runway in heavy crosswind can be a critical safety concern. FAR/JAR 25.237 "Wind velocities", states the following requirement for crosswind take-offs and landings: "*For landplanes and amphibians, a 90-degree cross component of wind velocity, demonstrated to be safe for take-off and landing, must be established for dry runways and must be at least 20 knots or 0.2* V_{S0}*, whichever is greater, except that it need not exceed 25 knots"*. The requirement clearly states that only dry runways have to be considered. The crosswind values for dry runways presented in the aircraft flight

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[4] The maximum water/slush depth usually does not exceed 15 mm.

manual are the maximum demonstrated in the certification flight test program. Operators generally treat these crosswind guidelines as limits, however, there is no legal restriction on exceeding them (Ref. 10). Guidelines for the crosswind values on wet and contaminated runways are obtained through analytical methods, engineering judgement and simulation techniques. No test flights are required to establish these crosswind values. Crosswind limits for wet and contaminated runways are normally lower than the values for dry runways (See Figure 8). Interesting is that Boeing has recently revised its crosswind guidelines (See Ref. 10). For the B737, B757 and B767 there is no longer a difference between the crosswind values for dry and wet runways.

4 Operational aspects

4.1 Pilot related aspects

As explained in section 2.2, the runway conditions both affect take-off and landing performance. A crew intending to take-off from or land on a wet or contaminated runway must account for these runway conditions. Therefore, the captain needs to have information about the exact runway conditions at the moment of the take-off or landing. For instance, he needs to know the extent and nature of the runway contamination and also its depth. With this information the crew can calculate the required runway length, reduction in V_1 and/or maximum take-off weight before taking off. It is interesting to note that there are differences in practice throughout the aviation community. For instance, the maximum allowable snow depth for a take-off, applied by three different operators, was 100 mm (4 in.), 71 mm (2.8 in.) and 61 mm (2.4 in.) for the same aircraft.

Another important source of information used by pilots (especially when assessing landing performance), is the runway braking action. For many years, extensive research has been conducted on runway friction. The establishment of a correlation between friction values measured using some kind of friction tester and that of an actual aircraft was the main objective in these studies. An excellent example of such a study is given in Ref. 11. The studies conducted so far, show that the correlation of the braking friction between test device and an aircraft, varies from good to a poor correlation. This is caused by the fact that the aircraft's tire and operational characteristics (such as tire pressure and ground speed) differs significantly with the friction testers. It is therefore not surprising that Boeing claims that there is no relation between friction testers and aircraft performance on wet and contaminated runways (see Ref. 3). It must be noted that in general the correlation between friction testers and aircraft performance is very reasonable on snow and ice covered runways. There is also another problem with the use of friction values obtained from test devices. There appears to be a great deal of confusion among pilots as to the actual meaning of braking action reports and friction values of testers to the landing and rejected take-off performance of their aircraft (Ref. 12). The braking action on a runway can also be based on pilot reports. However, studies have shown that there is no correlation between pilots reports and actual friction values of a runway (See e.g. Ref. 12 and 13). Intensive research on the subject of runway friction testers is still continuing. One of the more recent initiatives, is the development of an international friction index for runway friction devices by an ASTM Task group.

The directional control problems as mentioned in section 2.4 ask for special pilot training in slippery runway operations. Contaminated runway take-off procedures may call for fixation of the nosewheel in the centered position by the pilot-not-flying, lifting the nosewheel out of the precipitation early in the take-off run, and increased vigilance on asymmetric thrust application and any deviation from the runway centreline (a “low take-off abort threshold”).

4.2 Airport operators related aspects

Airport operators have a major duty to ensure the safety of aircraft operations at their facilities. Therefore they are responsible for monitoring, reporting and improving the runway surface conditions of their facility. The ICAO “Airport Services Manual, Part 2: Pavement Surface Conditions” deals with for instance the requirements for maintaining runway friction, periodic assessment of runway conditions using friction testers, and removal of contaminates like snow (See Ref. 14 for more details). In the national Aeronautical Information Publications AIP, an overview is presented of available runway friction testers, and possible contaminate removal equipment for each international airport in the state. The equipment necessary for contaminate removal depends on many factors like airport location, climate and density of take-offs and landings which are but a few to consider. For more detailed information about airport related aspects in relation to runway surface condition, the ICAO “Airport Services Manual, Part 2: Pavement Surface Conditions” is highly recommended.

5 Analysis of historical accident data

In order to quantify the relative risk of operations on wet and contaminated runways, historical accident and movement data were analysed. The following approach was applied:

- identify a sample of take-off and landing accidents, including contributing factors and circumstances (e.g. runway surface conditions)
- compile airport movement data
- determine probabilities of runway surface condition using historical weather data

5.1 Accident data sources

Searches were conducted in the NLR Air Safety database. Additional data were obtained from Boeing and ALPA. These sources provided sufficient data to enable compilation of a virtually complete listing of reported accidents fulfilling the selection criteria presented in section 5.2.

5.2 Accident selection criteria

The following criteria were used in selecting accidents:

- The accidents must be an overrun[5] or veer-off[6] that occurred during take-off or landing.
- The accidents occurred during the period 1976 through 1995.
- The accidents occurred on an airport that is selected for this study (See section 5.3).
- The accidents involved fixed wing aircraft; turbojet and turboprop aircraft with a maximum take-off mass equal to or exceeding 5,700 kg.
- The accident flights had the following characteristics: engaged in the transportation of cargo or passengers, scheduled international and domestic flights. Military, training, and test flights were excluded.
- Accidents due to sabotage, terrorism, and military action were excluded.
- The accidents must have resulted in *at least* minor damage to the aircraft and/or minor injuries.

5.3 Airport movement data

This study was limited to European airports only. The European countries considered are listed in Table 2. The airport sample employed consists primarily of ICAO Principal International Airports. The final principal airport sample consists of 134 airports.

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[5] Overrun accident= an accident in which the aircraft could not be stopped on the runway and went beyond the end of the runway.

[6] Veer-off accident= an accident in which the aircraft could not be stopped on the runway and left of the side of the runway edge.

Movement data were obtained from the NLR aircraft movement database. This database contains movement data from different sources like annual movement totals per airport from ICAO and FAA publications, individual IFR flights from Eurocontrol[7], and scheduled flight data from the Official Airline Guide (published by the Reeds Travel Group). The last two sources are the most detailed since for each individual flight the date, origin (airport), destination (airport), aircraft type and operator are known. For this study data from the scheduled flight database were used. This database contains all scheduled passenger and cargo flights (turboprops and jets), worldwide, from 1976 through 1997. The scheduled flight database can be joined with airport, aircraft and operator databases that are also part of the NLR movement database. Comparison with published movement information (e.g. from annual airport statistics) shows that the database is accurate.

5.4 Weather data

In order to quantify the risks of operating on wet and contaminated runways the total number of take-offs and landings conducted on wet or contaminated runways must be known. The ideal situation would be to have for each individual take-off or landing the exact runway conditions at time of operation. However, such detailed information is not available. There are number of alternatives to overcome this problem. For instance there are a number of very large databases, which contain historical weather data for a large number of weather stations (including airports). There is historical weather data for about 15,000 stations worldwide. For a number of these stations, average weather data is available on a 3-hourly basis. However, for a particular weather station this data is not always complete or correct. Data of the weather stations have been stored on a large number of tapes at NOAA, in the USA. Extensive queries on these tapes are very time-consuming and thus expensive. Therefore, for this study an alternative approach was followed. If aircraft movements for a long period are considered (say about ten years), climate data can be used to accurately estimate the number of take-offs and landings on wet and contaminated runways. Detailed climate tables for airports worldwide were obtained from the Federal Climate Complex Asheville in the US. These tables contain data on the percent frequency of hourly precipitation conditions per month derived from 3 hourly observations for at least 20 years per weather station. This information can be used as an approximation for the frequency of the runway being wet or contaminated[8]. It is realised that this approach assumes that the proportion of time when the runway is wet or contaminated is equal to the proportion of time when e.g. rain or snowfall occurs. However, for small number of airports (which encounter all kinds of weather throughout the year, including heavy snowfall), detailed information on the runway surface condition was available. Comparison with these data showed that the

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[7] Contains more than 50 million individual IFR flights including military flights, covering a period from 1987-1997.

[8] A similar approach is followed in Ref. 15.

assumption made here represents the actual frequency of occurrence very well (difference less than ±8%).

For each selected airport the monthly frequency of hourly precipitation conditions was used to calculate the number of take-offs and landings conducted per month on a wet or contaminated runway. The total numbers of movements per month for each airport were obtained from the NLR movement database. From these calculations it followed that 24% of all take-offs and landings for the airports considered, were conducted on wet or contaminated runways during the period 1976 through 1995.

The average annual number of take-offs and landings on wet and contaminated runways per country are listed in Table 2.

5.5 Discussion and results

5.5.1 Univariate analysis

The total accident sample fulfilling the criteria stated in section 5.2 consists of 91 accidents, of which 68 involved jet aircraft and 23 turboprop aircraft. Of the 91 accidents, 43 were overruns and 48 veer-offs.

Table 3 presents the distribution of accidents by flight phase and runway condition. It follows from Table 3 that of all accidents in the sample, 25% occurred during take-off and 75% during the landing. This compares well with the data in the ALPA worldwide database on overruns and veer-offs (21% during take-off and 79% during landing). Of the landing accidents, 51% occurred on a wet or contaminated runway, whereas of the take-off accidents 43% occurred on a wet or contaminated runway.

In more than 50% of the accidents there was substantial damage or the aircraft was destroyed (See Table 4). There were only 5 fatal accidents (5.5%), which indicates that a veer-off or overrun accident is likely to be survivable, probably due to the low impact forces during this kind of accidents.

All 23 take-off accidents occurred after a rejected take-off (RTO). Of these RTO’s 9 (39%) were initiated after V1 was passed (See Table 5), with 8 of them on a dry runway. Of the RTO’s before V1, 8 occurred on a wet or contaminated runway.

Of the 29 overruns that occurred during landing, 16 (55%) landed too far on the runway usually with a speed higher than normal. Of these 16 landing overruns, 12 (75%) occurred on a wet or contaminated runway.

In 32 of the 48 veer-off accidents in the sample there was a directional control problem. In 32% of the cases this was accompanied with strong crosswinds. The majority of the veer-offs with directional control problems in combination with strong crosswinds, was on wet or contaminated runways (82%).

Of the 33 accidents on a wet or water/slush covered runway, hydroplaning occurred in 24% of the cases (See Table 6). It should be noted that the occurrence of hydroplaning could not be determined for 16 accidents (48.5%). This limitation should be considered when interpreting the results of Table 6.

5.5.2 Bivariate analysis

An estimate of the risk of an accident on a wet or contaminated runway relative to a dry runway can be obtained through the use of a risk ratio (RR). This risk ratio is given by the following equation:

$$RR = \frac{a / A}{n / N}$$

Where

a = number of accidents on a wet or contaminated runway
A = number of accidents on a dry runway
n = number of take-offs and landings on a wet or contaminated runway
N = number of take-offs or landings on a dry runway

The magnitude of the risk ratio provides insight into the relative association of the runway surface condition with the risk of an accident. Note that a positive association does not prove any causation. A risk ratio of 1 means there is no difference in risk if a runway is wet/contaminated or not. A risk ratio greater than 1 indicates a higher probability of an accident. The higher the risk ratio the stronger the risk associated with the runway surface condition becomes. Since the risk ratio is estimated using a sample, a test must be conducted to show whether it is statistically significant or not. For this study 2 x 2 contingency tables were used to analyse this. A 95% confidence level was assumed for all calculations.

Table 7 presents the findings from the evaluation of the relative association of the runway surface condition on the risk of an accident. All the risk ratios are significant at the 0.05 level.

Table 7 shows that the risk of an overrun or veer-off of jet and turboprop aircraft during take-off or landing on a wet or contaminated runway, is 4 times greater than on a dry runway.

The differences in risk ratio's between jet and turboprop aircraft are not statistically significant. This is interesting because it is often suggested that jets have a higher risk when operating on wet and contaminated runways than turboprop aircraft because of their higher operating speeds.

During the landing there is a slightly higher risk ratio than during the take-off for both the jet and turboprop aircraft combined as for the jet aircraft alone. Table 7 suggests that for turboprop aircraft alone the risk ratio is much higher in the take-off than in the landing. However, this is probably caused by the limited sample of 4 accidents on which this risk ratio was determined. Note that although this sample was limited the risk ratio was statistically significant at the 0.05 level.

Separate calculations for the number of take-offs and landings on snow and ice covered runways were not made. Such operations are rare compared to the operations on wet runways. Since the accident sample contains 12 accidents on snow/ice covered runways, the associated risk would be much higher than the risk ratio's presented in Table 7.

6 Conclusions and recommendations

6.1 Conclusions

- Based on a sample of European airports there appears to be a four-fold increase in the accident risk for aircraft operating on wet and contaminated runways.

- There is no significant difference in the accident risk among jet and turboprop aircraft.

- After many years of research on runway surface condition and the awareness of the impact of it on safety margins, operations on wet and contaminated runways are still associated with a higher accident probability.

- There appears to be no significant difference in accident risk during take-off and landing on wet and contaminated runways.

6.2 Recommendations

- Pilots should be aware that whenever a touchdown far down the wet or contaminated runway is likely, a go-around should be considered.

- The risk value of aircraft operations on wet and contaminated runways should be conveyed to all operators and airport authorities.

- Crosswind capabilities on wet and contaminated runways should be considered in Airworthiness documents like JAR and FAR.

- Deficiencies in the current version of AMJ 25X1591 should be removed as soon as possible.

- Research into hydroplaning of radial tires and precipitation drag of snow should be started.

- The risk quantification of operations on wet and contaminated runways should be conducted for other regions like North America.

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Table 1: Typical take-off, landing and hydroplaning speeds of commercial jet and turboprop aircraft.

Aircraft type	**Standard tire pressure of main gear** [†] **psi**	**Typical rotation speed kts**	**Take-off hydroplaning speed kts** $9\sqrt{p}$	**Typical touchdown speed kts**	**Landing hydroplaning speed kts** $7.7\sqrt{p}$
A300	196	145	126	136	108
A310	180	137	121	138	103
A320	175	128	119	135	102
A330	190	146	124	137	106
A340	186	146	123	142	105
BAe 146	133	119	104	117	89
B727	167	158	116	137	100
B737	175	137	119	133	102
B747	200	176	127	153	109
B757	170	146	117	132	100
B767	190	135	124	136	106
B777	190	150	124	138	106
DC-10	170	175	117	147	100
MD-11	205	168	129	148	110
MD-87	184	134	122	133	104
F28	101	127	90	125	77
F100	142	131	107	130	92
IL-62	157	138	113	129	96
TU-154	135	131	105	121	89
ATR 42	109	101	94	106	80
ATR 72	114	107	96	113	82
BAe ATP	86	106	83	103	71
BAe 748	86	102	83	95	71
DASH 7	107	80	93	84	80
DASH 8	131	91	103	100	88
Do-228	75	76	78	85	67
F50	82	97	81	99	70
Saab 340	115	105	97	110	83
Saab 2000	165	124	116	125	99

[†] Source: Jeppesen Sanderson 1995.

Table 2: List of countries considered for the presented study with their average annual number of operations on wet and contaminated runways.

Country	**Average annual number of take-offs and landings on wet and contaminated runways** (percentage of total)
Austria	24%
Belgium	22%
Denmark	19%
Finland	21%
France	14%
Germany*	23%
Greece	5%
Ireland	29%
Italy	11%
Luxembourg	20%
Netherlands	20%
Norway	26%
Poland	19%
Portugal	9%
Spain	6%
Sweden	19%
Switzerland	20%
Turkey	12%
United Kingdom	20%

*East-Germany included.

Table 3: Accident distribution by flight phase and runway condition.

Flight phase	**Runway condition**	**No.**	**%**
LANDING	DRY	33	36.3
LANDING	SNOW/ICE	7	7.7
LANDING	WATER/SLUSH	4	4.4
LANDING	WET	24	26.4
TAKE-OFF	DRY	13	14.3
TAKE-OFF	SNOW/ICE	5	5.5
TAKE-OFF	WATER/SLUSH	1	1.1
TAKE-OFF	WET	4	4.4

Table 4: Damage to the aircraft in the sample.

Damage	**No.**	**%**
DESTROYED	14	15.4
SUBSTANTIAL	34	37.4
MINOR	42	46.2
UNKNOWN	1	1.1

Table 5: Distribution RTO accidents.

RTO AFTER V1?	**No.**	**%**
YES	9	39.1
UNKNOWN	3	13.0
NO	11	47.8

Table 6: Hydroplaning on wet and water/slush covered runways.

Hydroplaning?	**No.**	**%**
YES	8	24.2
UNKNOWN	16	48.5
NO	9	27.3

Table 7: Risk Ratio for several combinations of aircraft type and flight phase.

Flight phase	**Jet & Turboprop aircraft**	**Jet aircraft**	**Turboprop aircraft**
Take-off & Landing	4.1	4.1	3.9
Take-off	3.2	2.5	10.8
Landing	4.4	4.9	3.2

All Risk Ratios are significant at the 0.05 level.

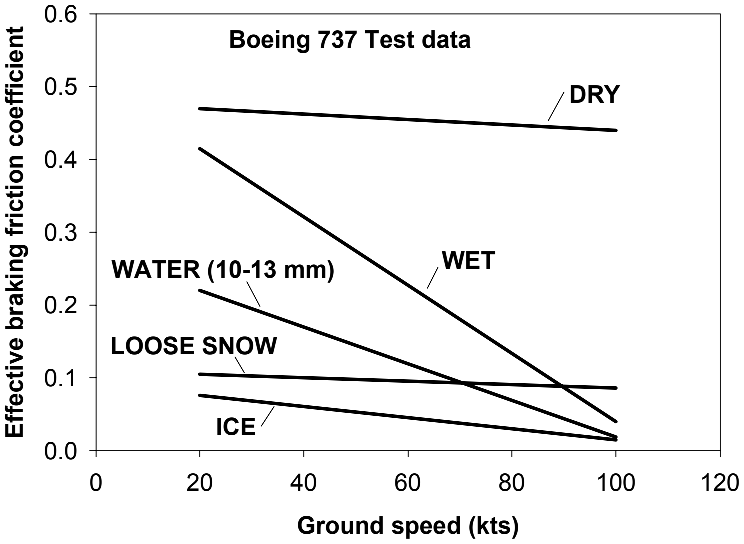

Figure 1: B-737 Tire-to-ground braking performance for different runway conditions.

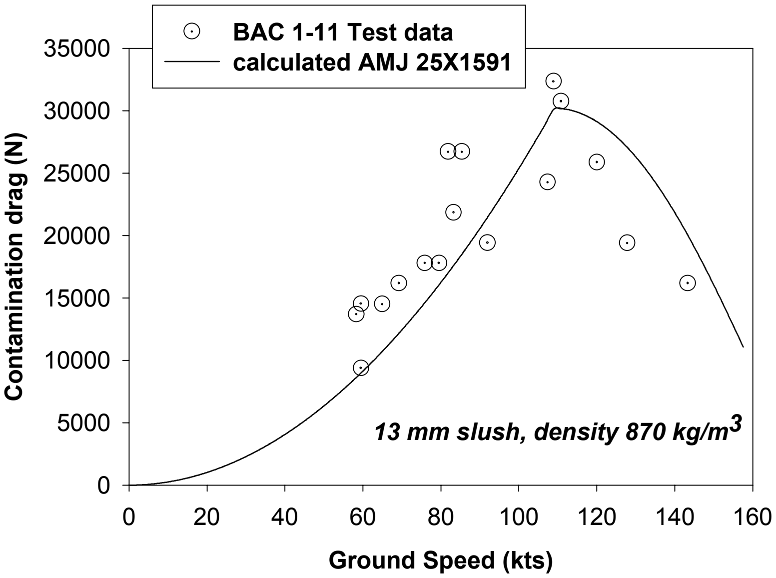

Figure 2: Contamination drag versus ground speed of a BAC 1-11 aircraft.

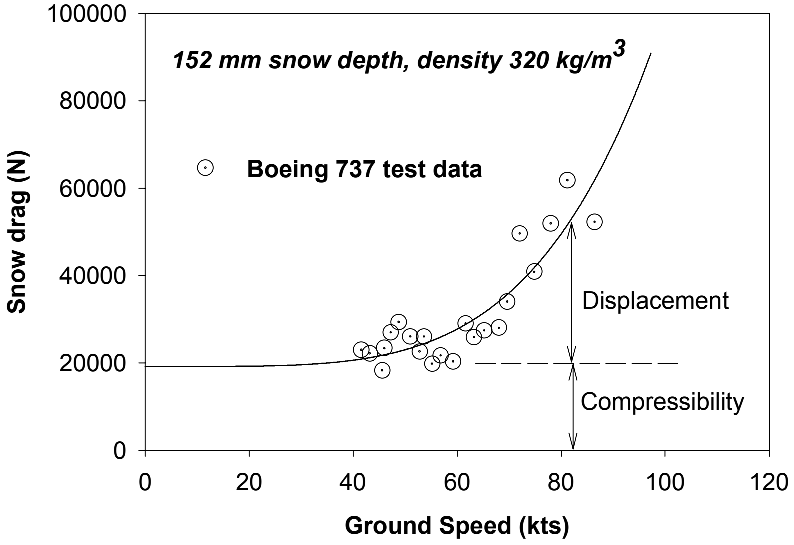

Figure 3: Snow contamination drag versus ground speed for a B-737 aircraft.

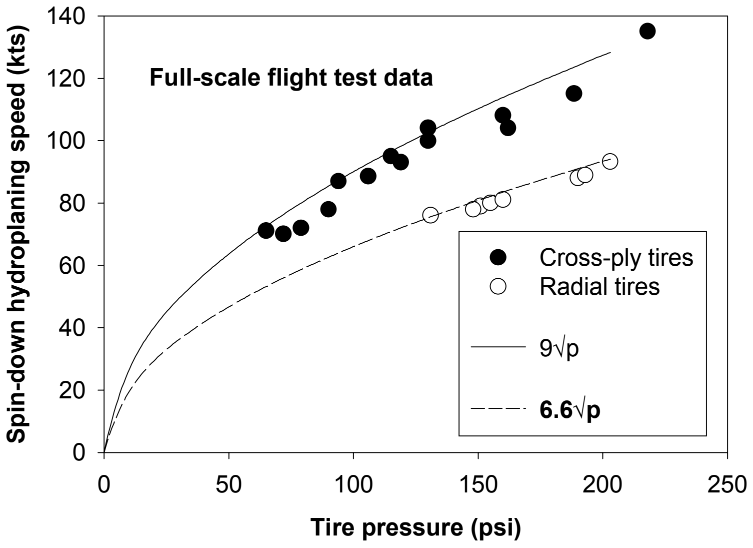

Figure 4: Experimental hydroplaning speeds versus tire pressure on water covered runways.

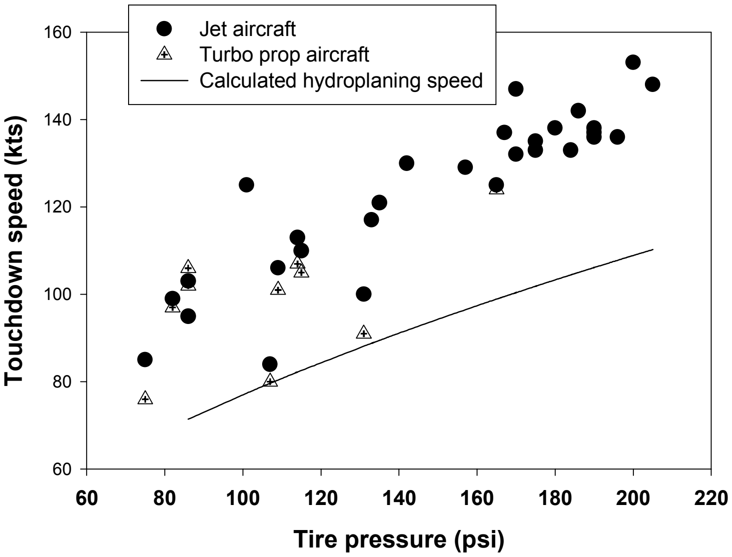

Figure 5: Touchdown and hydroplaning speeds versus main gear tire pressure.

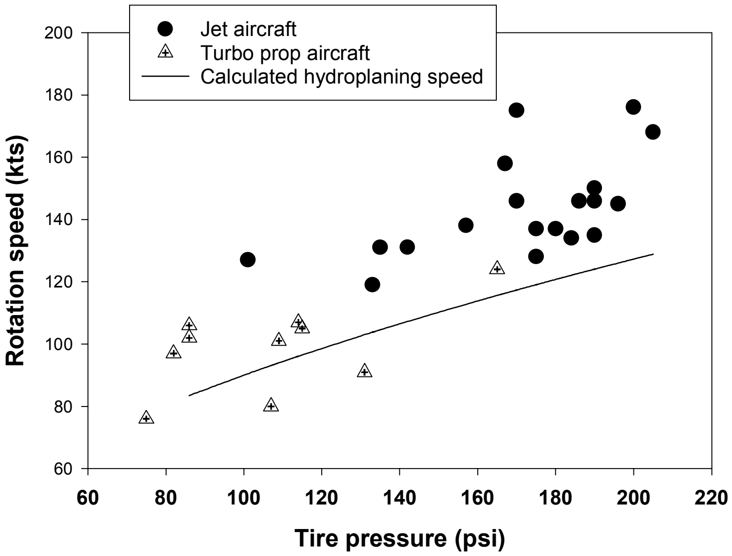

Figure 6: Rotation and hydroplaning speeds versus main gear tire pressure.

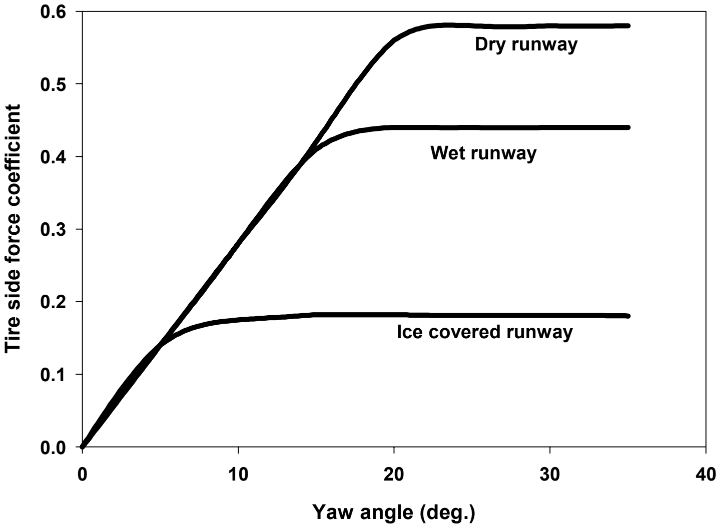

Figure 7: Tire side force coefficient as functions of tire yaw angle and surface conditions.

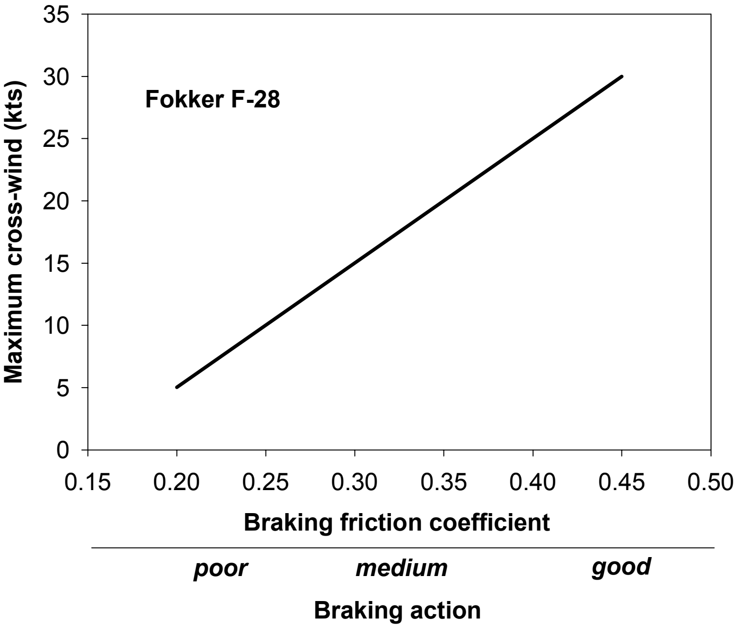

Figure 8: Maximum crosswind versus braking friction for an F-28 aircraft (from Ref. 15).

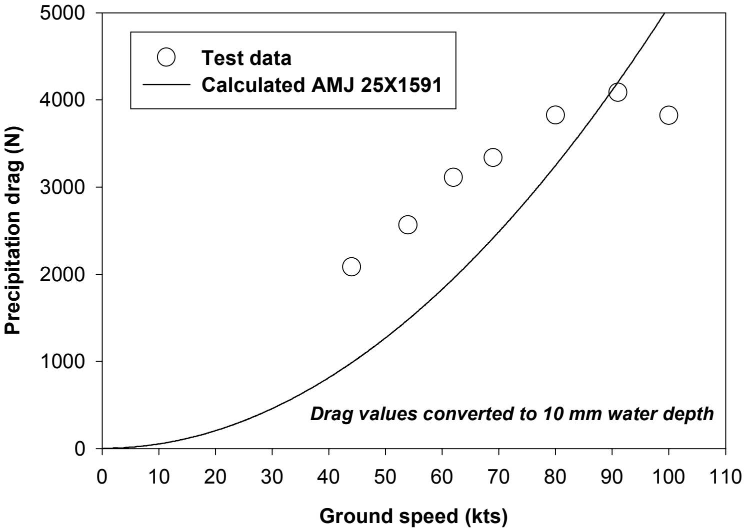

Figure 9: Calculated and measured main gear precipitation drag of a Citation II in a pond (from Ref. 7).